Author(s) Dedehayir, Ozgur; Mäkinen, Saku

Title Measuring industry clockspeed in the systemic industry context

Citation Dedehayir, Ozgur; Mäkinen, Saku 2011. Measuring industry clockspeed in the systemic industry context. Technovation vol. 31, num. 12, 627-637.

Year 2011

DOI http://dx.doi.org/10.1016/j.technovation.2011.07.008

Version Post-print

URN http://URN.fi/URN:NBN:fi:tty-201311261474

Measuring Industry Clockspeed in the Systemic Industry Context

Ozgur Dedehayir[a, *] and Saku J. Mäkinen[a]

[a] CITER, Center for Technology and Innovation Research, Department of Industrial Management, Tampere University of Technology, PO Box 541, FI 33101, Tampere, Finland

* Corresponding author:
Ozgur Dedehayir
ozgur.dedehayir@tut.fi
tel: +358 44 586 8514
fax: +358 3 3115 2207

Abstract
Industry clockspeed has been used in earlier literature to assess the rate of change of industries but this measure remains limited in its application in longitudinal analyses as well as in systemic industry contexts. Nevertheless, there is a growing need for such a measure as business ecosystems replace standalone products and organisations are required to manage their innovation process in increasingly systemic contexts. In this paper, we firstly derive a temporal measure of technological industry clockspeed, which evaluates the time between successively higher levels of performance in the industry's product technology, over time. We secondly derive a systemic technological industry clockspeed for systemic industry contexts, which measures the time required for a particular sub-industry to utilise the level of technological performance that is provisioned by another, interdependent sub-industry. In turn, we illustrate the use of these measures in an empirical study of the systemic personal computer industry. The results of our empirical illustration show that the proposed clockspeeds together provide informative measures of the pace of change for sub-industries and systemic industry. We subsequently discuss the organisational considerations and theoretical implications of the proposed measures.

Keywords: systemic industry; technological system; reverse salient; industry clockspeed

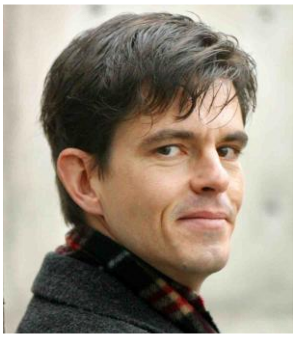
This paper has been published in Technovation 31(2011)627–637

http://dx.doi.org/10.1016/j.technovation.2011.07.008

Vitae

Ozgur Dedehayir, Ph.D., is a Research Fellow at the Tampere University of Technology (TUT), Finland. He is a member of CITER (Center for Innovation and Technology Research), conducting his research on the evolution of the PC technological system, focusing on processor and graphics related technical performance in computer gaming. The central theme in his research is the concept of reverse salience, which depicts the disequilibrium between different sub-systems in a continuously evolving socio-technical system. He received a B.Sc. in Mechanical Engineering from the University of Melbourne, Australia, and an M.Sc. in Industrial Management from TUT, Finland.

Saku J. Mäkinen, PhD, is Professor of Technology and Innovation Management and the Head of the Department of Industrial Management at Tampere University of Technology (TUT), Finland. Prof. Mäkinen was formerly with the Department of Marketing, Faculty of Business Administration, National University of Singapore, NUS. He received an M.Sc. in Electrical Engineering and a PhD in Technology Strategy, both from TUT, Finland. He has widely published in international forums like Technological Forecasting and Social Change, and IEEE Transactions on Engineering Management in the areas of his research interests, which include technology and innovation management, strategy, and technology and industry co-evolution.



Measuring Industry Clockspeed in the Systemic Industry Context

1 Introduction

Industries change over time, thereby altering the competitive environment of organisations (McGahan, 2004; Eisenhardt and Brown, 1998; Porter, 1985). The performance as well as the survival of organisations is dependent on how they negotiate the changing industry through appropriate technological choices along the time path of industry evolution (Gort and Wall, 1986; Strebel, 1987; Rice and Galvin, 2008). In making these technological choices, organisations additionally face the need to manage their innovation process in an intertwined environment where actors form business ecosystems (Tiwana et al., 2010; Adner and Kapoor, 2010; Adner, 2006). However, the pace of industry change itself varies over time (Klepper and Graddy, 1990; Suarez and Lanzolla, 2005), emphasising the need for organisations to deploy technological strategies in a timely fashion and engage in time-based competition (Stalk, 1988; Bessant et al., 1996). In this dynamic environment, organisations face increasing time pressure to innovate (Gupta and Sounder, 1998), which calls for flexible new product development processes that facilitate both rapid and anticipative management of the timing of innovations (MacCormack et al., 2001). Consequently, knowledge concerning the speed of change in the industry can benefit organisations to adapt to their dynamic, competitive environments (Bourgeois and Eisenhardt, 1988; Hannan and Freeman, 1977; Van de Ven and Poole, 1995; Subramanian et al., 2011).

Industry change has been measured using different parameters, such as the number of organisations in the industry (Chesbrough, 2003; Suarez and Utterback, 1995; Carroll and Hannan, 1989), the number of industry patents (Agarwal, 1998; Brockhoff et al., 1999), and the industry"s annual turnover (Gooroochurn and Hanley, 2007). In this paper we focus on the clockspeed measure of industry change, which differentiates between industries by comparing their rates of change in product technology, process technology, and organisational capability (Fine, 1998). While the clockspeed measure has so far been used to evaluate the rate of change of specific industries, it has not been used to measure the rate of change of the industry in its systemic industry context. Nevertheless, there is a growing need for such a measure as business ecosystems replace standalone products (Tiwana et al., 2010) and organisations are required to manage their innovation process in a systemic context.

Here, by systemic industry we refer to a hierarchical network of sub-industries (Ethiraj and Puranam, 2004) that specialise in producing the interdependent technical sub-systems of a hierarchically structured technological system (Murmann and Frenken, 2006; Tushman and Murmann, 1998; Clark, 1985). In this manner, sub-industries are interdependently connected to one another due to the interrelatedness of their output technologies. Systemic industries may therefore produce complex product systems (CoPS) such as aircraft engines, flight simulators, and offshore oil platforms, (Hansen and Rush, 1998; Hobday, 1998; Miller et al., 1995), and modular systems such as PCs (personal computers) and automobiles (Baldwin and Clark, 1997; Langlois and Robertson, 1992; Persson and Åhlström, 2006) that integrate functionally interdependent sub-systems, produced by their own specialised sub-industries, into holistic systemic products.

In systemic industries, a clockspeed measure that compares the pace of change of a particular sub-industry with respect to the pace of change of other, interdependent sub-industries can greatly aid organisations to cope with their dynamic environment. This is because the new product development (NPD) processes of organisations in systemic industries are intertwined with performance improvements in the sub-system technologies that are central to their own sub-industry, as well as with the interfaces between other, interdependent sub-industries that produce interdependent technological sub-systems (Ethiraj and Puranam, 2004). Moreover, an organisation inside a sub-industry may remain more competitive by utilising information about the rate of change of interdependent sub-industries because performance deficiencies in complementary technologies may jeopardise the ability of the organisation to create its own value for end-users (Adner and Kapoor, 2010). A clockspeed measure for the systemic context could therefore aid organisations to recognise whether their systemic industry and its sub-industries can be considered to lie within moderately changing or high-velocity markets (Eisenhardt and Martin, 2000), and act accordingly through NPD processes.

In this paper we aim to extend the current understanding of the rate of industry change by firstly developing an additional measure of industry clockspeed, namely, technological industry clockspeed. This clockspeed measure is premised on the product technology measure proposed by Fine (1998), and measures the time between successively higher levels of performance in the industry‟s product technology across time. Secondly, we develop a clockspeed measure for systemic contexts, namely, systemic technological industry clockspeed, by considering the performance discrepancies that emerge between interrelated sub-systems over time. In these states of technological disequilibrium (Rosenberg, 1976), we focus on the reverse salient sub-system (Hughes, 1983), which utilises the lowest level of performance provisioned by the system‟s technological performance frontier and thus hinders the performance delivery of the systemic product. In turn, the systemic technological industry clockspeed measures the duration of time required for the reverse salient sub-system to utilise the provisioned level of performance. We demonstrate the use of these clockspeed measures in an illustrative, longitudinal study of the systemic PC (personal computer) industry, focusing on specific sub-industries that produce the sub-systems which are central for computer gaming on the holistic PC system.

2 Theoretical background

2.1 Industry dynamics and clockspeed

The evolution of industries is marked by changing competitive environments (Audretsch, 1995; Malerba et al., 1999; Wezel, 2005). Organisations subsequently make technological and competitive choices along the time path of industry evolution (Gort and Wall, 1986; Strebel, 1987; Rice and Galvin, 2008), which determine the rates of product and process innovation (Abernathy and Utterback, 1978), the entry and exit of organisations (Klepper and Graddy, 1990; Gort and Klepper, 1982; Utterback and Suarez, 1993; Klepper, 1996), and the changing basis of product competition (Christensen, 1997) that are witnessed throughout the industry‟s development. From an organisational standpoint, the evolution of the industry is important, since different phases pose varying conditions that influence the performance as well as the survival of the organisation (Suarez and Utterback, 1995; Jovanovic, 1982; Jovanovic and MacDonald, 1994; Agarwal et al., 2002; Agarwal and Gort, 1996). Moreover, organisations occupy „macro-niches‟ and ‟micro-niches‟ that pose differing competitive landscapes (Baum and Singh, 1994), which also have differing dynamics in their pace of change.

Industries not only change due to competitive dynamics but do so at different rates, subsequent, for example, to the differing pace of introduction and utilisation of technological innovations in the industry (Klepper and Graddy, 1990; Suarez and Lanzolla, 2005; Audretsch, 1995). Consequently, organisations must implement and dynamically alter strategies to cope with the different rates of change in the industry‟s evolution (Eisenhardt and Martin, 2000; Eisenhardt and Tabrizi, 1995; Teece et al., 1997; Helfat et al., 2007), which are manifest, for instance, in the innovations and technological changes (e.g. Romanelli and Tushman, 1994). The changing pace of industry development thus requires the timely modification of the organisation‟s activities and assets in order to remain competitive in the industry (McGahan, 2004; Eisenhardt and Brown, 1998; McGahan, 2000).

Under rapidly changing circumstances, organisations may engage in time-based competition that centres on improving manufacturing, reducing sales and distribution time, and generally improving innovation capability (Stalk, 1988; Bessant et al., 1996), as readily witnessed in fast-cycle industries (Bourgeois and Eisenhardt, 1988; Williams, 1992) such as the computer hardware and software industry (Eisenhardt and Tabrizi, 1995; Rosas-Vega and Vokurka, 2000). Such transformations of organisational activities have been shown to be effective if they do not purely concentrate only on productivity gains but at the same time consider innovativeness, timing, and flexibility (Benner and Tushman, 2003; Brown and Eisenhardt, 1997). Especially in dynamic environments, organisations engage in time-based competition and exploration to focus on reducing the time to market of their innovations (Bayus, 1997; Cohen et al., 1996), in other words, the duration of time required for the conception, development, production, and delivery of the innovation (Datar et al., 1997; Meyer and Utterback, 1995).

Different metrics have consequently been developed to evaluate and explain the rate of change of industries. However, in this paper we specifically focus on the clockspeed measure of industry change introduced by Fine (1998). The clockspeed of industries has been analysed in the literature with various methods, such as the changes in product technology using the proxy of the rate of new product introductions, the changes in process technology using the proxy of the rate of obsolescence of process technologies, and the changes in organisational capability using the proxy of the rate of change in organisational structure (Fine, 1998). A number of quantitative studies have subsequently illustrated these methods in the analysis of endogenous and exogenous factors that lead to different rates of change in industries (Nadkarni and Narayanan, 2007; Souza et al., 2004; Mendelson and Pillai, 1999; Guimaraes et al., 2002). As demonstrated in these studies, the clockspeed measure differentiates between the high and low clockspeeds of specific industries. However, organisations positioned in dynamically changing competitive environments additionally require a temporal clockspeed measure of industries that can detect possible life cycle effects (Fine, 1998), thereby providing a guideline for the implementation of NPD processes (Mu et al., 2009; Brown and Eisenhardt, 1995; Bessant and Francis, 1997).

In this paper we aim to develop an additional measure of industry clockspeed, which is premised on the product technology measure proposed by Fine (1998). Rather than assessing the rate of new product introductions, our clockspeed measure, namely technological industry clockspeed, measures the time between successively higher levels of performance in the industry‟s product technology evolution, traditionally observed as S-curves (Fisher and Pry, 1971; Foster, 1986; Ehrnberg, 1995; Sood and Tellis, 2005; Nieto et al., 1998; Roussel, 1984; Lee and Nakicenovic, 1988; Becker and Speltz, 1983). Therefore, shorter spans of time between successively higher levels of performance indicate faster industry clockspeeds. As a consequence, we take an evolutionary view (Van de Ven and Poole, 1995), such that we assign clockspeed measures to assess the changes in activities of the population of entities (i.e. a population of organisations or those inhabiting niches), where the population consists of the organisations that share common form with respect to inputs and outputs and which lie within a boundary defined by their markets (Hannan and Freeman, 1977). The clockspeed measure indicates changes at the population or industry level, which arises from the search for "technical and evolutionary fitness" at the organisational level (Helfat et al., 2007).

2.2 Systemic industries and the time gap measure of clockspeed

Systemic industries produce technological systems (Bonaccorsi and Giuri, 2000; Barnett, 1990) that are hierarchically structured networks of interdependent technical sub-systems (Murmann and Frenken, 2006; Tushman and Murmann, 1998; Clark, 1985). Systemic industries therefore comprise sub-industries (Ethiraj and Puranam, 2004) which are specialised in producing the different technical sub-systems that, due to their functional relatedness, work together to provide the performance of the systemic industry"s product to the end-user (Garud and Kumaraswamy, 1995; Ulrich, 1995). Therefore, the utility of the systemic products is provided by the integration of functionally interdependent sub-systems that are produced by their own specialised sub-industries, for example engines and airframes in the case of aircraft (Bonaccorsi and Giuri, 2000; Schilling, 2000), and microprocessors, graphics processors, and software in the case of PCs (Ethiraj and Puranam, 2004; Macher and Mowery, 2004).

The networked structure of systemic industries may arise over time from the vertical specialisation of industries (Macher and Mowery, 2004; Stigler, 1951;

Hyvättinen, 2006) and the modularisation of products and processes (Baldwin and Clark, 1997; Langlois and Robertson, 1992; Baldwin and Clark, 2000; Brusoni and Prencipe, 2001). Further, systemic industries are depicted in complex product systems (CoPS) such as nuclear plants, weapon systems, and turnkey industrial equipment (Bonaccorsi et al., 1996), which are high cost capital goods that are customised and therefore manufactured on a project basis rather than mass produced (Hansen and Rush, 1998; Hobday, 1998; Miller et al., 1995; Prencipe, 2000), and large technical systems (LTS) such as electric power and railway networks (Hughes, 1983; Mayntz and Hughes, 1988; Geels, 2006). In this manner, modular systems, CoPS, and LTS are representatives of systemic industries because they are technological systems that integrate a large number of different, interdependent technical sub-systems, which are developed by specialised producers.

The evolution of these technological systems is the outcome of underlying change mechanisms that are supply-side, in other words technology push mechanisms, on the one hand and/or demand-side, in other words market pull mechanisms, on the other (Dosi, 1982; Adner and Levinthal, 2001; Mowery and Rosenberg, 1979). Consequently, systemic industries and technological systems undergo change subject to technological evolutions including both intra- and inter-industry innovations taking place within the hierarchy of sub-industries (Henderson and Clark, 1990), driven by endogenous and exogenous factors. The systemic relationship between sub-industries additionally suggests that changes in the technological output of one sub-industry may affect the technological output of other, interdependent sub-industries and also the output of the systemic industry as a collective whole.

However, the evolution of sub-industries leads to the emergence of discrepancies in the level of technological development and the level of utilisation of these technological developments between interdependent sub-industries. These discrepancies are results of different levels of technological performance that are delivered by the sub-systems, and they, at the same time, curb the level of performance that is delivered by the systemic product to the end-user. In this state of disequilibrium, the technical sub-system that provides the lowest level of technological performance relative to other sub-systems, and subsequently limits the output performance of the technological system, is termed the reverse salient (Hughes, 1983). Its low level of performance means that the reverse salient strays behind the system"s technological performance frontier that denotes the highest level of performance (Dosi, 1982) established by the relatively advanced, or salient, sub-system. Furthermore, the reverse salient inhibits the performance delivery of the technological system because technological improvements in other sub-systems cannot materialise at the holistic system level performance delivery until the reverse salient advances sufficiently to capitalise on its own potential gains (Rosenkopf and Nerkar, 1999). Hence, examples of reverse salients include the motor and capacitor sub-systems of the early direct-current electric system that inhibited the efficient distribution of electricity (Hughes, 1983), the gyroscope sub-system of the ballistic missile technological system that limited the accuracy of missiles (MacKenzie, 1987), and the computing hardware sub-system in the flight simulator technological system that prevented application capabilities in simulations (Rosenkopf and Nerkar, 1999).

This state of technological disequilibrium, at a particular point in time, reflects the lower level of performance that is utilised by the reverse salient sub-system with respect to the level of performance that is provisioned by the interdependent, salient sub-system. Here, the provisioning and utilisation of performance is not limited to merely complementary sub-systems of the technological system (Teece, 1986), such as hardware and software sub-systems of the PC, but rather stems from the interdependence between sub-systems in general. Subsequently, the technological advancement of a sub-system at the technological performance frontier provisions, directly or indirectly, a level of performance potential to other sub-systems that, driven by the evolution of the technological system, is utilised by these sub-systems over time. The length of time required for the reverse salient to utilise the level of performance that is provisioned by the interdependent, salient sub-system importantly informs of the rate of development of the reverse salient sub-system in the technological system context.

It therefore follows that the duration of time required for the sub-industry that produces the reverse salient technical sub-system (hereafter referred to as the reverse salient sub-industry) to produce the higher level of technological performance that is embedded in the technical sub-system produced by the salient sub-industry, denotes the rate of change of the reverse salient sub-industry in its systemic industry context. We subsequently use this duration of time for the reverse salient sub-industry to utilise the level of technological performance provisioned by the salient sub-industry to measure the systemic technological industry clockspeed. Similar to the technological industry clockspeed, shorter spans of time between the provisioning and utilisation of technological performances indicate faster clockspeeds in the systemic industry context. For organisations positioned in dynamically changing systemic industries, the systemic technological industry clockspeed offers a central measure in considering the time-to-market decisions in the NPD process.

3 Methodology

In this paper we develop two clockspeed measures. Firstly, we propose a technological industry clockspeed which evaluates the rate of performance accumulation in an industry with respect to a given technology over time, following the traditional S-curve model of technological performance evolution (Fisher and Pry, 1971; Foster, 1986; Ehrnberg, 1995; Sood and Tellis, 2005; Nieto et al., 1998; Roussel, 1984; Lee and Nakicenovic, 1988; Becker and Speltz, 1983; Ayres, 1988). In this manner, we derive the evolution of the technological sub-system by quantitatively measuring the change in a particular technological performance indicator over time (Sahal, 1981).

Secondly, we propose a clockspeed measure for the systemic industry context, which compares the rate of technological performance development of a sub-industry with the rate of development of other, interdependent sub-industries, namely, the systemic technological industry clockspeed. To derive this clockspeed measure, we consider the provisioning and utilisation of technological performance in the technical sub-systems produced by interdependent sub-industries. We begin by considering the technological evolution of two interdependent sub-systems within a given technological system. We assume that one sub-system provisions a certain level of technological performance (i.e. the salient sub-system), while the other sub-system utilises the provisioned technological performance (i.e. the reverse salient sub-system). To measure the systemic technological industry clockspeed we then evaluate the time gaps of the technology provisioning and utilisation from the superimposition and comparison of the technological evolution curves of the two sub-systems on a common set of axes (see Figure 1).

Insert Figure 1 about here

Our schematic representation of reverse salience in Figure 1 compares the technological performance evolution of the reverse salient, represented by the dashed line, with the technological performance evolution of the salient sub-system, represented by the solid line. Thus, the solid line represents the technological performance frontier, and at the same time, the potential level of technological performance that can be utilised by the reverse salient across time. The magnitude of systemic technological industry clockspeed at any point along the time axis is measured by calculating the horizontal separation of the reverse salient from the salient line at that point. This separation reflects the length of time that is required for the reverse salient sub-system to utilise the level of technological performance that had been provisioned by the salient sub-system at an earlier point in time.

In this manner, we develop both proposed clockspeed measures from the relational perspective of time (Hood, 1948; Zaheer et al., 1999), whereby time derives from the relations of occasions (Rhodes, 1885). Here, we consider, for example, occasion *A* as the salient sub-industry‟s launch of a new product with a new, higher level of technological performance, and a later occasion *B* as the reverse salient sub-industry‟s launch of a new product utilising the same level of performance that was launched at occasion *A* by the salient sub-industry. Subsequently, with respect to the systemic industry, the duration of time required for the reverse salient sub-industry to produce the technical sub-system with the same level of technological performance that is embedded in the technical sub-system produced by the interdependent, salient sub-industry, determines the systemic technological industry clockspeed of the reverse salient sub-industry. Hence, Figure 1 illustrates two technological industry clockspeed measurements for the reverse salient sub-industry, denoted by Δt_{A1} and Δt_{A2}, at time t_3 and t_4, and two systemic technological industry clockspeed measurements for the reverse salient sub-industry in its systemic context, denoted by Δt_{B1} and Δt_{B2}, at time t_3 and t_4, respectively.

3.1 The PC technological system

In our empirical illustration, we have considered the PC industry as a systemic industry that produces the PC technological system, whereby the utility of the holistic PC system to the consumer is provided by the integration of functionally interdependent sub-systems that are produced by their own specialised sub-industries (Ethiraj and Puranam, 2004; Macher and Mowery, 2004). Further, we have analysed the PC technological system by focusing specifically on its function as a computer gaming platform. The PC technological system provided a suitable empirical setting for our illustration due to its significance as a platform for computer gaming since the 1990s (Hayes and Dinsey, 1995; Poole, 2004), its systemic nature (Baldwin and Clark, 1997; Langlois and Robertson, 1992; Schilling, 2000), and its highly dynamic nature of technological evolution (Eisenhardt and Tabrizi, 1995; Rosas-Vega and Vokurka, 2000). In particular, the evolution of the PC technological system has witnessed and embraced Moore‟s law (Moore, 1965), which has established the pace of change in the PC industry and its sub-industries. Therefore, actors in the systemic PC industry, like hardware and software developers, have become accustomed to expect this type of dynamics in utilising the evolving performance of technology in NPD processes. All of the above lend us a rich setting with continuously changing performance disparities, thereby making the PC technological system informative for illustration purposes.

Our empirical illustration concentrates on the technical sub-systems that are central for the delivery of gaming performance in the PC. In our study we therefore analyse the PC game software as one technical sub-system, focusing on its co-evolution with two important and interdependent hardware sub-systems: the CPU (central processing unit) and GPU (graphics processing unit), respectively. The interdependence of these sub-systems is apparent, since PC game software is intended to function together with the CPU and GPU sub-systems, utilising the performance which they make available. Moreover, the hardware inherently acts as a platform upon which game software can be developed (Tiwana et al., 2010; Kanev and Sugiyama, 1998). As part of this process, many hardware manufacturers provide support for software development, for example, in the form of software development kits (SDK) following the launch of their new hardware, which game developers anticipate and strategically select and utilise in the development of their new products. This naturally results in a time delay for the software to fully utilise the performance of available hardware. This delay is further exacerbated by the developers‟ need to test the compatibility of the software and hardware, for example, by testing each new game‟s capability to function with individual video cards (Ripolles and Chover, 2008). Furthermore, the search for technology-market opportunities, realisation of concepts, and the desire to avoid risks of project delays and cost over-runs in a highly dynamic technological ecosystem motivates software developers to delay their technology selection as much as possible (MacCormack et al., 2001).

Due to the resulting delay in utilising the technological performance provisioned by the CPU and GPU sub-systems, the PC game sub-system inevitably emerges as the reverse salient that curbs the holistic PC system performance. Our empirical study therefore illustrates the systemic technological industry clockspeed of the PC game software sub-industry, which, in producing game software, requires some duration of time to utilise the provisioned level of technological performance embedded in the hardware products of the CPU and GPU sub-industries. Here, we make an important distinction between the co-evolution of technical sub-systems (e.g. that of hardware and software sub-systems), and the technical performance levels that can be observed for these sub-systems. While co-evolution processes influence sub-system performances, in this study we focus only on the resultant technical performance levels. As a result, although we acknowledge the commonly held view that game software drives the development of computer hardware (e.g. Shirley et al., 2008) we focus merely on the performance utilisation delays that inherently exist in software development, rather than seeking the mechanisms which may bring this about.

3.2 The data

For each of the studied technical sub-systems we selected technological performance indicators that would allow the analysis of performance evolution and the measurement of clockspeeds. For the PC game software sub-system we have considered that the software is designed to utilise a certain level of hardware performance such that the intended game qualities can materialise on the holistic PC system. For this purpose, the game software stipulates a set of minimum hardware performance requirements with which the software will function as designed. However, the game software can additionally be designed to deliver a second, higher level of gaming experience (i.e. recommended hardware performance requirements), for example by making additional game features accessible during game play. This higher level of gaming performance can be experienced if the specified level of hardware performance is available, which is discretely higher than the performance specified by the minimum requirements. Nevertheless, in our study we have focused only on the functional performance of the game software and not on the additional gaming experience that is designed into the software. Therefore, we use the minimum requirements as a proxy for the intended level of functional performance that the PC system as a whole should be delivering from the software developers‟ point of view. Consequently, we have used the minimum hardware requirement stipulated by the PC game software as its technological performance indicator. In this manner, we identify a PC game to have a higher level of technological performance than another when its stipulated minimum hardware requirements are higher than those of the latter. This is because a PC game that requires a higher level of hardware performance has more capacity to deliver a higher level of functional performance on the holistic PC system.

While the performance of the CPU can be measured along different dimensions (for example MIPS – millions of instructions per second, number of transistors, bus bandwidth, etc.), we have selected the performance indicator of processing speed, measured in Hertz (Hz), since this is the parameter that is most important for PC game developers and publishers for game functionality. The processor speed indicates the

CPU‟s speed of operation, governing the computational performance of the PC through its interaction with software programs such as PC games. Higher speeds mean faster data manipulation, which increases the holistic PC system‟s potential to deliver performance such as during gaming. Similarly, while the performance of the GPU can be measured along different dimensions, we have selected the performance indicator of graphics memory, measured in megabytes (MB), since this is the parameter that is most important for PC game developers and publishers for game functionality. The graphics memory denotes the GPU‟s ability to store and make available graphics data to the PC. Larger memory increases the PC‟s potential to deliver graphics performance during, for example, game play.

Our empirical illustration comprised two parts. First, we studied the technological evolutions of the CPU and PC game sub-systems. We measured the technological performance of the CPU using the parameter of processor speed and the PC game using the parameter of minimum processor speed requirements, both measured in Hertz. Second, we studied the technological evolutions of the GPU and PC game sub-systems. We used the parameter of graphics memory to measure the technological performance of the GPU, and the parameter of minimum graphics memory requirement to measure the technological performance of the PC game, both measured in megabytes. The technological evolutions of the CPU and PC game sub-systems, as well as the GPU and PC game sub-systems, were in turn superimposed onto respective sets of axes. As a result, we were firstly able to measure the technological industry clockspeeds of the sub-industries using the processor speed and graphics memory technological performance indicators, and secondly, to evaluate the measures of the systemic technological industry clockspeed for the PC game software sub-industry in its systemic context with respect to the CPU and GPU sub-industries, respectively.

We collected data on CPU processor speeds from processor performance databases found on Intel and AMD (Advanced Micro Devices) corporate web sites, the two primary manufacturers of CPUs. In the generation of this data set we omitted CPUs that were designed for applications other than desktop PCs because our study focuses on games that are played by consumers on personal computers. Additionally, we omitted multi-core CPUs from the data set because this new technological platform represents a significant shift in the technological paradigm of the CPU, whereby processing speed may no longer be the most prevalent indicator of CPU performance, and we deemed this additional dimension unnecessary in our illustration of the clockspeed measurement. Similarly, we accessed GPU graphics memory data from the corporate web sites of NVIDIA and ATI (acquired by AMD on October 2006), the two dominant players in the graphics processor industry. The data on PC game minimum processor speed requirements as well as minimum graphics memory requirements were, in turn, collected from the web sites of game publishers and game developers, as well as the gaming community Gamespot.com and a major on-line PC game vendor, Amazon.com. The list of PC games used in our empirical analysis was generated as a result of filtering steps that ensured the reliability of the data. Firstly, we limited the list of PC games to only those that had been reviewed and rated by either one reputable online source, Gamespot.com, or one reputable printed source, PC Gamer magazine (the reputation of these sources was identified by experts from the game development industry). The reputability of these sources was deemed to provide the required list of all the PC games that influenced the industries involved in a meaningful way. A game which had therefore not been reviewed by either of these sources was discarded on the basis that it did not meet the quality standards of the gaming industry at large and that its inclusion could therefore reduce the reliability of our data set. Further, we limited the list of PC games to those which had been launched in the United States.

In our data gathering method we selected appropriate time scales, as outlined by Zaheer et al. (1999), which fit the objective of our research. We firstly considered the existence interval, in other words the length of time over which the phenomenon occurs, to be one day, because the launch of new CPU and GPU hardware, and launch of new PC game software is associated with a particular day of the year. Secondly, in recording the data, we did not select a specific recording interval because our study has been designed to gather and analyse data, *ex-post*. We thirdly used varying aggregation intervals to report the gathered data, implementing an event-driven rather than an interval-driven recording strategy. Finally, we selected an observation interval that stretches from August 1995 until the end of 2008. We selected the beginning of the observation interval to correspond to the launch of the Windows 95 operating system that established a new technological platform upon which hardware and PC game software could be developed and therefore produced a significant change in the gaming industry (Hayes and Dinsey, 1995). Altogether, 600 CPU and 2900 PC game related data points on processor speed, as well as 120 GPU and 2050 PC game related data points on graphics memory, were collected and evaluated to reveal the technological evolution curves of the sub-systems and therefore the technological industry clockspeeds of the individual sub-industries, and in turn, the systemic technological industry clockspeed of the PC game software industry in its systemic context with the CPU and GPU sub-industries, respectively.

4 Results and discussion

In line with our schematic framework of reverse salience in Figure 1, we first plot the technological development curves of the CPU and PC game sub-systems with respect to the technological performance indicator of processing speed, and the technological development curves of the GPU and PC game sub-systems with respect to the technological performance indicator of graphics memory. We present these plots in figures 2 and 3, respectively.

Insert Figure 2 about here

Insert Figure 3 about here

In the above figures, the development curves depict the successively higher levels of technological performance that are introduced by the CPU, GPU, and PC game sub-industries, over time. Figures 2 and 3 also show that the technological performance development of the PC game software sub-industry trails the technological performance development of the CPU and GPU sub-industries, respectively, at all times within the timeframe of analysis. By not fully utilising the level of technical performance that is provisioned by the hardware sub-systems, the PC game sub-system curbs the performance delivery of the PC system. We subsequently ascribe the PC game sub-system as a reverse salient, according to the definition of a reverse salient, which is the sub-system that delivers the lowest level of technological performance and concurrently hinders the meta-system level performance delivery.

From the technological development curves shown in figures 2 and 3, we measure the technological industry clockspeeds of the CPU, GPU, and PC game sub-industries from the durations of time between the launch of products with successively higher levels of technological performance. We present the evolution of the technological industry clockspeed measures of the CPU sub-industry in Figure 4, and the PC game software sub-industry, using the minimum processor speed requirement performance indicator, in Figure 5.

Insert Figure 4 about here

Insert Figure 5 about here

Figure 4 indicates that after an early period of low technological industry clockspeed in the CPU sub-industry, an increase in the clockspeed is witnessed from approximately 1999 until 2003, as the time between successive launches in technological performance levels reduces. We posit that the latter period, in which a CPU with higher level of technological performance is launched every 200 days or less, indicates the high tempo of time pacing in the sub-industry (Eisenhardt and Brown,

1998) and the intensifying focus of the CPU sub-industry on the processor speed performance. Subsequently, organisations in the CPU sub-industry engage in time-based competition in response to the rapidly changing technological environment to maintain competitiveness (Stalk, 1988), thereby continuing the period of frequent launch of products with higher performance. However, recent years, following the period of intense time-based competition, show a decrease in the technological industry clockspeed. Interestingly, this period of time coincides with the technical limitations that materialised in CPU development, leading to diminishing gains in processor speeds, which may have led to the increasing duration of time between successively higher performing CPUs. However, these technical reverse salients in the CPU were circumvented by the CPU sub-industry in 2005 through the introduction of a new technological paradigm reflected in the multi-core CPU, while the processor speed performance of the single core paradigm stagnated at the end of 2004, as illustrated in Figure 2.

The technological industry clockspeed of the PC game software sub-industry using the minimum processor speed requirement performance indicator, shown in Figure 5, similarly displays a period of increasing clockspeed from the beginning of the analysed timeframe until approximately the end of 2004, after which a brief period of high variation in the clockspeed is witnessed.

We in turn present the evolution of the technological industry clockspeed measures for the GPU sub-industry in Figure 6, and for the PC game software sub-industry, using the minimum graphics memory requirement performance indicator, in Figure 7.

Insert Figure 6 about here

Insert Figure 7 about here

Both figures 6 and 7 show significant variation in the GPU and PC game software sub-industry technological industry clockspeeds across the timeframe of analysis. Reflecting on the evolution of these sub-industries, represented by their technological performance evolution curves plotted in Figure 3, we believe that the sub-industries are progressing through the early phases of their respective technology life cycles, a phase which was also witnessed in the technological industry clockspeed evolutions of the CPU and PC game software sub-industries using minimum processor speed requirement. We therefore suspect a gradual intensification of time-based competition based on graphics performance among organisations in the GPU and PC game software sub-industries, leading to increased clockspeeds, as the sub-industries progress through their life cycles over time.

Our analyses, overall, show that the technological industry clockspeeds of the sub-industries slow down to as low as two to three years in the rate of launch of new, higher levels of technological performance. This outcome is commensurate with the findings of Mendelson and Pillai (1999), who have also shown the rhythm of development activity in the PC and minicomputer industries to stretch to as much as three years. In our study, we additionally analysed whether the technological industry clockspeed differentiates the sub-industries from one another in their systemic contexts. As a result, the mean for the technological industry clockspeed measure for the CPU sub-industry was 263 days (std. dev. 245), and for the PC game software sub-industry, using minimum processor speed requirement as performance indicator, 372 days (std. dev. 267). Further, the mean for the technological industry clockspeed measure for the GPU sub-industry resulted in 546 days (std. dev. 248) and for the PC games software sub-industry, using minimum graphics memory requirement as performance indicator, in 541 days (std. dev. 247). At face value, we therefore observe that the dynamics of the technological industry clockspeed measures for the CPU and of PC game software sub-industries, using minimum processor speed requirement as performance indicator, are comparable to one another, and similarly the GPU and PC game software sub-industries, using minimum graphics memory requirement as performance indicator, exhibit dynamics of the technological industry clockspeed measure that are akin to each other. Furthermore, the observed clockspeed measures show that the variances of the two sub-industry pairs are different overall (Levene„s test, $p < .0001$), and further, that the means of the pairs are also different (two-tailed t-test, $p < .000$). These results support the systemic relationship between the sub-industry pairs, whereby the technological performance that is provisioned by one sub-industry influences the technological performance that is utilised by the other, interdependent sub-industry.

Finally, to derive the systemic technological industry clockspeed of PC game software, we consider the level of technological performance that is provisioned by the CPU and GPU sub-industries, and evaluate the time delay for the PC game software sub-industry‟s utilisation of the processor and graphics performance, respectively.

Figures 8 and 9 display the evolutions of the systemic technological industry clockspeeds across the timeframe of our analysis.

Insert Figure 8 about here

Insert Figure 9 about here

The systemic technological industry clockspeed of the PC game software sub-industry with respect to the CPU sub-industry development shows a continuously increasing time delay of technological performance utilisation. At first glance, this result suggests that the higher levels of computer gaming performance delivered in the holistic PC system, in other words the greater utility the consumer receives in playing computer games on the PC, subsequent to the interdependence of the CPU and PC game software sub-systems, requires longer lengths of time to materialise as the systemic industry evolves. Interestingly, this outcome contrasts with the evolution of the sub-industry‟s own technological industry clockspeed measure presented earlier in Figure 5, which showed increasing clockspeed and intensifying time-based competition among organisations within the sub-industry. Hence, from an organisational standpoint, the combination of these results suggests that while PC game software developing organisations do see value in engaging in time-based competition to remain competitive in the context of their own sub-industry, they do not necessarily derive competitive advantage by engaging in time-based competition in the systemic context. It therefore appears that PC game software developers engage in time-based competition that centres on satisfying needs other than those of strictly utilising the level of processing performance that is provisioned by the CPU sub-industry.

In contrast, the longitudinal analysis of the PC game software sub-industry"s systemic technological industry clockspeed with respect to the GPU sub-industry development shows three sequential eras marked by increasing, constant, and finally decreasing clockspeed. This evolution of the systemic technological industry clockspeed indicates the diminishing competitive advantage that PC game software developers derive from time-based competition centring on graphics performance, in the systemic context. Interestingly, the changes in the systemic technological industry clockspeed reflect the changing basis of competition that is expected to take place throughout the life cycle of an industry (Christensen, 1997). In this manner, we interpret that in the first era of increasing clockspeed, the basis of competition in the PC game software sub-industry has centred on utilising, with reducing delay, the level of graphics performance provisioned by the GPU sub-industry. This era therefore emphasises the importance that organisations assign to reacting, in a timely manner, to changes in the systemic industry that are manifest in the rate of change in interdependent sub-industries. Nevertheless, we posit that the following eras of constant and decreasing systemic technological industry clockspeed denote a shift away from the basis of competition that utilises the provisioned graphics memory capacity by the GPU sub-industry. The decrease in the systemic technological industry clockspeed may, for example, reflect the shift in the basis of competition to the timely utilisation of technological performance provisioned by other sub-industries.

5 Conclusion and implications

In this paper we have contributed to the study of systemic industries that produce technological systems, by developing means through which the rate of change of sub-industries can be measured. To this end, we have extended the current understanding of industry evolution by developing a temporal measure of the sub-industry‟s own technological industry clockspeed, and further, by developing a temporal measure of the sub-industry‟s systemic technological industry clockspeed. First, we have developed the measure of the sub-industry‟s own technological industry clockspeed by evaluating the durations of time between the launch of products with successively higher technological performance. And second, building on the theory of reverse salience, we have developed the systemic technological industry clockspeed measure by evaluating the length of time that is required for the reverse salient sub-industry (i.e. the sub-industry producing the sub-system with the lowest level of technological performance) to utilise the level of technological performance provisioned by the advanced, salient sub-industry. In turn, we have demonstrated the use of these temporal clockspeed measures in an illustrative, longitudinal analysis of the systemic PC industry that is commonly perceived as being a technology-intensive industry (Eisenhardt and Tabrizi, 1995). In our illustration we have focused specifically on the sub-industries that produce the technological sub-systems which are central for computer gaming in the holistic PC system.

The results of our empirical illustration show that the technological industry clockspeeds of the studied CPU, GPU, and PC game software sub-industries evolve across time, which verifies Fine‟s (1998) notion of some deviation in the industry‟s rate of change over time. In these observations, we suggest that increasing technological industry clockspeeds signify intensifying time-based competition among organisations in the respective sub-industries that focus on quicker development of new products with higher technological performance. Additionally, the observed patterns of technological industry clockspeed evolution suggest that there may be different eras of change that emerge across the evolution of these sub-industries. Moreover, these technological industry clockspeed eras, in a similar manner to the number of organisations, product sales, and innovations (Abernathy and Utterback, 1978; Gort and Klepper, 1982; McGahan, 2000) may be linked to the different phases of industry evolution. The limited observation interval of our empirical study, however, prevents us from comparing the different life cycle phases of the studied sub-industries and the different technological industry clockspeed eras.

Our empirical results further suggest that in the systemic industry context, the systemic technological industry clockspeed of the reverse salient sub-industry may progress through three sequential eras marked by increasing, constant, and finally decreasing clockspeed. We suspect that this pattern of change indicates the diminishing competitive advantage that organisations in the sub-industry derive from time-based competition centring on the utilisation of the level of technological performance that is provisioned by the salient sub-industry. Moreover, organisations within the reverse salient sub-industry may over time engage in time-based competition that centres on satisfying other needs within the systemic context, thereby reflecting the shifting basis of competition that is expected to take place during the development of the sub-industry (Christensen, 1997).

We believe that this shift may materialise in the systemic context for several reasons. Firstly, the NPD efforts of organisations in the reverse salient sub-industry may be delayed in response to the technological progress in interdependent sub-industries due to the increased learning demands imposed by increasing complexities. In our empirical illustration, despite their capacity to anticipate future demand for hardware performance, game developers may not be able to fully utilise the potential performance levels due to numerous other game attributes which require attention. These include artistic, graphical, character-role, and plot related considerations, which are interlinked to one another as well as to the hardware performance through which they materialise.

Secondly, the decreasing clockspeed in the systemic industry context may be attributed to the growing discrepancy between the NPD processes in the salient and reverse salient sub-industries. In this manner, the results of our empirical illustration may be caused by the uncoupling of the hardware manufacturers" and game software developers" NPD activities, which may inform of the degree of interdependence between these sub-industries.

Thirdly, technological developments in the salient sub-industry (i.e. hardware industries) may substantially overshoot the performance demands of consumers (Christensen, 1997) . As a result, organisations in the reverse salient sub-industry (i.e. software developers) may shift their new product development focus away from utilising the technological performance provisioned by the salient sub-industry, toward following the technological requirements of consumers. Nevertheless, the limitation of our paper necessitates further research that considers consumer demand and its evolution in analysing such transition between competitive domains of the reverse salient sub-industry.

And fourthly, the observed shift may result from the change in the basis of competition from utilising the provisioned performance of one sub-industry, to utilising the provisioned performance of another. In our illustrative study, such a shift may, for example, take place when the PC game software sub-industry reorients its NPD focus from utilising the processor speed performance provisioned by the CPU sub-industry, to utilising the graphics memory performance provisioned by the GPU sub-industry. The temporal limitation imposed by our observation interval does not, however, allow us to determine the point of transition between these competitive domains, thereby requiring supplementary research. Furthermore, future studies can additionally extend the scope of analysis, limited in this paper for illustrative purposes, to study the evolutions of other interdependent sub-industries linked to computer gaming on the PC system. This extension will allow the study of a sequence of competitive domain transitions for the PC game software sub-industry in its systemic industry context, as the sub-industry successively shifts its competitive focus in utilising technological performance that is provisioned by different sub-industries.

The proposed measures of industry clockspeed can be integral parts of the decision making process concerning the designed performance levels of new products and the timing of their introductions, and hence offer both managerial and theoretical implications. The systemic technological industry clockspeed measure firstly pinpoints the rate of technological performance gap closure between different sub-industries and therefore the development of technological performance that can be delivered by the systemic product, over time. This is valuable information for organisations which are embedded in systemic industries that produce technological systems, such as CoPS, LTS, and modular systems, because these organisations derive competitive advantage by understanding the value of performance improvements in the sub-system technology that is central to their own sub-industry, as well as through the management of the interface between other, interdependent sub-industries that produce the interdependent technological sub-systems (Adner and Kapoor, 2010; Ethiraj and Puranam, 2004). As a result, firms are able to formulate strategies by not only monitoring the rate of growth and the level of R&D activity in their own industries (Griffiths and Webster, 2010), but also by observing the changes taking place in their immediate environments (Subramanian et al., 2011).

Furthermore, the systemic technological industry clockspeed measure employed in longitudinal studies reveals the shifts in technological performance utilisation of sub-industries and therefore informs of change in the technological development focus of the systemic industry. Organisations in systemic industries can benefit from this external information by reducing uncertainties and risks associated with their R&D activities (Wang et al., 2010), and at the same time deploying appropriate competitive strategies and firm structures with respect to NPD processes (de Visser et al., 2010). In this manner, organisations may set their own pace of change to match the environmental pace of change (Eisenhardt and Martin, 2000), in other words concurrently utilise the information on the technological industry as well as systemic technological industry clockspeeds. From an organisational standpoint, understanding the changing basis of competition (Christensen, 1997) within the specific sub-industry, as well as within the systemic industry context, can assist organisations in coping more effectively with their dynamic and competitive environment, thereby positively influencing performance and survival.

Acknowledgements

We are grateful for the valuable comments and suggestions of two anonymous referees, who have helped us further develop this paper.

References

Abernathy, W.J., Utterback, J.M., 1978. Patterns of industrial innovation. Technology Review 80 (7), 40-47.

Adner, R., 2006. Match your innovation strategy to your innovation ecosystem. Harvard Business Review April, 98-107.

Adner, R., Kapoor, R., 2010. Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations. Strategic Management Journal 31, 306-333.

Adner, R., Levinthal, D., 2001. Demand Heterogeneity and Technology Evolution: Implications for Product and Process Innovation. Management Science 47 (5), 611-628.

Agarwal, R., Gort, M., 1996. The Evolution of Markets and Entry, Exit and Survival of Firms. The Review of Economics and Statistics 78 (3), 489-498.

Agarwal, R., 1998. Evolutionary trends of industry variables. Research Policy 16, 511-525.

Agarwal, R., Sarkar, M.B., Echambadi, R., 2002. The conditioning effect of time on firm survival: an industry life cycle approach. The Academy of Management Journal 45 (5), 971-994.

Audretsch, D.B., 1995. Innovation and Industry Evolution. The MIT Press, Cambridge, MA.

Ayres, R.U., 1988. Barriers and breakthroughs: An "expanding frontiers" model of the technology-industry life cycle. Technovation 7 (2), 87-115.

Baldwin, C.Y., Clark, K.B., 2000. Design Rules: The Power of Modularity. MIT Press, Cambridge, MA.

Baldwin, C.Y., Clark, K.B., 1997. Managing in an age of modularity. Harvard Business Review 75 (5), 84-93.

Barnett, W.P., 1990. The Organizational Ecology of a Technological System. Administrative Science Quarterly 35 (1), 31-60.

Baum, J.A.C., Singh, J.V., 1994. Organizational niches and the dynamics of organizational mortality. The American Journal of Sociology 100 (2), 346-380.

Bayus, B.L., 1997. Speed-to-market and New Product Performance Trade-offs. Journal of Product Innovation Management 14, 485-497.

Becker, R.H., Speltz, L.M., 1983. Putting the S-curve to work. Research Management September-October, 31-33.

Benner, M.J., Tushman, M.L., 2003. Exploitation, exploration, and process management: The productivity dilemma revisited. The Academy of Management Review 28 (2), 238-256.

Bessant, J., Caffyn, S., Gilbert, J., 1996. Learning to Manage Innovation. Technology Analysis and Strategic Management 8 (1), 59-70.

Bessant, J., Francis, D., 1997. Implementing the new product development process. Technovation 17, 189-197.

Bonaccorsi, A., Giuri, P., 2000. When shakeout doesn't occur: The evolution of the turboprop engine industry. Research Policy 29, 847-870.

Bonaccorsi, A., Pammolli, F., Tani, S., 1996. The changing boundaries of system companies. International Business Review 5 (6), 539-560.

Bourgeois, L.J., III, Eisenhardt, K.M., 1988. Strategic Decision Processes in High Velocity Environments: Four Cases in the Microcomputer Industry. Management Science 34 (7), 816-835.
Brockhoff, K.K., Ernst, H., Hundhausen, E., 1999. Gains and pains from licensing - patent-portfolios as strategic weapons in the cardiac rhythm management industry. Technovation 19, 605-614.
Brown, S.L., Eisenhardt, K.M., 1997. The Art of Continuous Change: Linking Complexity Theory and Time-Based Evolution in Relentlessly shifting organizations. Administrative Science Quarterly 42, 1-34.
Brown, S.L., Eisenhardt, K.M., 1995. Product development: past research, present findings, and future directions. Academy of Management Review 20 (2), 343-378.
Brusoni, S., Prencipe, A., 2001. Unpacking the black box of modularity: Technologies, products and organizations. Industrial and Corporate Change 10 (1), 179-205.
Carroll, G.R., Hannan, M.T., 1989. Density delay in the evolution of organizational populations: A model and five empirical tests. Administrative Science Quarterly 34 (3), 411-430.
Chesbrough, H., 2003. Environmental influences upon firm entry into new sub-markets Evidence from the worldwide hard disk drive
industry conditionally. Research Policy 32, 659-678.
Christensen, C.M., 1997. The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Harvard Business School Press, Boston, Massachusetts.
Clark, K.B., 1985. The interaction of design hierarchies and market concepts in technological evolution. Research Policy 14 (5), 235-251.
Cohen, M.A., Eliashberg, J., Ho, T., 1996. New Product Development: The Performance and Time-to-Market Tradeoff. Management Science 42 (2), 173-186.
Datar, S., Jordan, C., Kekre, S., Rajiv, S., Srinivasan, K., 1997. New Product Development Structures and Time-to-Market. Management Science 43 (4), 452-464.
de Visser, M., de Weerd-Nederhof, P., Faems, D., Song, M., van Looy, B., Visscher, K., 2010. Structural ambidexterity in NPD processes: A firm-level assessment of the impact of differentiated structures on innovation performance. Technovation 30, 291-299.
Dosi, G., 1982. Technological paradigms and technological trajectories. Research Policy 11, 147-162.
Ehrnberg, E., 1995. On the definition and measurement of technological discontinuities. Technovation 15 (7), 437-452.
Eisenhardt, K.M., Brown, S.L., 1998. Time pacing: Competing in markets that won't stand still. Harvard Business Review March-April, 59-69.
Eisenhardt, K.M., Tabrizi, B.N., 1995. Accelerating Adaptive Processes: Product Innovation in the Global Computer Industry. Administrative Science Quarterly 40 (1), 84-110.
Eisenhardt, K.M., Martin, J.A., 2000. Dynamic capabilities: what are they? Strategic Management Journal 21, 1105-1121.
Ethiraj, S., Puranam, P., 2004. The Distribution of R&D Effort in systemic Industries: Implications for Competitive Advantage. In: Baum, J.A.C., McGahan, A.M. (Eds.), Business Strategy Over the Industry Life Cycle. Elsevier Ltd, Oxford, pp. 225-253.
Fine, C.H., 1998. Clockspeed: Winning Industry Control in the Age of Temporary Advantage. Perseus Books, Reading (MA).

Fisher, J.C., Pry, R.H., 1971. A simple substitution model of technological change. Technological Forecasting and Social Change 3 (1), 75-88.
Foster, R.N., 1986. Innovation: The Attacker's Advantage. Summit Books, New York, USA.
Garud, R., Kumaraswamy, A., 1995. Technological and organizational designs for realizing economies of substitution. Strategic Management Journal 16, 93-101.
Geels, F.W., 2006. Co-evolutionary and multi-level dynamics in transition: The transformation of aviation systems and the shift from propeller to turbojet (1930-1970). Technovation 26 (9), 999-1016.
Gooroochurn, N., Hanley, A., 2007. A tale of two literatures: Transaction costs and property rights in innovation outsourcing. Research Policy 36, 1483-1495.
Gort, M., Wall, R.A., 1986. The evolution of technologies and investment in innovation. The Economic Journal 96 (383), 741-757.
Gort, M., Klepper, S., 1982. Time paths in the diffusion of product innovations. The Economic Journal 92 (367), 630-653.
Griffiths, W., Webster, E., 2010. What governs firm-level R&D: Internal or external factors? Technovation 30, 471-481.
Guimaraes, T., Cook, D., Natarajan, N., 2002. Exploring the Importance of Business Clockspeed as a Moderator for Determinants of Supplier Network Performance. Decision Sciences 33 (4), 629-644.
Gupta, A.K., Sounder, W.E., 1998. Key drivers of reduced cycle time. Research Technology Management July-August, 38-43.
Hannan, M.T., Freeman, J., 1977. The Population Ecology of Organizations. The American Journal of Sociology 82 (5), 929-964.
Hansen, K.L., Rush, H., 1998. Hotspots in complex product systems: emerging issues in innovation management. Technovation 18 (8/9), 555-561.
Hayes, M., Dinsey, S., 1995. Games War. Bowerdean Publishing Company Ltd., London.
Helfat, C.E., Finkelstein, S., Mitchell, W., Peteraf, M.A., Singh, H., Teece, D.J., Winter, S.G., 2007. Dynamic Capabilities. Understanding Strategic Change in Organizations. Blackwell publishing.
Henderson, R.M., Clark, K.B., 1990. Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. Administrative Science Quarterly 35 (1), 9-30.
Hobday, M., 1998. Product complexity, innovation and industrial organisation. Research Policy 26, 689-710.
Hood, W.C., 1948. Some Aspects of the Treatment of Time in Economic Theory. The Canadian Journal of Economics and Political Science 14 (4), 453-468.
Hughes, T.P., 1983. Networks of Power: Electrification in Western Society, 1880-1930. The John Hopkins University Press, USA.
Hyvättinen, H., 2006. Interface standards and creating innovation markets - implications on SMEs in a technology programme. Technovation 26, 262-273.
Jovanovic, B., MacDonald, G.M., 1994. The life cycle of a competitive industry. The Journal of Political Economy 102 (2), 322-347.
Jovanovic, B., 1982. Selection and the evolution of industry. Econometrica 50 (3), 649-670.
Kanev, K., Sugiyama, T., 1998. Design and simulation of interactive 3D computer games. Comput. & Graphics 22 (2-3), 281-300.

Klepper, S., Graddy, E., 1990. The evolution of new industries and the determinants of market structure. The RAND Journal of Economics 21 (1), 27-44.
Klepper, S., 1996. Entry, exit, growth, and innovation over the product life cycle. The Amercian Economic Review 86 (3), 562-583.
Langlois, R.N., Robertson, P.L., 1992. Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries. Research Policy 21, 297-313.
Lee, T.H., Nakicenovic, N., 1988. Technology life-cycles and business decisions. International Journal of Technology Management 3, 411-426.
MacCormack, A., Verganti, R., Iansiti, M., 2001. Developing products on internet time: The anatomy of a flexible development process. Management Science 47 (1), 133-150.
Macher, J.T., Mowery, D.C., 2004. Vertical Specialization and Industry Structure in High Technology Industries. In: Baum, J.A.C., McGahan, A.M. (Eds.), Business Strategy Over the Industry Life Cycle. Elsevier Ltd, Oxford, pp. 317-355.
MacKenzie, D., 1987. Missile accuracy: a case study in the social processes of technological change. In: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems. The MIT Press, USA, pp. 195-222.
Malerba, F., Nelson, R.R., Orsenigo, L., Winter, S.G., 1999. 'History friendly' models of industry evolution: The computer industry. Industrial and Corporate Change 8 (1), 3-40.
Mayntz, R., Hughes, T.P., 1988. The Development of Large Technical Systems. Campus Verlag, Frankfurt am Main.
McGahan, A.M., 2004. How Industries Change. Harvard Business Review 82 (10), 87-94.
McGahan, A.M., 2000. How industries evolve. Business Strategy Review 11 (3), 1-16.
Mendelson, H., Pillai, R.R., 1999. Industry Clockspeed: Measurement and Operational Implications. Manufacturing & Service Operations Management 1 (1), 1-20.
Meyer, M.H., Utterback, J.M., 1995. Product Development Cycle Time and Commercial Success. IEEE Transactions on Engineering Management 42 (4), 297-304.
Miller, R., Hobday, M., Leroux-Demers, T., Olleros, X., 1995. Innovation in complex system industries: The case of flight simulators. Industrial and Corporate Change 4, 363-400.
Moore, G.E., 1965. Cramming more components onto integrated circuits. Electronics 38 (8).
Mowery, D.C., Rosenberg, N., 1979. The influence of market demand on innovation: A critical review of some recent empirical studies. Research Policy 8, 103-153.
Mu, J., Peng, G., MacLachlan, D.L., 2009. Effect of risk management strategy on NPD performance. Technovation 29, 170-180.
Murmann, J.P., Frenken, K., 2006. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. Research Policy 35, 925-952.
Nadkarni, S., Narayanan, V.K., 2007. Strategic Schemas, Strategic Flexibility, and Firm Performance: The Moderating Role of Industry Clockspeed. Strategic Management Journal 28, 243-270.

Nieto, M., Lopéz, F., Cruz, F., 1998. Performance analysis of technology using the S curve model: The case of digital signal processing (DSP) technologies. Technovation 18 (6/7), 439-457.
Persson, M., Åhlström, P., 2006. Managerial issues in modularising complex products. Technovation 26, 1201-1209.
Poole, S., 2004. Trigger Happy: Video Games and the Entertainment Revolution. Arcade Publishing, New York.
Porter, M., 1985. Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, New York.
Prencipe, A., 2000. Breadth and depth of technological capabilities in CoPS: the case of the aircraft engine control system. Research Policy 29, 895-911.
Rhodes, E.H., 1885. The Scientific Conception of the Measurement of Time. Mind 10 (39), 347-362.
Rice, J., Galvin, P., 2008. Alliance patterns during industry life cycle emergence: the case of Ericsson and Nokia. Technovation 26 (3), 384-395.
Ripolles, O., Chover, M., 2008. Optimizing the management of continuous level of detail on GPU. Computers & Graphics 32, 307-319.
Romanelli, E., Tushman, M.L., 1994. Organizational transformation as punctuated equilibrium: An empirical test. The Academy of Management Journal 37 (5), 1141-1166.
Rosas-Vega, R., Vokurka, R.J., 2000. New Product Introduction Delays in the Computer Industry. Industrial Management and Data Systems 100 (4), 157-163.
Rosenberg, N., 1976. Perspectives on Technology. Cambridge University Press, Cambridge.
Rosenkopf, L., Nerkar, A., 1999. On the complexity of technological evolution: exploring coevolution within and across hierarchical levels in optical disc technology. In: Baum, J.A.C., McKelvey, B. (Eds.), Variations in Organization Science. Sage Publications, Inc., USA.
Roussel, P.A., 1984. Technological maturity proves a valid and important concept. Research Management Januray-February, 29-34.
Sahal, D., 1981. Patterns of Technological Evolution. Addison-Wesley, London.
Schilling, M.A., 2000. Toward a general modular systems theorys application to interfirm product modularity. The Academy of Management Review 25 (2), 312-334.
Shirley, P., Sung, K., Brunvand, E., Davis, A., Parker, S., Boulos, S., 2008. Fast ray tracing and the potential effects on graphics and gaming courses. Computers & Graphics 32, 260-267.
Sood, A., Tellis, G.J., 2005. Technological evolution and radical innovation. Journal of Marketing 69 (July), 152-168.
Souza, G.C., Bayus, B.L., Wagner, H.M., 2004. New-Product Strategy and Industry Clockspeed. Management Science 50 (4), 537-549.
Stalk, G.,Jr, 1988. Time -- The Next Source of Competitive Advantage. Harvard Business Review 66 (4), 41-51.
Stigler, G.J., 1951. The division of labor is limited by the extent of the market. The Journal of Political Economy 59 (3), 185-193.
Strebel, P., 1987. Organizing for innovation over an industry cycle. Strategic Management Journal 8 (2), 117-124.

Suarez, F.F., Lanzolla, G., 2005. The half-truth of first-mover advantage. Harvard Business Review 83 (4), 121-127.
Suarez, F.F., Utterback, J.M., 1995. Dominant designs and the survival of firms. Strategic Management Journal 16 (6), 415-430.
Subramanian, A.M., Kah-Hin, C., Shifeng, M., 2011. Capability reconfiguration of incumbent firms: Nintendo in the video game industry. Technovation 31, 228-239.
Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic Capabilities and Strategic Management. Strategic Management Journal 18 (7), 509-533.
Teece, D.J., 1986. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research Policy 15 (6), 285-305.
Tiwana, A., Konsynski, B., Bush, A.A., 2010. Platform evolution: Coevolution of platform architecture, governance, and environmental dynamics. Information Systems Research 21 (4), 675-687.
Tushman, M.L., Murmann, J.P., 1998. Dominant Designs, Technology Cycles, and Organizational Outcomes. Research in Organizational Behavior 20, 231-266.
Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Research Policy 24, 419-440.
Utterback, J.M., Suarez, F.F., 1993. Innovation, Competition, and Industry Structure. Research Policy 22 (1), 1-21.
Van de Ven, A., Poole, M.S., 1995. Explaining development and change in organizations. Academy of Management Review 20 (3), 510-540.
Wang, J., Lin, W., Huang, Y., 2010. A performance-oriented risk management framework for innovative R&D projects. Technovation 30, 601-611.
Wezel, F.C., 2005. Location dependence and industry evolution: Founding rates in the United Kingdom motorcycle industry, 1895-1993. Organization Science 26 (5), 729-754.
Williams, J.R., 1992. How Sustainable is Your Competitive Advantage? California Management Review 34 (3), 29-51.
Zaheer, S., Albert, S., Zaheer, A., 1999. Time Scales and Organizational Theory. Academy of Management Review 24 (4), 725-741.

Appendix: Figures and tables:

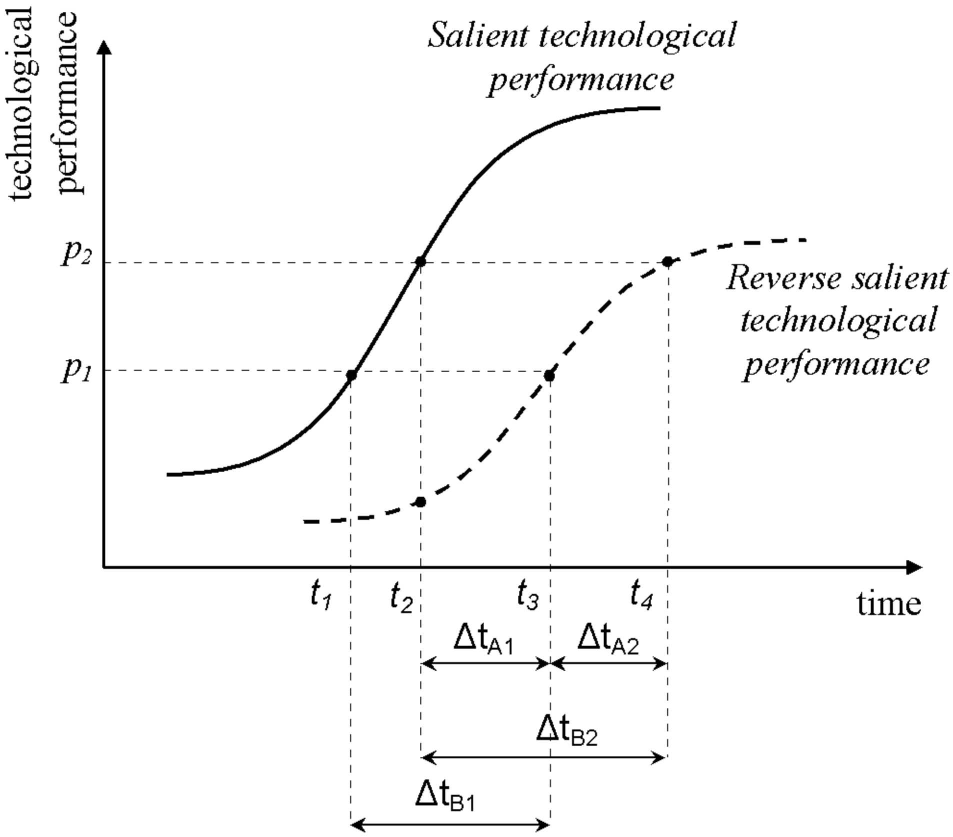


Figure 1. Schematic of clockspeed measurements from superimposed S-curves of the salient and reverse salient sub-systems.

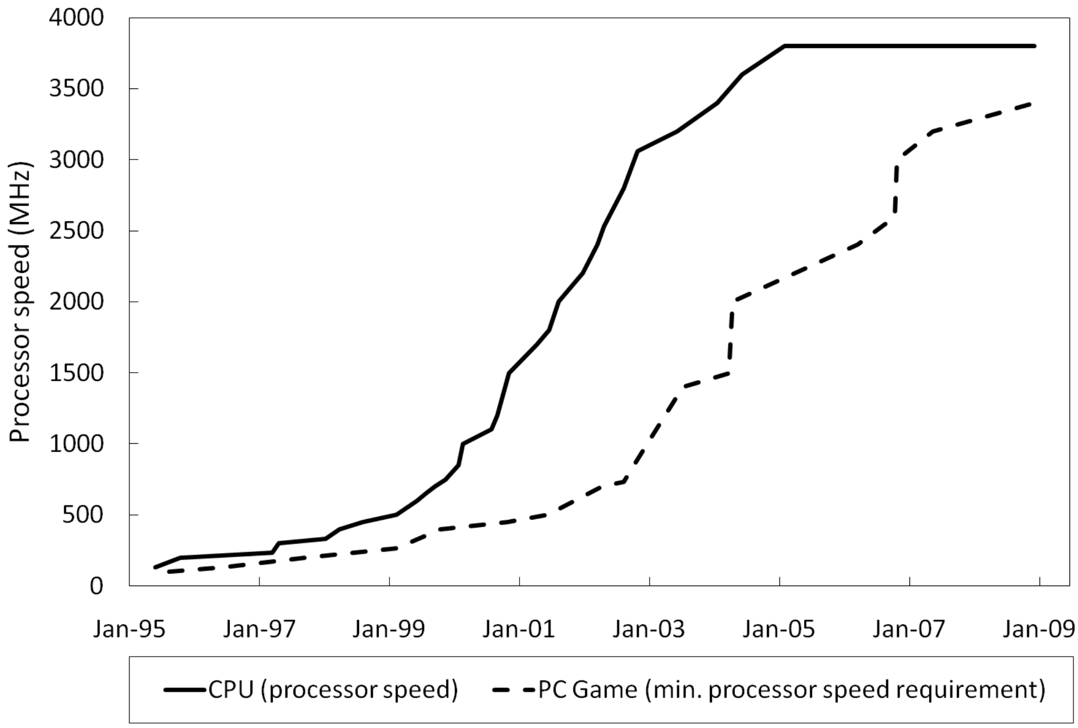


Figure 2. The technological performance S-curves for CPU and PC game sub-systems with respect to processor speed.

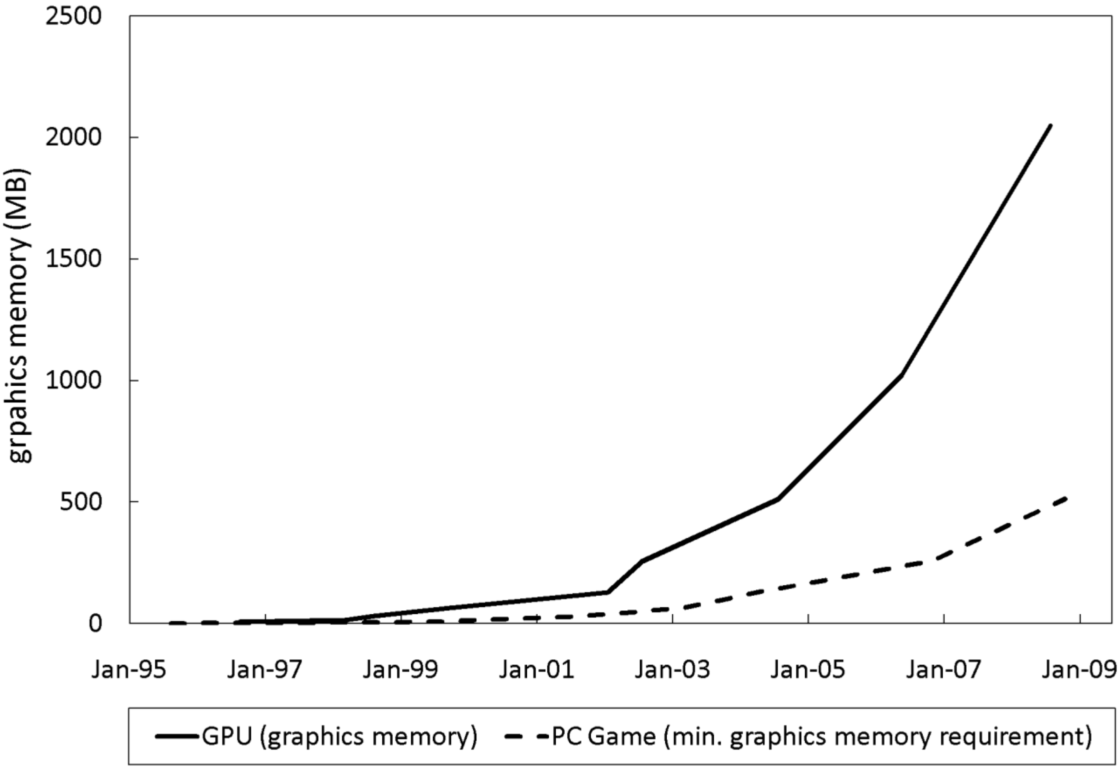


Figure 3. The technological performance S-curves for GPU and PC game sub-systems with respect to the amount of graphics memory.

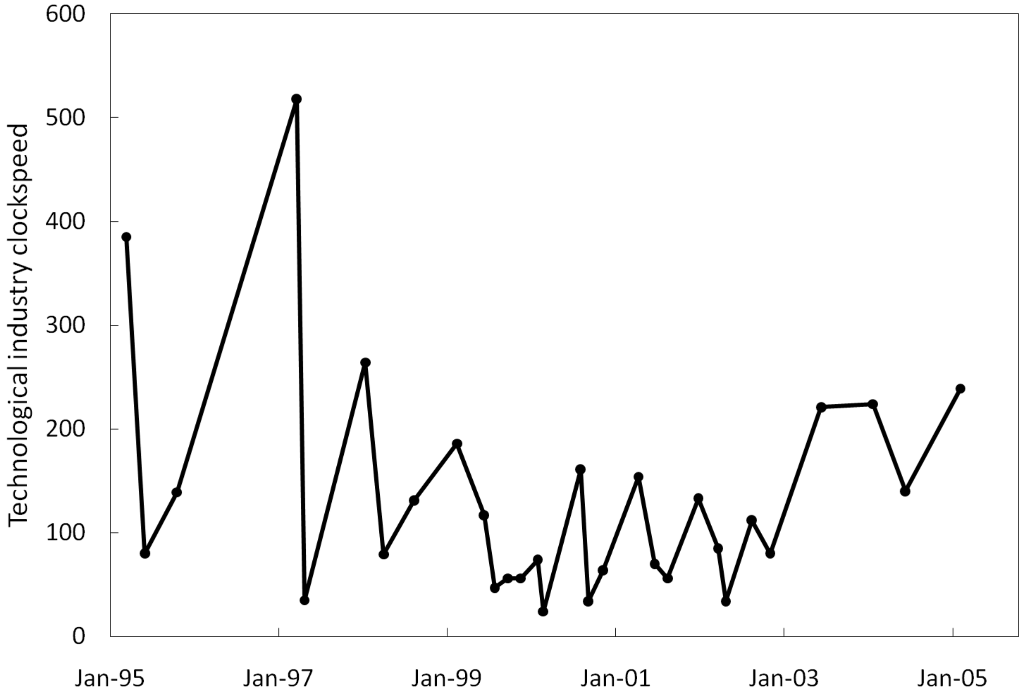


Figure 4. The technological industry clockspeed of the CPU sub-industry measured as the number of days between product launches with successively higher processor speed.

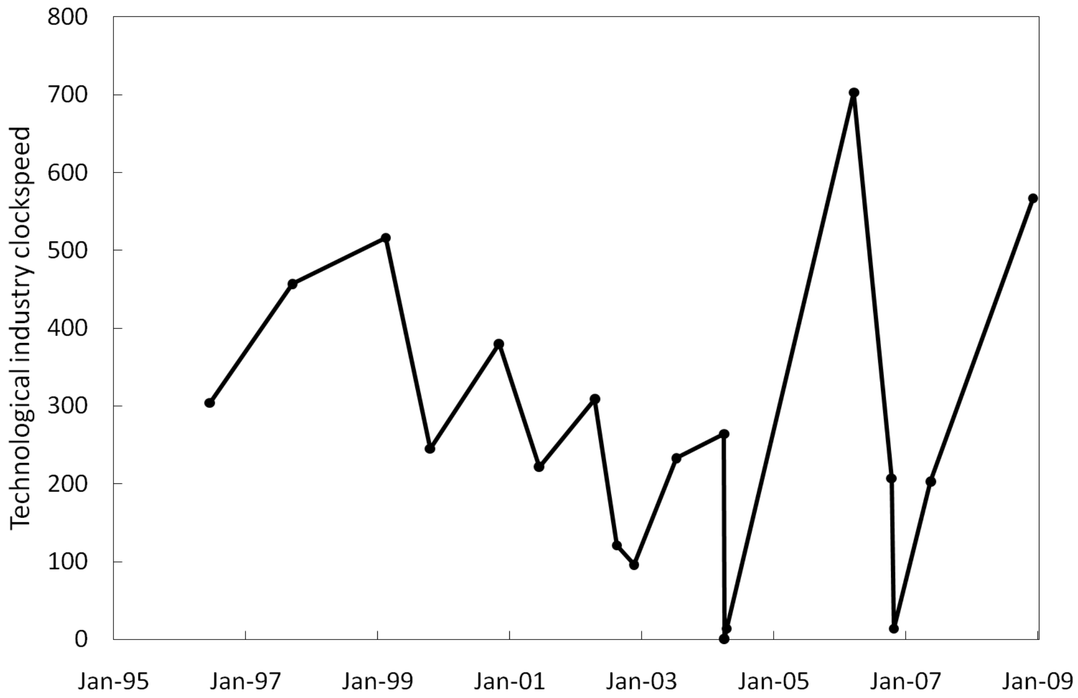


Figure 5. The technological industry clockspeed of the PC game sub-industry measured as the number of days between product launches with successively higher minimum processor speed requirement.

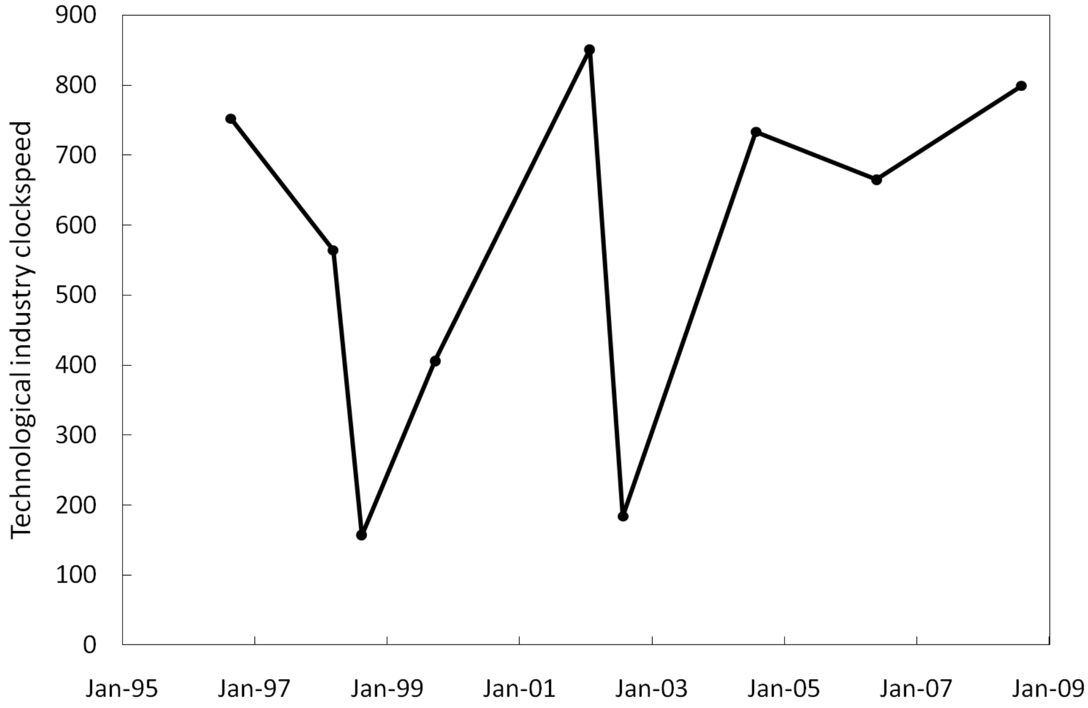


Figure 6. The technological industry clockspeed of the GPU sub-industry measured as the number of days between product launches with successively higher graphics memory.

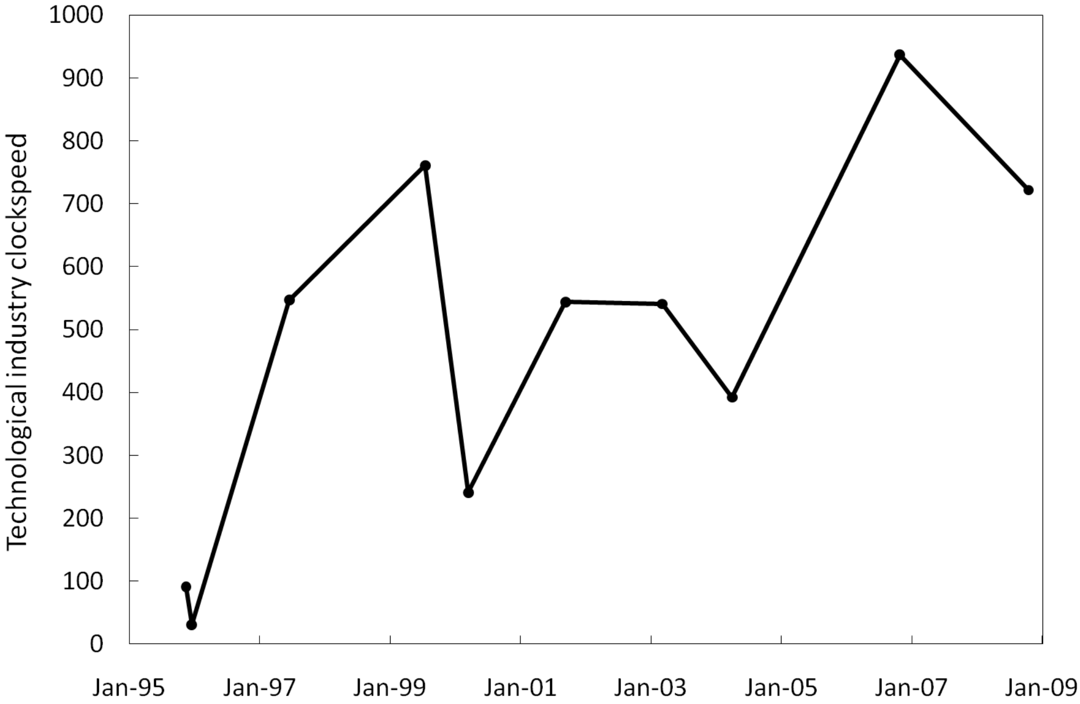


Figure 7. The technological industry clockspeed of the PC game sub-industry measured as the number of days between product launches with successively higher minimum graphics memory requirement.

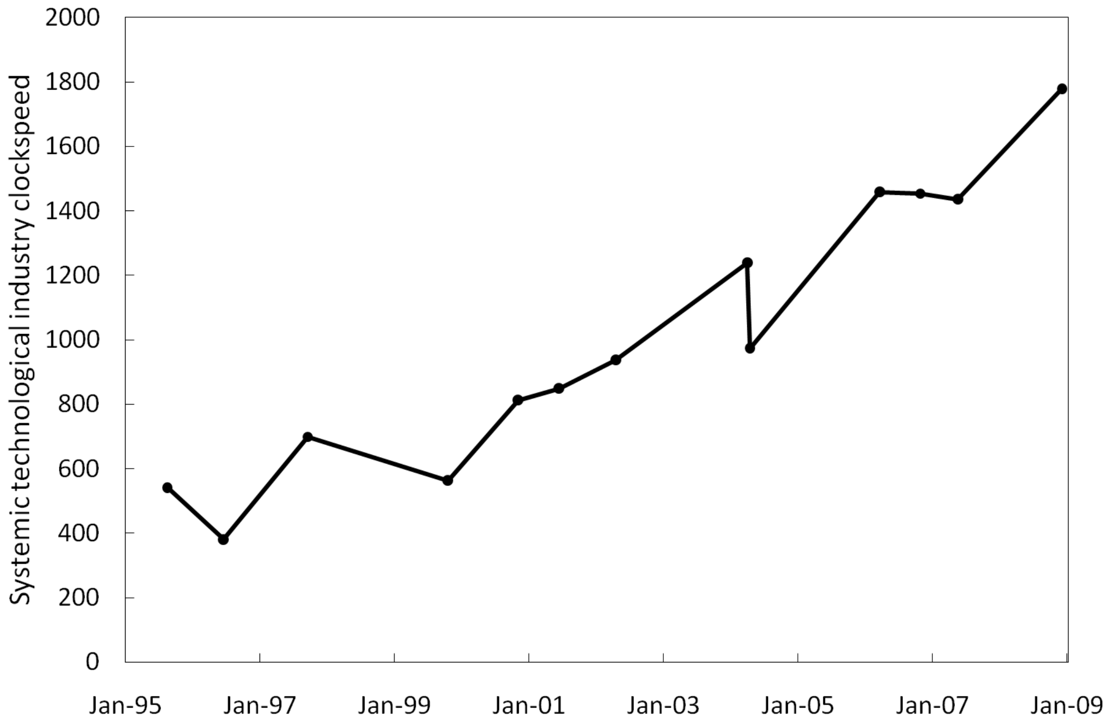


Figure 8. The systemic technological industry clockspeed of the PC game sub-industry with respect to the CPU sub-industry.

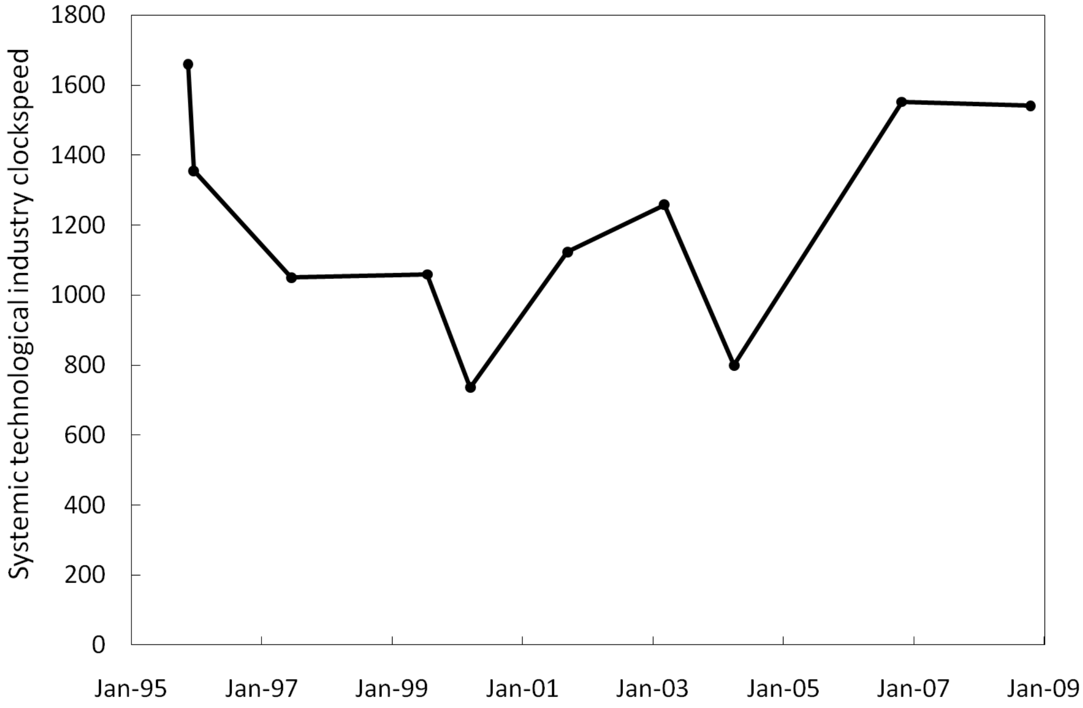


Figure 9. The systemic technological industry clockspeed of the PC game sub-industry with respect to the GPU sub-industry.