Closeness to the Frontier and Technological Change - Evidence from the Computer Games Industry[a]

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Abstract

This paper examines the link between closeness to the frontier and product success in industries where a complement is required to use the focal product. Here, the complement has to be as close to the frontier as the focal product. Complements falling short of this requirement cannot support the focal product. As a consequence, products close to the frontier have a smaller market potential. In this context, technological change has two implications. First, it accelerates product obsolescence as the technological frontier is pushed. Second, it increases market potential as better complements are available to support the focal product. Using a dataset covering 571 computer games with revenue data over 7 years, we find that closeness to the technological frontier has a positive effect on revenue. However, the results suggest a decreasing marginal effect, which implies an inverted U-shaped relationship for closeness to the frontier and revenue. In addition, we find that technological change has a negative effect unless the product is sufficiently close to the technological frontier.

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1 Introduction

A large stream of research has been devoted to understand the technological frontier. How nations and firms converge to either the national or global frontier (Bartelsman et al. 2008) and how fast they do so (Iacovone and Crespi 2010). Further, Coad (2008) shows how the optimal business strategy is contingent on the distance to the industry frontier and Acemoglu et al. (2002) demonstrate how economic growth is affected differently conditional on the nation's closeness to the frontier. Generally, scholars have argued that closeness to the technological frontier is beneficial because innovations foster economic growth. From this it is inferred that nations, firms and products should ideally get as close to the technological frontier as possible. However, what would happen if a position close to the technological frontier would be detrimental to product success?

We argue that a position close to the technological frontier is particularly harmful for products which require a complement. Complements are generally intended to support the primary product and do not have to meet any requirements. However, in some cases complements are expected to provide a certain performance which is tightly linked to characteristics of the focal product. This means that the closer the product is to the technological frontier, the closer the complement has to be to the technological frontier itself.

Complements that cannot provide the required performance are not useful to support the primary product. Hence, individuals owning low-performance complements will not be able to use a high-performance focal product. The firm therefore needs to consider that developing a product close to the technological frontier equates to reducing market potential. On the other hand, high-performance products are usually more appealing to consumers. This increases the chance of consumers buying the product.

While a position closer to the technological frontier diminishes market potential, it increases product attractiveness at the same time. This trade-off becomes clear when considering the extremes. First, a product that is technology-wise outdated could be supported by almost any complement. This means that anyone could buy it but no one would bother as its weak performance would not be very appealing. On the other hand, market potential would be very 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, once a product is introduced to the market, its characteristics cannot be changed; i.e. the absolute level performance remains flat for the rest of the product life cycle. Technological change pushes the frontier which has two implications: On the one hand, new product introductions lead to better substitutes for the product which ultimately lead to its obsolescence. On the other hand technological change also increases performance on the complements side. This way, more consumers are able to use the focal product. While the first effect decreases attractiveness, the latter increases market potential. This raises three specific questions that we address in this paper:

- Is there an inverted U-shaped relationship for closeness to the technological frontier and revenues?
- How is revenue driven by technological change?
- Does technological change influence the effect of CTF on revenues?

The empirical context of our study is the computer game industry, which is well-suited for the analysis for several reasons. First, system requirements are a fair measure of how close a game is 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. Using this data, we can calculate a measure for monthly hardware availability on the market and the panel structure of the dataset indicates the pace of technological change. In addition, the NPD group provides a panel with monthly revenue and sales data for the computer games, and we use MobyGames as a source for game-specific information like genre and release date. Additionally, GameSpot provides system requirements for the games which are then matched with the benchmark scores from the Futuremark dataset to obtain a measure of CTF.

Our first major result is that games that are closer to the technological frontier are more successful. While higher system requirements reduce market potential, they also make the game more attractive. This means that more consumers buy the product. 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 competition through better substitutes. 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 of technological change outweighs its negative effect of better substitutes.

Our paper is structured as follows: In section 2, we elaborate on the theoretical mechanism. Section 3 briefly outlines the computer game industry and section 4 introduces the data and variables used in our regression. Section 5 presents the empirical specification as well as the results which are then examined on their robustness in section 6. Section 7 concludes.

2 Theoretical Mechanism

Products that need a complement to function 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, will work once they are combined with an adequate complementary product. This means that they do not have particular requirements on the performance of their complement. For standardized products like the DVD it is perfectly acceptable to use any DVD-Player. Moreover, the performance of the primary product is the same no matter what the performance of the complementary item is.

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

Generally, performance of the primary product can be increased with a more powerful complement. However, it always requires a minimum performance. Complements with lower performance are not capable to support the focal product. For computer games, this is commonly referred to as the minimum system requirements specifying the hardware a computer needs to provide. Any system configuration weaker than this lower threshold is not able to run the game. Accordingly, all individuals owning a computer which does not meet the minimum system requirements are excluded from the consumption of this product.

Products close to the technological frontier appeal to consumers. However, development cost increase drastically the closer the product gets to the frontier. Firms are therefore expected to shy away from producing cutting-edge products. Even if a position close to the technological frontier would be costless, there are 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

Generally, it has been implicitly argued that nations, firms and products should get as close to the technological frontier as possible (Acemoglu et al. 2002; Bartelsman et al. 2008; Iacovone and Crespi 2010). In the same vein, Cantner et al. (2012) argue that firms producing high quality products (relative to price) are more successful. Although we believe that a position closer to the technological frontier is generally beneficial, we argue that the relationship is non-linear 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 can provide the required performance, it cannot support the focal product. These requirements are basically a function of the characteristics of the primary product. The closer the focal product is to the technological frontier, the closer the complement has to be to the frontier itself.

While the distribution of complement performance is exogenous to the firm, the choice of complementary product performance is endogenous for the individual. Hence, the firm reduces market potential as it increases technological sophistication. That is because the CTF of the focal product defines the threshold for the complementary item. All individuals with complementary products weaker than this threshold are excluded from consumption.

At the same time, products close to the frontier are more appealing to consumers. As individuals have a preference for innovative products, the chance 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 focal product would address the whole market of potential consumers but no one would bother buying it. Its far distance to the technological frontier is not appealing to consumers. By reducing the distance, the firm 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. Bringing the product closer to the frontier results in even more attractiveness which is, however, outweighed by the smaller market potential.

2.2 Technological Change

The above explained rationale for choosing CTF of a product does not consider any form of technological change. This, however, matters for at least two reasons. First, technological change leads to the obsolescence of the product because better substitutes are introduced. Adner and Snow (2010) discussed several strategies how old technologies can handle the threat of substitution by new products. However, often firms and products fail to (or even cannot) react to new competition.

This has been investigated in the context of firms and its technologies. As the environment changes, firms failing to adapt to new situation will increase the gap to environmental demands over time. This eventually leads to organizational obsolescence (Srensen and Stuart 2000). Often inertia is mentioned as a reason for why firms might not be able to adapt to these external changes (Hannan and Freeman 1984; Amburgey et al. 1993).

In the same vein, we argue that technological change significantly affects the survival of products. However, in our case, products are perfectly inert as the absolute technological sophistication is, by definition, fixed as soon as it is introduced to the market. This means that product characteristics cannot be changed after its release. New rival product introductions are more sophisticated from a technological perspective and hence push the technological frontier. Therefore, the relative level of technological sophistication of our focal product decreases as the technological frontier moves further away. Similar to the argument of Hannan and 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 side. 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 that were not able to use the focal product before might be after upgrading their complementary item. These consumers are then potentially able to use the focal product. This process of upgrading, while rather discrete on an individual level, continuously shifts the distribution of performance of complements at an aggregated level. Therefore, by definition, market potential of any product increases automatically as time progresses.

This results in an interesting trade-off when it comes to choosing the CTF for the product. In a world without technological change, the firm simply had to trade off product attractiveness with market potential. Now it has to consider that technological change exerts competitive pressure, especially for less developed products. As the technological frontier is pushed continuously, 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 zero revenue. The profit maximizing firm will therefore have an incentive to choose a shorter initial distance to the frontier than in a setting without technological change. 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 complementary items will increase thus increasing market potential for the focal product.

On the other hand, given that development costs increase drastically the closer the product gets to the technological frontier, firms might shy away from producing cutting-edge products. In the end, the firm has to decide whether the additional revenue a slight reduction in distance to the frontier yields exceeds the additional costs of development.

Additionally, in this dynamic setting, firms might experience a second force, besides the cost aspect, giving an incentive to choose a lower CTF. Highly anticipated new product releases might be interesting for consumers even if they are not cutting-edge. That is because new products are intrinsically appealing. Firms producing products close to the technological frontier might on the one hand survive for a longer time, however, they are likely to miss out on this initial hype. That is because their initial closeness to the technological frontier strongly limits their market potential. The shorter the distance of the product to the frontier the higher are the requirements on the complement. Hence, only few consumers have the possibility to even use the focal product at the time it is released. By the time that technological change increased the performance of complements, the initial hype effect has already leveled off.

To conclude, the firm has to trade off survival on the market with development costs as well as the opportunity to capture as much of the initial hype effect as possible.

3 Empirical Context

To test our theory, we use the computer games industry as the empirical context of our study. This one is well suited for the analysis, as playing a computer game requires a complementary good, 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 close to the frontier because they value realistic graphics and convincing game physics; both resulting in higher requirements on the computing power. Obviously, there are as well components of the game that do contribute to the success of the game but do not affect the distance to the frontier like an intriguing story or funny characters. Unfortunately, there is no way to objectively quantify any of these dimensions. Therefore, our analysis focuses exclusively on the closeness to the technological frontier of the game.

For firms in this environment, we identified two main trade-offs related to choosing CTF. First, shorter distance to the frontier diminishes market potential but, on the other hand, increases product attractiveness. Second, developers have to take the effect of technological change into account; the introduction of better substitutes will have a negative effect while, on the other hand, the performance of computers will rise which increases market potential. However, producing a product close to the frontier is costly. Both trade-offs are discussed in more detail in the following subsections.

3.1 Requirement of a complementary item

Clearly, technological change gave developers room for powerful graphics and more realistic game physics, which doubtlessly contributed to the advance of computer games. However, developers face a trade-off when choosing CTF. On the one hand, better graphics contribute to the gaming experience and therefore increase the chance of consumers buying it. On the other hand, the sophistication of graphical effects raises system requirements. This excludes those gamers whose PCs cannot provide sufficient computing power, thus limiting market potential. Hence, the developer has to make a strategic decision of whether he 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. This follows trivially by considering a hypothetical game with maximum system requirements. On the one hand its closeness to the frontier would be highly appealing to consumers. However, on the other hand, the market potential would be reduced to only a handful of consumers as most computers cannot provide the required hardware performance.

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 this assumption 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 clearly 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 games 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, as more powerful PCs are bought, average hardware availability improves. This implies that more computers are capable to run the game which increases market potential. Put differently, market potential increases while product attractiveness decreases. This raises again the question of how to strategically best choose the closeness to the technological frontier. From a nave point of view, one would assume that firms should choose the shortest distance to the frontier possible. This way the product would not be threatened by better substitutes and technological change would, by definition, increase market potential over time.

However, costs for producing a product close to the frontier increase drastically in closeness, which renders producing cutting-edge products uneconomically. This implies another interesting trade-off for game developers: Either they choose a higher distance to the frontier, save costs but risk disappearing from the market earlier, or they choose a costly, higher level. In the latter case, the computer game would realize lower sales during the first stage (due to smaller market potential) but report above average figures in the following periods.

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, which provides detailed information regarding genre and release date, and indicates further if a game uses licensed content, is part of a series, or utilizes a third party graphics engine.

This is paired with a dataset from the NPD Group, a leading supplier of data for this industry. This NPD data provides monthly unit and dollar sales and covers the period 1995-2008, inclusive. 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 and 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. This information includes not only 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 average hardware availability for every point in time between March 2001 and March 2010. This yields a complete time-series of monthly 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 we combine the observations from the four datasets into one. That is because the same hardware configuration would obtain different benchmark values when running it with 3DMark2001 compared to 3DMark2003.

This makes it necessary to standardize the values, i.e. to "deflate" all benchmark scores to a 3DMark2001-level. For this, we use the 3DMark2001 dataset to 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 our covariates. Additionally, we control for a squared term of processor speed to capture a potentially non-linear relationship.

Unfortunately, the 3DMark2001 data does not report RAM, which could also be a potential driver of benchmark results. Further, although our 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. In addition, we calculate the monthly system availability on the consumer side as the average benchmark scores of computers benchmarked within the last 12 months. With benchmark data starting in March 2001, we can compute an indicator for 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.

4.2.2 Closeness to the Technological Frontier

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

$$CTF_{i,t} = \frac{SystemRequirements_i}{mean(SystemAvailability_t)} \tag{1}$$

The Futuremark dataset provides benchmark scores by dates, which are then used to calculate a measure for the mean system availability by month which we use as an indicator for the technological frontier. To obtain a measure of closeness to this frontier, we divide the game's system requirements, expressed as a 3DMark2001 benchmark score, by the average benchmark score. This 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.

4.2.3 Control Variables

While the use of game-fixed effects already captures all time-constant game-specific effects in our panel regression we still control for some 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 (age_i), defined as the number of months since the date of launch.

Also, we use 12 dummies to 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.

As argued above, we expect technological change (TC_t) to drive sales significantly. Using our benchmark data, we calculate this measure as the change of average benchmark score from one month to the next in percent. However, this variable shows a strong time trend which would be highly correlated with our variable age_i. 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 our cross-section regression, we can have to control for all the time-constant covariates. For instance, we control for the genre as these might be differently successful. We further control for the logarithmized count of developers, the team size (TS_i), engaged in the creation of the computer game, as this variable is expected to significantly drive development costs. 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 and Table 2 reports the respective correlations. The total logarithmized revenue ranges between 2.485 and 17.89, which equals roughly $58.8 million. 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

Looking at the statistics of $CTF_{i,t}$, 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 $CTF_{(i,t)}$. Clearly, recommended hardware requirements are significantly higher but are 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 Game's Total Success

In our first regression we want to identify the effect of closeness to the frontier on the total success of a game with a cross section. We therefore use the sum of revenues of the first 12 months as an indicator of the game's total success. In our dataset, the average game made 83.7% of its total revenue within the first year.

We use a cross-section of our dataset with aggregated revenues as the dependent variable and CTF_i at the date of release. The following OLS regression model is estimated using robust standard errors:

$$Log(TotalRev)_i = \alpha_0 + CTF_i + CTF_i^2 + X_i + \sum_{g=1}^{g} dg + \sum_{m=1}^{12} dm + u_i \tag{2}$$

The variable X_i is a vector of multiple control variables that are all 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 the monthly revenue.

We use the following specification

$$Log(Rev_{(i,t)}) = \alpha_0 + age_{i,t} + TC_t + TC_t * CTF_i + \sum_{m=1}^{12} dm + u_i + \epsilon_{i,t} \tag{3}$$

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.

We use an interaction term to find out 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 $\epsilon_{i,t}$, 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

Here, we find positive and highly significant coefficients for team size. The additional controls all have the expected sings and are 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 to some extent. 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 also negative and significant. However, the interaction term for technological change and closeness to the frontier is positive which indicates that technological change is not generally detrimental to sales but can be positive if the product is sufficiently close to the technological frontier.

Insert Table 4 here

Our results reveal an interesting (second) trade-off. As expected, the effect of technological change is negative. That is because, as technology advances, better products are released. For older products it therefore becomes increasingly difficult to attract consumers, which eventually leads to obsolescence.

On the other hand, our results show that technological change can have a positive effect as it increases market potential. This effect is particularly relevant for games close to the technological frontier. For those, the initial market potential is small as the high system requirements exclude a large proportion of potential consumers. As technological change improves average hardware availability (because consumers replace old PCs with new ones), market potential increases for the game.

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 that the results are not sensitive 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. One with the full revenue information, one with first 36 months revenue, one with first 24 months and one with first 6 months of revenue. Results are reported in Table 5. We find that the results are 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 Calculation of Closeness Measure

As mentioned in section 4, we translated the game's system requirements into a 3DMark2001 benchmark score using the regression coefficients. In the regression, we controlled for two different types of graphic cards. We chose to use the coefficient for ATI graphic cards to predict the benchmark score for the games. This choice, obviously, was completely arbitrary.

To show that the results are not sensitive to different calculations of the closeness measure, we predict two additional benchmark scores as closeness indicators of games: One assuming that an NVIDIA graphic card is required and one omitting any coefficients of graphic cards. The results are reported in Table 6 and show that, again, the relationship remains stable. While the linear term is positive and significant, the squared term is negative and significant.

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. Hence, the variable is dropped because of perfect multicollinearity. Model (4) of Table 6 shows that as well in a log-log-specification, the relationship between closeness to the frontier and product success remains positive and significant.

7 Concluding Remarks

In this paper we investigate the effect of closeness to the technological frontier on the success of computer games, using data from 571 games over the 2002-2008 time period. Our regressions have uncovered a number of interesting findings. First, we find that computer games that are 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, 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 preliminary 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 the handicap requirement. 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 a large-scale research, which we hope to have inspired with our paper. More research on this topic would clearly 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 our dataset only provides information on minimum system requirements. Clearly, in order to enjoy the game, more powerful hardware is recommended. 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 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, which, again, is an idiosyncrasy of the gaming community. However, since these biases are systematic they do not make our findings less valid.

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.

Using system requirements as a measure of closeness to the technological frontier might have a down side in this context. As we do not have any information on the development process of the game, we do not know if the programmers might have 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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Appendix

Table 1: Summary Statistics

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

Table 2: Correlation Table

Variables	(1)	(2)	(3)	(4)
(1) $TotalRev_i$ / $Rev_{i,t}$	1.000			
(2) Closeness to Frontier CTF_i	0.140	1.000		
(3) Detrended Technological Change TC_t	0.499	0.179	1.000	
(4) Teamsize TS_i	0.463	0.014	-0.014	1.000

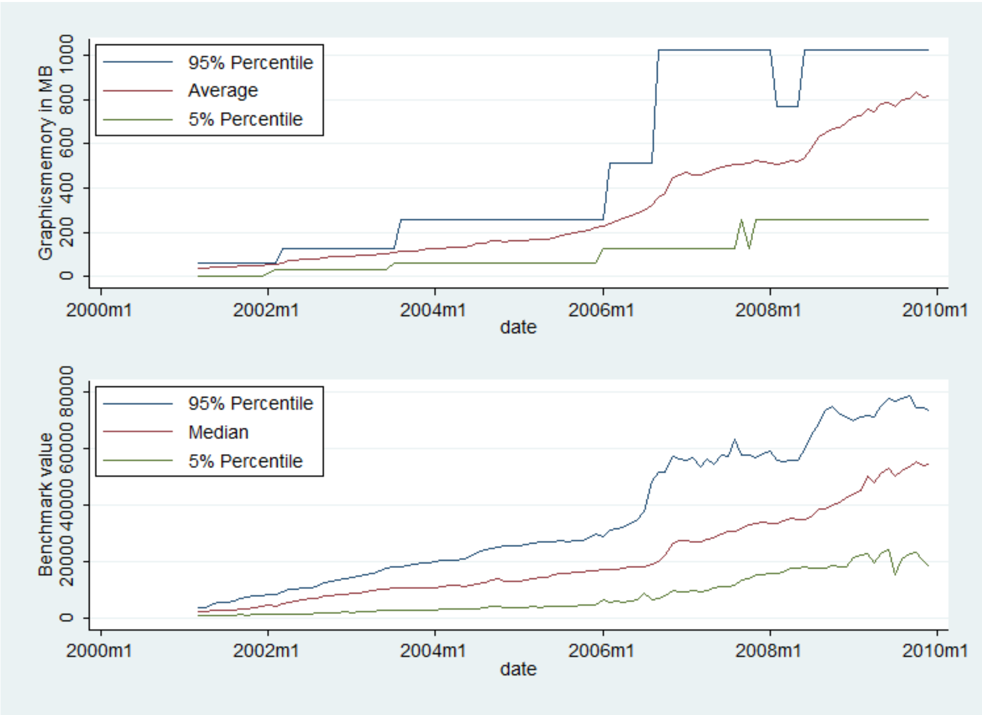

Figure 1: Development of Graphics Memory and Benchmark Scores 2001-2010

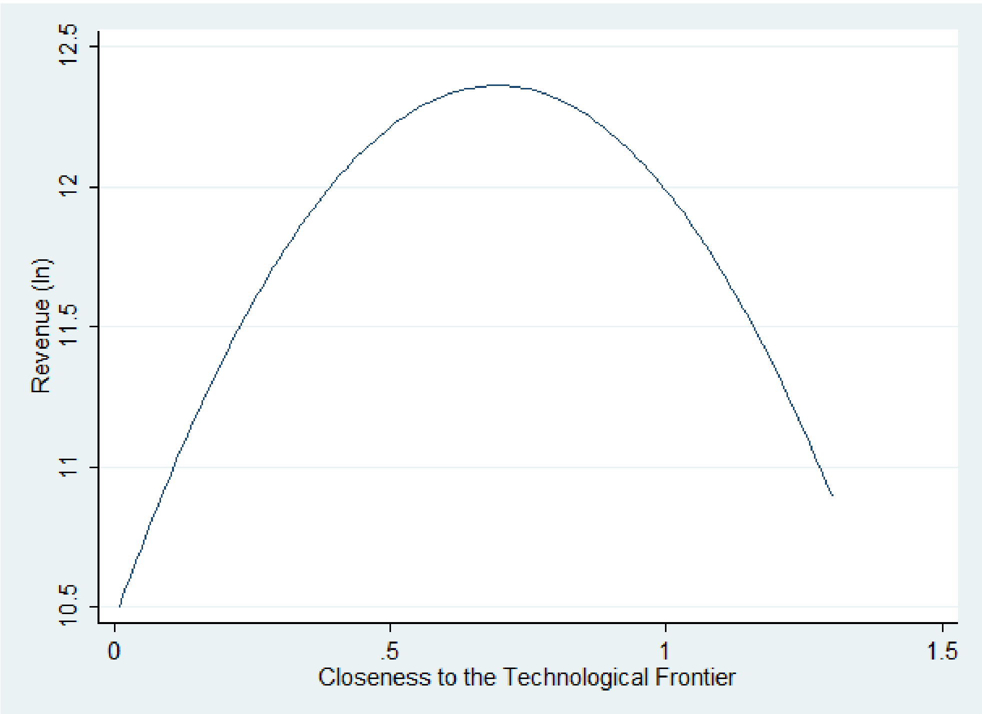

Figure 2: Relationship *CTF* and Revenue

Table 3: Static Model (Dep. Var.: $TotalRev_i$)

Variable	(1)	(2)	(3)
Closeness to Frontier CTF_i		2.114***	5.514***
		(0.654)	(1.511)
Closeness to Frontier squared CTF_i^2			-3.977**
			(1.586)
Teamsize TS_i	0.004***	0.004***	0.005***
	(0.001)	(0.001)	(0.001)
Series Dummy	YES	YES	YES
Licensed Content Dummy	YES	YES	YES
Special Technology Dummy	YES	YES	YES
3D-Engine Dummy	YES	YES	YES
Genre	YES	YES	YES
Calendar Month	YES	YES	YES
R-squared	0.347	0.368	0.374
N	571	571	571
F-Test	12.479	11.272	11.729

* p<0.1, ** p<0.05, *** p<0.01
Robust standard errors in parentheses.

Table 4: Dynamic Model (Dep. Var.: $Rev_{i,t}$)

Variable	(1)
$age_{(i,t)}$	-0.124***
	(0.002)
Detrended Technological Change TC_t	-18.916***
	(4.282)
Interaction $TC_t * CTF_i$	69.853***
	(11.895)
Calendar Month	YES
Estimation Method	FE
R-squared	0.764
N	32,743
F-Test	516.011

* p<0.1, ** p<0.05, *** p<0.01
Notes: Fixed-effect OLS point estimates. Standard errors are clustered at the game level. The specification 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: Robustness Checks (Dep. Var.: $TotalRev_i$)

Variable	(1)	(2)	(3)	(4)	(5)
Closeness to Frontier 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 squared CTF_i^2	-4.134**	-4.000**	-3.963**	-3.977**	-3.796**
	(1.645)	(1.673)	(1.661)	(1.586)	(1.622)
Teamsize TS_i	0.005***	0.005***	0.005***	0.005***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Series Dummy	YES	YES	YES	YES	YES
Licensed Content Dummy	YES	YES	YES	YES	YES
Special Technology Dummy	YES	YES	YES	YES	YES
3D-Engine Dummy	YES	YES	YES	YES	YES
Genre	YES	YES	YES	YES	YES
Calendar Month	YES	YES	YES	YES	YES
R-squared	0.383	0.382	0.383	0.374	0.358
N of obs	571	571	571	571	571
F-Test	12.973	13.030	13.120	11.729	12.238

* p<0.1, ** p<0.05, *** p<0.01

Robust standard errors in parentheses.

Model (1) estimates the full sample

Model (2), (3), (4) and (5) calculate total revenues as first 36, 24, 12 and 6 months revenues, respectively.

Table 6: Robustness Checks (Dep. Var.: $TotalRev_i$ for Model (1)-(3). $Rev_{i,t}$ for Model (4))

Variable	**(1)**	**(2)**	**(3)**	**(4)**
Closeness to Frontier CTF_i	5.514***	5.215***	3.561***	
	(1.511)	(1.283)	(1.266)	
Closeness to Frontier squared CTF_i^2	-3.977**	-4.360***	-3.831***	
	(1.586)	(1.196)	(0.995)	
Teamsize TS_i	0.005***	0.005***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Closeness to Frontier (ln) CTF_i				0.760***
				(0.182)
Series Dummy	YES	YES	YES	YES
Licensed Content Dummy	YES	YES	YES	YES
Special Technology Dummy	YES	YES	YES	YES
3D-Engine Dummy	YES	YES	YES	YES
Genre	YES	YES	YES	YES
Calendar Month	YES	YES	YES	YES
R-squared	0.374	0.367	0.355	0.371
N of obs	571	571	571	571
F-Test	11.729	11.625	11.673	11.720

* p<0.1, ** p<0.05, *** p<0.01

Robust standard errors in parentheses.

Model (1) uses a CTF measure with no graphic card compenent, whereas model (2) and (3) use the CTF measure each calculated with an NVIDIA and ATI graphic card, respectively.

Model (4) estimates the panel specification using the log of CTF.

A quadratic term was dropped due to multicollinearity.

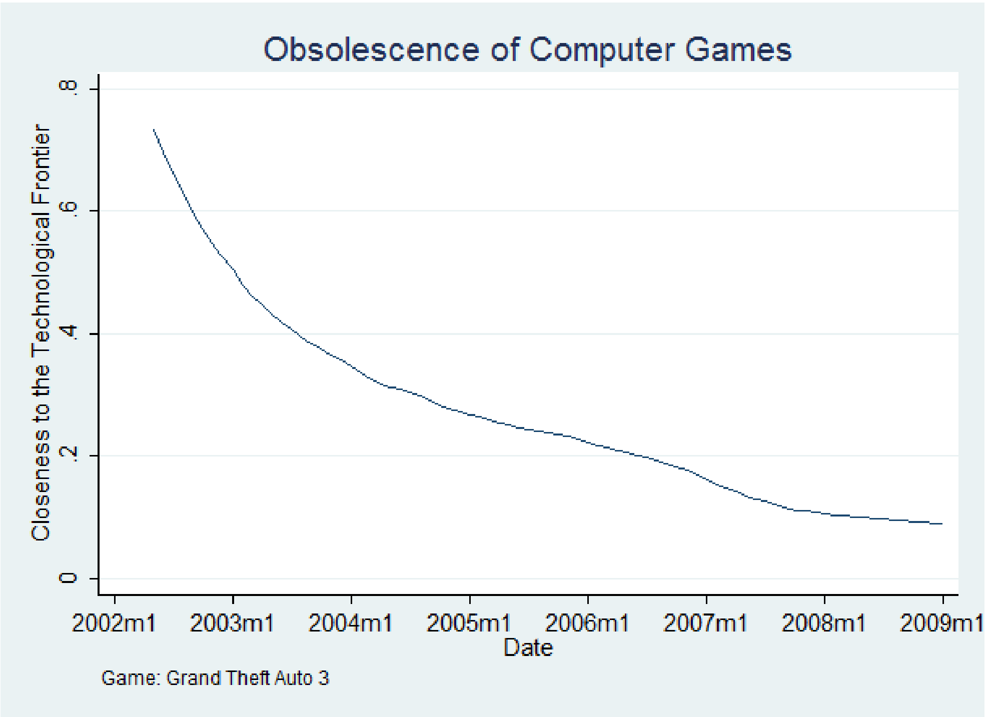

Figure 3: Obsolescence of Computer Games