THE TIPPING POINTS OF TECHNOLOGY DEVELOPMENT

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TAUNO KEKÄLE, PETRI HELO

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1 INTRODUCTION: THE DEFINITION OF TIPPING POINT

In his book "Critical Mass", Philip Ball (2004:286) describes the phenomenon of the critical point, as it is currently understood in physics. Ball writes: "A critical point represents forked path: a place where choices are made. This is how, you may recall, a critical phase transition [in physical phenomena] differs fundamentally from the first-order transitions of, say, freezing and melting. When a liquid teeters on the brink of its freezing point, every part of it stares the same fat in the face: to become a solid. But if we cool a fluid through its critical temperature, suddenly it can exist either of two states, both equally appealing: a liquid or a gas. As a consequence, the system becomes exquisitely sensitive to random fluctuations. A tiny change in presence may tip the balance. This instability means that the critical state is highly precarious, constantly on the verge of rolling down into one valley or another."

Any technology innovation can either be accepted or rejected by the potential customers. The diffusion ultimately is also affected, according to Dosi (2000), by the rate to which the innovation is imitated by competitors. Typically the acceptance is not instantaneous, but is claimed to follow an S-curve whose precise form varies considerably across innovations (Dosi, 2000:185). Cumulative acceptance of an innovation among customers gains momentum slowly, until it reaches a critical point where the sales start to grow exponentially, and after that the development cannot easily be stopped any more by the existing technology leaders. Dosi goes on to explain that the diffusion patterns can depend on, except the innovations themselves, on specific intermediate innovations (e.g. in manufacturing machinery or components) as well as disembodied knowledge spreading via mobility of people (Dosi, 2000:185). Moore (1995), again, discusses a decisive point (actually he does not see it a point, rather a hindrance, but in any way it will decide whether a technology breaks through to the great masses or becomes a toy for a small group of "geeks"); the "chasm".

The central idea of the concept of tipping point is that in some phase of the development or evolution of a phenomenon some small and apparently insignificant changes can turn up to have consequences out of proportion to themselves. The idea of tipping point assumes a gradually developing process, where every added incident is a new decision point. A decision point where one added incident makes the development follow one of two or several strongly differing paths is the tipping point. For the technology acceptance S-curves, tipping point is the point in time where the angle of the tangent of the technology acceptance curve changes in a statistically significant way (although normally observable only after-the-fact). Clayton Christensen has in many books promoted the idea of revolutionary "disruptive technologies" that destroy the market balance by coming in as underdogs and gradually building performance and serving underserved customers until it gains momentum and destroys the market position of the incumbent technologies.

These developments remind of those found in the field of physics. Many of the mathematical simulation models that have been run on physical phenomena (e.g. Watts and Strogatz, 1998), as well as the traditional innovation diffusion s-curves (e.g. Bass, 1969) also work on the same principle: if an agent is surrounded by enough individuals voicing one opinion, it will change its own opinion to mirror the others, and gradually more and more of the agents, in an accelerating phase, accept the product. Communication is seen to be one of the main factors in diffusion. This is also Moore's (1995) point: after the initial period in the acceptance S-curve, the rumours of the benefits of a new product start to spread exponentially to new areas of the market and cause wide acceptance behaviour. The tipping point in technology acceptance thus might be modelled e.g. by a critical number of users that have wide-enough communication networks to other potential users (cf. Granovetter, 1973).

However, as Ball (2004:294) notes, the real markets are full of conscious actors that do not just randomly fall in the system as straws on the back of a camel. Some actors believe the prediction, "get into panic buying", and make the prediction self-fulfilling (Ball's example is on stock market buying behaviour); others may believe the prediction and take careful compensatory action to avert the predicted development of a new technology. Through Christensen's work, it becomes very clear that the incumbent technology owners, after numerous successful years of serving the mainstream market, have considerable resources to put in to hinder the advance of the disruptive technology (the Resource-Process-Values model states this nicely; Christensen, Anthony and Roth, 2004). Finally, it is, Ball notes (2004:294), also possible that "nobody believes the prediction but the market crashes anyway". This may be due to complete non-predictability of the technologies development, with too many random events or interrelated technologies affecting the technology revolution, or lack of information on how the market works.

We claim that the technology diffusion involves a tipping point phenomenon understandable by (and eventually also modelable by the methods of) the field of physics. However, instead of delving into the modelling, in this paper we try to present examples of what happens at or around the tipping point, in an attempt to refine the understanding of these factors. According to our earlier model (Kekäle, Pirolt & Falter, 2002), the drivers of diffusion include properties of the innovation itself, such as the cost and complexity, compared to the benefits (the total economy of adapting the innovation, e.g. as a function of scale), but even more often the lack of capabilities, skills and knowledge among the potential customers are the decisive factors. Because the information age has recently changed the awareness and technological capacity of the customers, there is a need to go inside the "deciding events – the tipping points themselves, where market for the new technology still is "fluid", to see what events may tip them into "liquid" or "gas".

According to our earlier model (Kekäle, Pirolt & Falter, 2002), the drivers of diffusion include properties of the innovation itself, such as the cost and complexity, compared to the benefits (the total economy of adapting the innovation, e.g. as a function of scale), but even more often the lack of capabilities, skills and knowledge among the potential customers. Because the information age has recently changed the awareness and technological capacity of the customers, we attempt to refine the understanding of these factors in this paper.

Our examples include "careful compensatory action" (Ball, 2004:294) from the incumbents (in the example of silver-film camera manufacturers' actions against the emergence of digital cameras), development of complementary technology that may restart the S-curve for the incumbents (the effects on turbocharging and CDI injection on performance trajectories of car diesel engines), and the change of customer performance preferences and their effects on product preferences (processor speed was previously the important factor in PCs; multiple processors turned the emphasis to memory, which made it possible to develop new memory devices, that made laptop computers more interesting than "tabletop tower" computers for the customers).

2 THE NATURE OF TECHNOLOGY AS INNOVATION DIFFUSION PREDICTOR

There is quite a lot of research into the attributes of the innovation receptors (markets and marketing communication) as enablers of the diffusion. The less-studied set of factors (Rogers, 2003) includes the attributes of the technological innovations. According to Rogers, the five central attribute classes to be understood here are (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability and (5) observability.

Relative advantage of the innovation is, in theory, a clear issue. Potential adopters want to know the degree to which a new idea is better than an existing practice. This relative advantage can be found out about in marketing communication or (as Moore, 1995, proposes) from visionaries and early adopters. Compatibility is the degree to which the performance and features of the new innovation are consistent to the needs, values and planned use of the customers. Complexity and trialability refer to the ease of testing and using the new innovation, and finally observability refers to how easy it is to find out about the new innovation (Rogers, 2003). To our purposes, however, the two first sets of attributes are of most interest, and seem to interact closely to decide the tipping point from a technological viewpoint.

The relative advantage of a new product should be higher than that of the existing products in order for the demand to "tip" in favour of the new product over the old. For practical understanding of the technology development trajectories (Dosi, 1982), the relative advantage – the performance and attributes – are much more problematic issues than they first seem. Christensen (1997) has devoted a whole book in order to understand the nature of disruptive technologies, where newcomer companies with new technologies undermine incumbents' and existing products' markets by gradually improving the performance of the new technology. The incumbents do normally not notice the threat because of the big differences in the initial performance of the new technology, but the development of the new technology either is much quicker or then later on starts to increase at an ever-quickening (typically not linear, even though they have been drawn linear in Figure 1 for simplicity) curve because of accelerating innovation by several new entrants or innovation in enabling technologies.

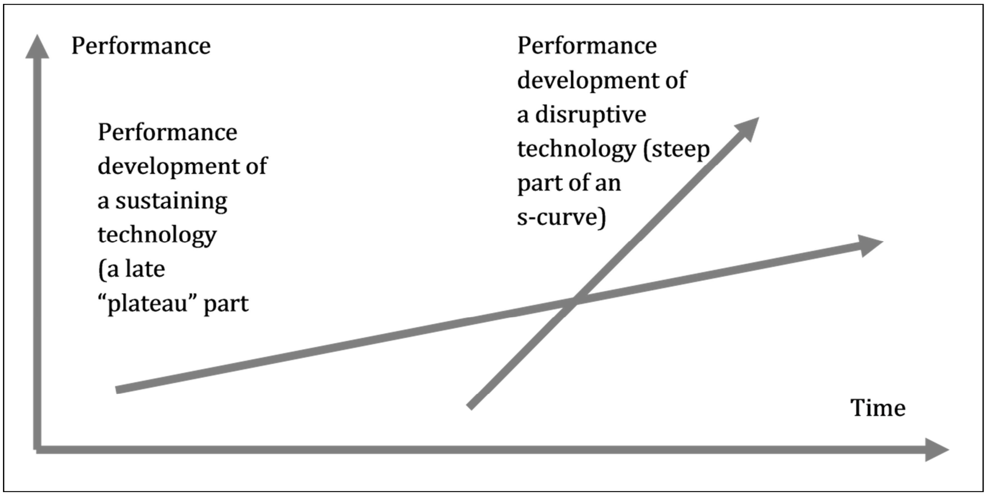

Figure 1 – A simplified view to the sustaining and disruptive technologies

To our opinion, the development process of a technology is clearly path-dependent. Whenever an improvement is made and a breakthrough stage reached, that can be built further upon, and typically there are milestones in the development that, when reached, may accelerate the development speed of the new technology. However, most figures in literature that present performance increase trajectories tend indeed to handle the performance development as a linear development, and also from a purely technological one-variable standpoint. From this viewpoint, modelling the "tipping point" would be very simple and the incumbents would be able to see the development of the new innovations well in advance: it would just be a case of extrapolating the developments of the major technological performance variables of the current and the new and finding the tipping point where these lines cross.

To complicate the technology diffusion picture, the other related concept presented by Rogers, compatibility, takes over from here, turning the view at the performance to be studied from a customer/user viewpoint. Customers, according to most of the economic theory, make rational decisions and will buy the product where the whole of the offering is the best compromise of satisfying all their needs concerning that product type. Thus, even if already the first computers with keyboards and printers were technologically superior to typewriters in their word-processing capability, some non-technical attributes (price, availability at a shop nearby, and required programming skills, along with the technical attributes of size and weight, and well-marketed improvements to existing typewriter technologies) kept these machines out from the offices and the typewriters in use for years (Utterback, 1996; Christensen, 1997). These compatibility issues may keep a well-performing new technology out of the market limelight for some time still after the key technological performance would be good enough. To our opinion, compatibility from a customer viewpoint does not have to be path-dependent, but can be affected to either direction (to the benefit of the newcomers as well as the incumbents) by the type of markets and/or the behaviour of the incumbents.

3 NATURE OF MARKETS AS INNOVATION DIFFUSION PREDICTORS

From the viewpoint of the tipping point idea for further study, we here argue that there are three basic types of markets for technologies. Firstly, there is the "traditional" Porterian (Porter, 1990) view to the market, where a product attracts customers who have need of that product and/or its functionality, and the demand gradually rises as information of the product performance reaches the customers, until a successor or competitor product or substitute gradually attracts some or all of that demand, or until most of the demand is fulfilled. In other words, customers value the product less when another product that attends the same basic need enters the market. This is also the basic idea of the S-curve technology diffusion models (e.g Bass, 1969; Dosi 2000).

The second type of market involves somewhat more complicated products and their complementors as a special type of intermediary innovation. Again, customers are attracted gradually by the performance of the product, but also the accumulating availability of other products – complementors – that the first product gives the option to use. Here, additional variables with potential for tipping points could be either the entry of some very significant complementor product that has a very big underlying demand, or the gradually accumulating total amount of complementor products. This is the basis of the customer lock-in strategies proposed by Hax & Wilde (2004), and in such markets the development of the technical performance of a new product is clearly not enough to predict the tipping point; the installed base of complementor technologies hinders the diffusion. This is the case of the PC computers: the "Wintel" standard has been adopted by about 90 % of personal computer users, leading them to acquire software, peripherals and other complementors that must also be renewed wholly or partly when changing e.g. to Mac or Linux system (Hax & Wilde, 2004). The Windows operating system in itself would probably not have made a big difference to the life of computer users, but it offered a simple interface to all kinds of computer software, word processors, spreadsheets, games etc. that no earlier operating system did.

Yet a special case of the previous type involves the network value of the users. While each user, especially in products that allow networking and human interaction, could be seen as an additional "complementor" that increases gradually the demand of the original product, the network dynamics between humans can be much more complicated than that, as evidenced by the social scripting/networking business ideas that recently gained in popularity (e.g. Facebook, Habbo Hotel, Skype, LinkedIn, and others). The theory of networks offers an interesting possibility: the existence of connectors. In the original network studies of Watts and Strogatz (1998) only a few of the long-distance "weak links" (Granovetter, 1973) were included. However, in e.g. research studying the spread of diseases, the activity of these long-distance links is found to be imperative, and in some studies it has been shown that the networks actually can have an "aristocracy" of only a few individuals that possess a disproportionate share of all the links. In this kind of "aristocratic" networks, the tipping point is very low or even nonexistent (Pastor-Satorras & Vespignani, 2001). This is an idea similar to arsonists' starting a fire simultaneously in several places, or the movie studios putting the blockbuster movies out in many locations around the world, simultaneously (Lane & Huseman, 2004).

Thus, there exists a third type of market where network externalities (Grant, 2002:94) are present. Here, the value of a product or service to the user depends strongly on the number of other users of the product, which again becomes an additional variable on which a tipping point can occur. This has clearly been the case of the slow adoption of the 3G mobile phones in Europe: the adoption rate is slow, because there is such a small amount of 3G services available; these, on the other hand, only develop profitably when there are enough handset owners/network users. (The 3G example also illustrates the need of enough infrastructures to exist; this slows down e.g. the acceptance of electric cars).

4 BEHAVIOUR OF THE INCUMBENT COMPANIES AS INNOVATION DIFFUSION PREDICTORS

As noted, it is assumed that the customers make rational choices. Already the value analysis developed by General Electric in the 1940s has taught us that customers are looking for value. Furthermore, between the lines in Moore's "Inside the Tornado" (1995), the Bass forecasting model (1969) and other relatively smooth S-curves there is the idea that there is only a very small portion of the potential customers (the "visionaries" or "innovators") that would accept the new product based on top performance in only one technical attribute. In these S-curve models, the "majority", the "laggards" and the "early and late adopters" only accept the product when the technology has developed to a package that includes a certain level of convenience of use and, especially, to an acceptable price; i.e., total value for the buyer.

While not by any means central theme of the book "Innovators' dilemma", Christensen (1997) lists several case studies that include counterattacks from incumbents with all methods available for them; price changes, technology improvements, marketing campaigns, etc. (e.g. the technological improvements made in typewriters to slow down the acceptance of PC computers, Figure 2). These and other typical disturbances lead to a wave-form, or succession of small S-curves, technology acceptance pattern, rather than one long smooth S-curve.

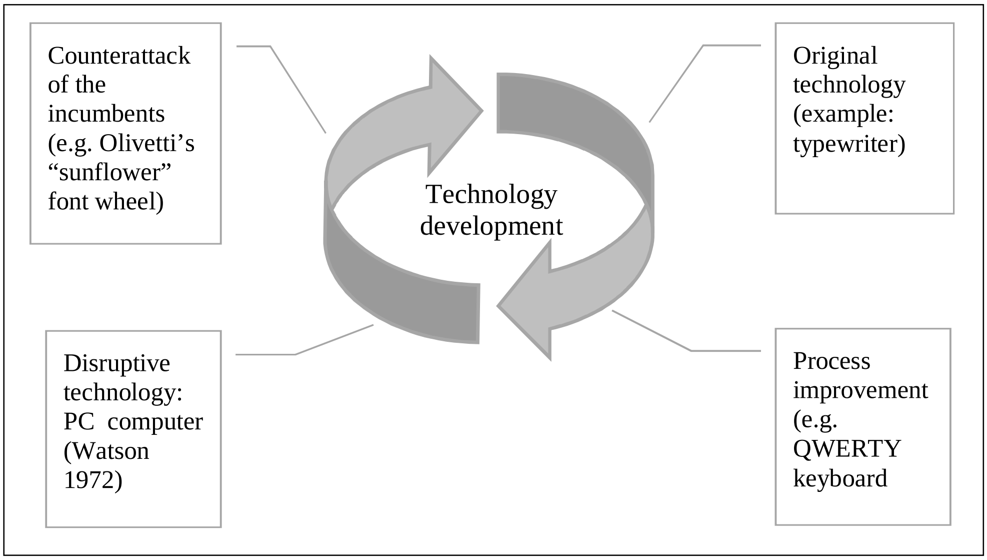

Figure 2 – Sustaining technology (product and process innovation), disruptive technology and "counterattack" from incumbents

On Figure 2 is an example of a typical mechanism of a technology (with product and process innovation) and "counterattack" from incumbents when faced with a disruptive technology (only one "circle" of the development spiral presented; in actual case, the counterattacks and process improvements were many, successive, from several typewriter manufacturers, e.g. a "one-line memory" presented by

Brother, all the while the performance of the disruptive PC technology improved).

5 CASE STUDIES: THE ATTRIBUTES THAT DECIDE THE TIPPING POINT

Three case studies (digital cameras, diesel automotive engines, and laptop computers) were studied by our research team for their main technology performance development over time. The trajectories of all three product technologies were remarkably similar and formed not an S-curve nor a straight line but a double S-curve, with a plateau of nearly no performance development during several years in the middle after a S-curve-type strong rise in the beginning, and another similar rise after the plateau.

Average technology performance curves could hide these plateaus, as would lines plotted from just some key technology development milestones, but when plotting the performance of the state-of-the-art and the lowest performance the product was actually sold with at any given time (in our camera example, the performance of typical professional-use and “tourist” cameras), even the plateaus are clearly visible. Now, it would seem that the fate of the previous technology generation is decided by the best performance, not the average. If this is so, it is interesting to note that while the average 10-megapixel level only now starts to satisfy the more-demanding camera users, it is notable that the technology has actually been performing on that level already for more than a decade. Thus, the slow take-off of the digital photography technology must be due to other reasons.

Looking back in the development of the cameras, three developments that each can explain their own part of the slow acceptance can be noted. For our conclusions, it can be useful to understand that the customers have clearly not been on the lookout only for a technologically good picture quality to emerge in digital cameras, but for a complete package.

Firstly, as the Figure 3 shows, the development has not been linear. The top of the line has been available – to a certain price – in the 6-megapixel level for nearly twenty years, but the average picture quality has remained under 2 megapixels until about the year 2000. The average, we assume, also indicates the "Joe Doe" price level. Furthermore, as the three lines (top/average/low) indicate, there has been much more numerous amount of less-than-1 megapixel cameras available than those with really good picture quality (this can be read from relative the closeness of the average line to the low-end line) which has served to keep the cautious adopters suspicious until the most recent years. Actually, these curves also illustrate the role of product and process technologies: product technology has reached a good-enough level for wide diffusion (e.g. 3 megapixels per sq.in.) already in mid-1990s, but the successive process innovation has made this level of performance widely available only in 2004.

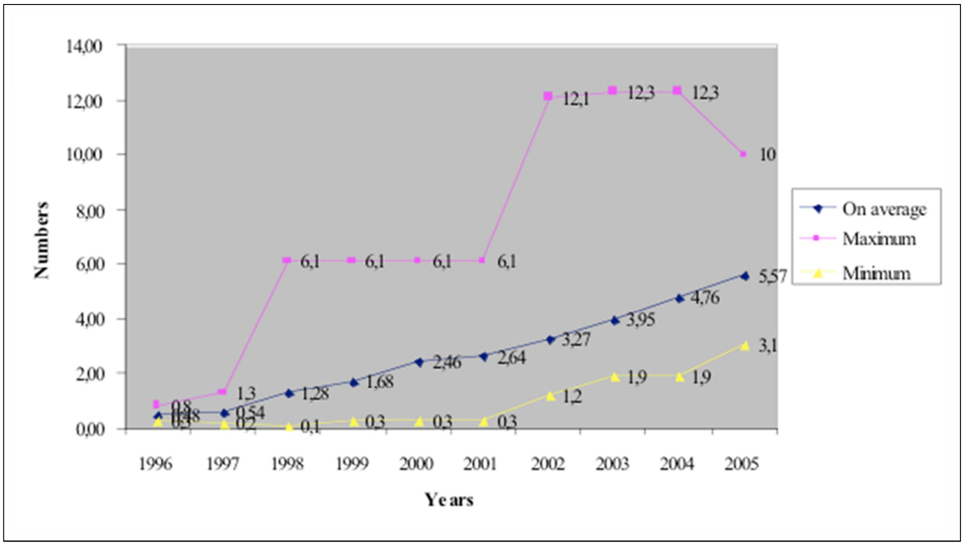

Figure 3 – Development of the amount of Megapixels per sq.in in hand-held digital cameras. Note the plateaus on both the minimum and maximum curves

Secondly, there are the complementors. Even if saving photos in a digital format takes much less space than paper prints or slides, many families are used to having their photos in albums or watching them with slide projectors. Furthermore, watching photos on computer displays has until recently been tiresome for the eyes and lacking in detail, due to the relatively low picture quality of displays available. It is now getting increasingly difficult to find materials for silver-film photography; supermarkets are discontinuing film and camera batteries, and amount of development studies is diminishing (many of these shops seem now to sell cellular phones, which shows one of the directions of development of "tourist" photography market).

Finally, there have clearly been many attempts among incumbents to revitalize the existing camera technology by attempting sustaining innovation. There have been in the late 1990s innovations such as the drop-in film cassette for ease of use, completely new levels of automation in small family cameras, diminishing size, "brushed-metal" designs imitating those of the digital cameras, and such. Furthermore, increasing use of new materials and electronics – together with global sourcing – has made it possible to reduce the prices of cameras; while a Canon 700 compact camera of the mid-1990s cost the equivalent of 150 euros, currently similar-performance 135-film format compact cameras are available from many manufacturers to about 50 euros (and to a much lighter weight).

The case of complementors of technology in accelerating the performance, and, thus, also the acceptance can be seen in the double development curves of the Mercedes-Benz diesel engine power to fuel consumption ratio since the 1990s and the development plateau between them (Figure 4). The possibilities of diesel fuel and combustion chamber design had seemingly been exhausted in the late 1980s and the development of relative horsepower per nominal fuel consumption stagnated. Due to extraordinary longevity of engines, taxi and other fleet buyers remained interested, but general buying public again shied away from diesels. This coincided with the diminishing of interest in diesel engines generated by the oil crisis (even leading Cadillac to briefly offer a diesel engine as standard power plant in its ultra-luxury Seville model in 1980-81) when fuel prices went down again and when the public saw that even a bad oil crisis is a temporary event. The heavy diesel engines were not suitable for smaller cars; given the choice, the customers changing their buying habits in the 1970s (we here talk about the North-American market) rather went for smaller petrol-fuelled cars than bigger diesel cars (in 1985, the main type of car sold by the GM was the intermediary-size car, e.g. Ford Taurus and Oldsmobile Ciera, and Honda Accord ws for a long time the most-sold car in the USA. See Womack, Jones & Roos, 1990).

The development of small-size, reliable turbocharging made it possible to increase the volumetric efficiency of a combustion chamber for over that of atmospheric intake pressures; the development of computing made direct common-rail fuel injection possible. The second phase of a double-S-curve in Figure 4, from the plateau stage (1985-1995) forward, shows a rapidly accelerating volumetric efficiency caused by the CDI technology development (in bigger M-B diesels, not discussed here, there is a “triple” S-curve where the turbocharging is a middle development phase between normally-aspirated 5- and 6- cylinder engines and the CDI). Thus, complementors and supporting technologies can recreate an S-curve in technologies where the performance limits have already been reached. In market terms, there now are actually effective diesel engines running in three-meter-long cars, showing highway traffic efficiencies of more than 75 mpg (or around 3 litres per 100 kilometres, in European terms; e.g. the small Volkswagen diesel models claim this level of efficiency); in Mediterranean Europe, for example, diesel-engined cars outsell petrol engines on the market since late1990s in a relation of 5 to 1. The example shows that it is very important to also follow the developments in related (turbocharging), and even in seemingly unrelated but society-changing (e.g. computing, telecommunication), technologies to be able to benefit from coming surges in performance trajectories. The next business model in car markets could be connected to the social networking phenomena; instead of selling cars to the individuals, the future customers might be carpools renting or leasing an electronic car for in-city use while using their private diesels for continental trips.

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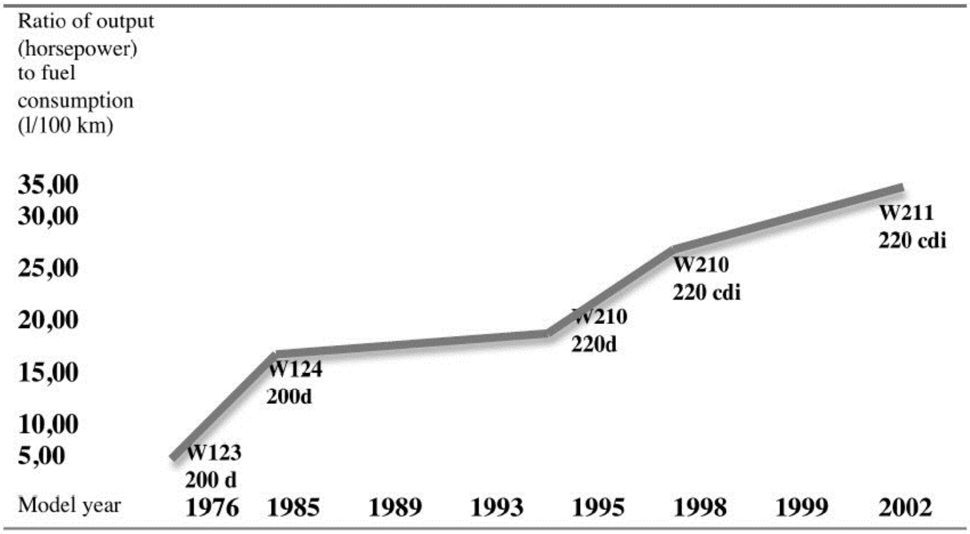

Figure 4 – The development of the horsepower output/fuel consumption ratio of Mercedes-Benz car diesels through model changes

There are many interesting cases such as the above to report. The last one that we present in this article is a set of two trajectories from computer-related microchip development. One of our researchers' findings was that, despite Moore's law that predicts exponential increase in microchip packaging density, the absolute processor performance (speed) trajectory has actually turned downwards. Our explanation is that there are issues other than density that explain performance; the problems with processing speed and heat generated was solved by dual processors, but at the same time the interest of the buying public – mostly due to mobile telephony and the freedom that made possible – had already turned to portability, where the memory and battery life were more interesting than number-crushing performance. In portable devices, the size and weight limitations do not allow carrying around big memory devices. On the other hand, portability and internet connections require high battery life and big working and storage memories. Consequently, Apple in their MacBook Air in 2007 made away with the CD-burner/reader completely; it is now at the end of an USB cable, to be connected when needed. This releases space for a bigger battery and saves size and weight. The switch of buyers' interest from tabletop computers to portable computers happened when the processor performance was actually on its way down from the all-time high, but coincides quite precisely with the accelerating development of memory capacity. Thus, changes in the markets – in people's lifestyles, for example – can affect the relative importance between performance trajectories. Traditionally, tabletop computers were mainly sold by processor speed; bigger tables enabled bigger and more numerous memory devices and fans for effective processors. When people started to demand mobility, the interest turned to completely other issues. For trajectory forecasters, this points out the importance to follow several trajectories, not only the one that has shown to be important in the past. The world out there is changing, invisibly, all the time.

6 CONCLUSIONS: IMPLICATIONS FOR MODELING OF THE TIPPING POINTS IN TECHNOLOGY ACCEPTANCE

It is in many traditional cases possible that the main elements of innovation diffusion are based on the performance of the product and the awareness of the customer base of this relative benefit (together with the time and the social system; Rogers, 2003). In the age of on-line, real-time communications and products mixed with services, it seems that the main attributes are the relative benefit and the nature of the market system (or the "enlarged product" content). This assumes a much bigger awareness and also a higher customer knowledge level than earlier. Furthermore, the relative benefit is not only to be understood as a technological performance feature, as some authors suggest, but from a real customer value perspective. The situation with relative benefit can thus, despite the path-dependent nature of technological performance development, develop to both the benefit of established companies as well as new entrants; the new entrants have on their side the technical performance, but this is of little use if the process innovation is delayed. The incumbents can on their side utilize usability innovations or process innovations that enable price reductions. There may be secondary-level innovations or underlying developments that may either restart an already sagging technology performance trajectory, as the case of microprocessors in the diesel engine performance, or there can be underlying societal developments that may turn the interest to technology performance trajectories other than what have traditionally been of interest (as the “freedom” through mobile telephony caused a market change, which again created technology issues in computer markets, helping trend-aware actors such as Apple to rise rapidly in market share despite only average performance in the previous trajectories). This makes technology forecasting difficult.

Even in the new situation created by the information and knowledge age, the tipping point where the new technology outperforms the old one on the market would still be the most important single point in the trajectory thinking, and modelling it would still involve assessing the respective development curves. The assessment of the new technology should, however, include both the state-of-the-art technical performance and the performance of the mass-produced products; the performance of the latter can stay miserably low years after the top-of-line is acceptable. Furthermore, there should be scenarios of "no development" and "usability and process innovations" to the existing products, to be compared to the best-worst-average performance of the new technology. Finally, the role of product complementors and network externalities in sustaining the existing innovation should be assessed.

Thus, the modelling of innovation diffusion, or technology trajectories, a very much related area, becomes not an exercise in linear extrapolation but scenario building (see e.g. Schwartz, 1996), and the insights should be used as scenarios overall: by preparing for each of these, even for the less probable scenarios. Developing a software package making the scenario-building and sensitivity analysis simple and the tipping point shifts visual is one of the follow-up research tasks. We will also continue to collect technology trajectory and market data in order to understand the factors affecting the developments of both the existing and the disruptive technologies in more detail.

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ABOUT THE AUTHORS

Tauno Kekäle, Professor. PhD. Vaasa University of Applied Sciences, Wolffintie 30, FIN-65200 Vaasa, e-mail: tauno.kekale@vamk.fi.

Petri Helo, Professor, PhD. University of Vaasa, Industrial Management, PO Box 700, FIN-65101 Vaasa, e-mail: phelo@uwasa.fi.