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Rebound effects of progress in information technology

Abstract Information technology (IT) is continuously making astounding progress in technical efficiency. The time, space, material and energy needed to provide a unit of IT service have decreased by three orders of magnitude since the first personal computer (PC) was sold. However, it seems difficult for society to translate IT's efficiency progress into progress in terms of individual, organizational or socio-economic goals. In particular it seems to be difficult for individuals to work more efficiently, for organizations to be more productive and for the socio-economic system to be more sustainable by using increasingly efficient IT. This article provides empirical evidence and potential explanations for this problem. Many counterproductive effects of IT can be explained economically by rebound effects. Beyond that, we conclude that the technological determinism adopted by decision-makers is the main obstacle in translating IT's progress into non-technical goals.

Zusammenfassung Die Informationstechnologie macht laufend erstaunliche Fortschritte hinsichtlich technischer Effizienz. Zeit-, Raum-, Material- und Energieaufwand pro Einheit von IT-Dienstleistungen haben sich seit dem Verkauf des ersten PC um drei Größenordnungen verringert. Es scheint jedoch

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schwierig zu sein, die Entwicklung der IT-Effizienz in Fortschritte hinsichtlich individueller, organisatorischer oder sozioökonomischer Ziele umzumünzen. Insbesondere scheint es dem Einzelnen schwer zu fallen, die zunehmend effiziente IT zu nutzen, um selbst effizienter zu arbeiten; Organisationen scheinen durch effizientere IT nicht produktiver zu werden und sozioökonomische Systeme dem Ziel der Nachhaltigkeit nicht näher zu kommen. Dieser Artikel stellt empirische Ergebnisse und mögliche Erklärungen für dieses Problem zusammen. Viele kontraproduktive Effekte der IT können durch Rebound-Effekte ökonomisch erklärt werden. Darüber hinaus kommen wir zu der Schlussfolgerung, dass es hauptsächlich der technologische Determinismus von Entscheidungsträgern ist, der bisher die Nutzung des informationstechnischen Fortschritts für nicht-technische Ziele behindert.

Keywords Rebound effect · IT productivity paradox · Human–computer interaction · Organizational impacts of IT · Environmental impacts of IT · Information society · Sustainable development

1 Introduction

We have experienced enormous progress in digital information technology (IT) over the last few decades. The amount of processing power or storage capacity that can be had per unit of money, space or weight has increased by several orders of magnitude. Moore’s (1965) well-known hypothesis has not been disproven thus far. The hardware of a contemporary personal computer (PC) operates about 1,000 times faster than that of the first PCs, and the development of working memory, external storage media and data transmission bandwidth tells a similar story.

Progress in IT, therefore, consists mainly of progress in efficiency. Efficiency in the broadest sense of the word is the ratio of the result of a process (output) to the required resources (input). If the efficiency of a process is doubled, then twice as much output can be produced with the same input as before or the same output with half the input. Efficiency simply indicates the ratio. Unlike effectiveness, efficiency is always a ratio.

That which is viewed as the output of a process is derived from the purpose assigned to it. Various kinds of efficiency can be defined depending on the resources that are taken into consideration on the input side. If we consider only the resource ‘time spent’, for example, we can talk about ‘time efficiency’. Other types of efficiency become apparent if other inputs are considered instead of time: the input of energy (energy efficiency), materials input (materials efficiency), the space needed (space efficiency) or the money that has to be spent (cost efficiency).

Information technology has made astounding progress in all types of efficiency mentioned, if hardware performance is viewed as the output. Already in the 1980 s, the business press introduced the much-cited analogy between IT and automotive technology: if the automobile industry had done what the computer industry had done, it was argued, a Rolls-Royce would cost $2.50 and get 2,000,000 miles to the gallon. Today, continuing this analogy, the Rolls-Royce would cost less than 25 cents and probably be distributed as a promotional gift.

This article is about the difficulty of translating IT's efficiency progress into progress in terms of individual, organizational or socio-economic goals. There is no simple relationship between an increase of efficiency on the technical level and better performance of the people and systems that use the technology. In particular, it seems to be very difficult

1. for individuals to work more efficiently,
2. for organizations to be more productive,
3. for the socio-economic system to be more sustainable

by using increasingly efficient IT. In claiming that it is *difficult* to translate IT efficiency progress into such higher level goals as those listed above, we are not arguing that it is *impossible*. On the contrary, we basically believe that IT has an enormous potential for supporting exactly these goals; but the practical deployment of IT is a field of systematically wasted opportunities. We will return to this point after having discussed some empirical results.

The general observation that an increase in technical efficiency may have counterproductive effects in the system using the technology is explained in neoclassical economics by the so-called *rebound effect*: if a good gets cheaper in terms of its price or any effort necessary to obtain it, the demand for this good usually increases. For this reason, efficiency improvements do not imply savings on the input side—the possibility of supplying more output per unit of input can even cause increasing use of the input resources. The rebound effect is defined as 100% if the potential savings on the input side are exactly compensated for by increasing demand. The reader who is interested in a more theoretical discussion of the rebound effect is referred to Binswanger (2001) and Hilty et al. (2005a, Chap. 5). The present article focuses on empirical evidence for rebound effects of IT efficiency progress and presents examples on different system levels, from the individual to the global perspective.

2 Individual work efficiency

It seems reasonable to assume that people doing desk work with a PC will increase their time efficiency when the PC is replaced by a more powerful model. However, we found in an empirical study that this is not always true for basic PC-based tasks such as organizing files and editing documents containing text and pictures, including some tasks that challenge the hardware by requiring a lot of processing power. The validity of the results may be limited to the specific hardware and software products we used for the experiment.

2.1 Experimental design

Our laboratory experiment was based on PC configurations typical of the years 1997, 2000 and 2003. As Table 1 shows, the hardware used differed greatly in clock speed, working memory and hard disk capacity. Since the test only involved file handling and text editing, it was sufficient to install the operating system and a word processor. We used reconstructions of PC configurations used widely in business in the respective year. All software

Table 1 The PC hardware and software used for the experiment (*source*: Empa)

System	A	B	C
Year	1997	2000	2003
CPU Clock rate	233 MHz	801 MHz	1,992 MHz
RAM Capacity	64 MB	128 MB	256 MB
Hard disk capacity	2 GB	20 GB	56 GB
Operating system	Microsoft Windows NT	Microsoft Windows 2000	Microsoft Windows XP
Word processor	Microsoft Word 97	Microsoft Word 2000	Microsoft Word 2002

components were installed taking the default parameter settings. The appearance of the desktop interface was kept similar on all computers to optimally satisfy blind test conditions. A switch box made it possible to connect the same mouse, keyboard and monitor to each of the three computers.

We defined two tasks for testing user performance on the three systems: a file-handling and a text-editing task:

1. The file-handling task included locating, copying, moving and deleting files and groups of files varying in size from 24 kB to 42 MB.
2. The text-editing task focused on locating, inserting and deleting text, changing fonts and formats in a document of 150 pages as well as copying and pasting photographs between two documents, including the exact positioning of these pictures.

The experiment was performed on 42 subjects recruited from a service organization with 180 employees. Subjects had to execute each of the tasks twice on each computer system in randomized order. The whole test took 45–90 min per subject. We measured the time the subjects needed to complete each task, logged user interactions and processor workload on the computer and videotaped the screen signal. For more details on the methodology, please refer to Hilty et al. (2005b).

2.2 Results

The test revealed a statistically significant decrease in user performance on system C (2003) as compared to system B (2000) for the file-handling task. As shown in Fig. 1, average user performance was best in both tasks on the 2000 system, despite the fact that the hardware of the newer system performed much better according to benchmarking results.

This result was surprising because Windows 2000 had never been in use in the organization for which the subjects were working, and most of them had never used it before. At the time of the test, the migration from Windows NT to Windows XP was nearly complete, and most of the subjects were already using Windows XP for their everyday work.

In order to find explanations for our result, we examined the effort required from the user and the machine to complete the tasks in detail. Since most user actions during task execution were mouse positionings (usually followed by a single mouse click, and less often by no click or a double click), we used the number of mouse positionings as an indicator of the user's effort. The

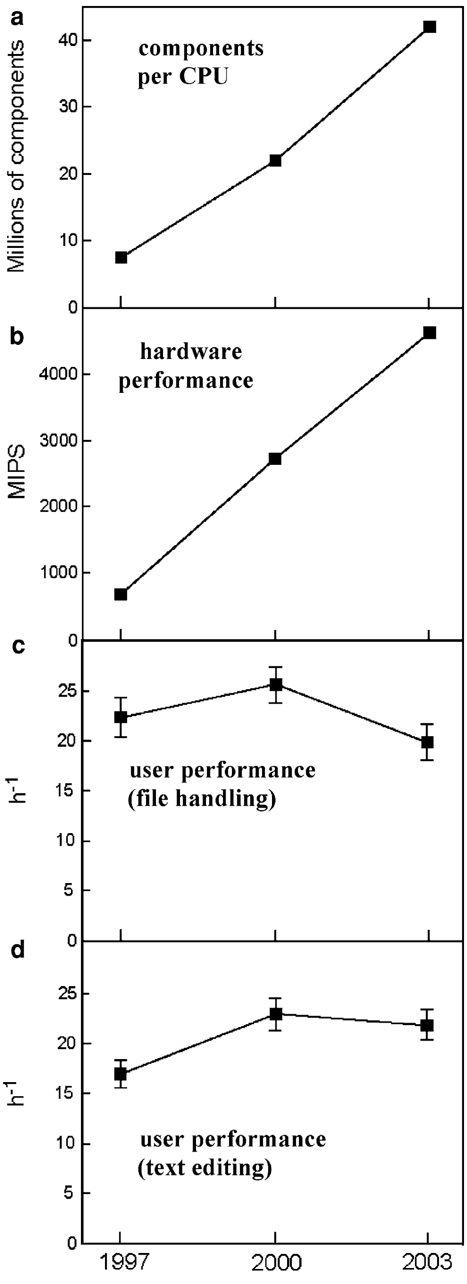

Fig. 1 Computer performance and performance of the subjects on file-handling and text-editing tasks. **a**. Number of components in the PC's CPU. **b**. CPU performance measured as millions of instructions per second. **c**. Performance of subjects measured by the number of fulfilled file-handling tasks per hour. **d**. Performance of subjects measured by the number of fulfilled text editing tasks per hour. Error bars denote square error means. *Source* Empa

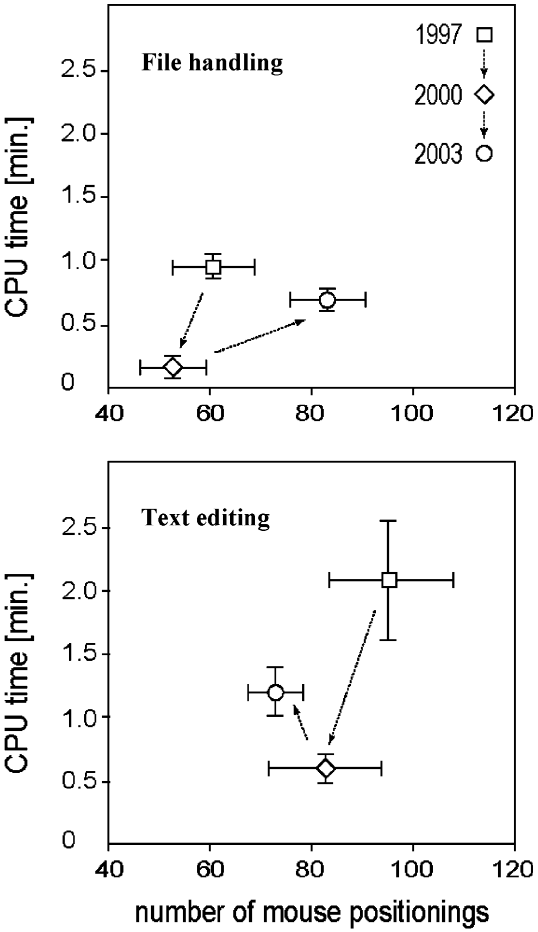

Fig. 2 Human effort, measured by number of mouse positionings, versus machine work, measured by CPU time, for executing the tasks for the second time on a given computer. **a**. Mean values for the file-handling task. **b**. Mean values for the text-editing task. *Arrows* indicate the temporal sequence of computers. *Error bars* denote square error means. *Source* Empa

computer's work was measured in CPU time (the integral of processor utilization over time).

As Fig. 2 (top) shows, the file-handling task required much less CPU time on the 2000 system than on the 1997 (NT) system, but again much more on the 2003 (XP) system, and the same is true for the number of mouse positionings the users performed (significant difference, $p=0.016$). Whereas, when they managed with roughly 50 mouse positionings on Windows 2000 on the average, they needed more than 80 positionings for the same task on Windows XP.

The text-editing task (Fig. 2, bottom) shows a decrease in mouse positionings from 1997 to 2000 to 2003, but an increase in CPU time from 2000 to 2003. Given the fact that the 2003 hardware executes more than twice as many instructions per second than the 2000 hardware, one should instead expect a significant decrease.

2.3 Discussion

The main conclusion from this experiment is that changing over to a faster computer running newer software does not necessarily lead to higher work efficiency; at least for the types of tasks we used in our experiment. On the contrary, it is even possible that both—the machine and the user—need to work significantly longer in order to replicate a given task with a newer system. In our experiment, this effect became significant for the file-handling task, although the users were already more familiar with the newer system than they had ever been with the older one.

We suppose that this counter-intuitive result can be explained by a combination of rebound effects:

1. Higher hardware performance allows for higher software functionality. Software designers make use of this freedom in adding functions without taking care of the conceptual structure of the whole functionality. As a consequence, the average time to access a given function increases. A closer examination of the video traces taken in our experiment supports this explanation. Many subjects lost a lot of time with mouse positionings that were necessary to access functions which could be accessed more directly in the previous system.
2. Higher hardware performance entices software developers to create inefficient implementations ('inefficient' with regard to processor cycles and/or working memory; both affect overall system performance). There is some evidence for this explanation in the performance log files created in our test. However, we must point out that our experimental design was not aimed at investigating this aspect.

Both of these effects concern the decision-making of the system designers, not of the users. User behaviour was constrained by the tasks given, which required the subjects to exactly reproduce a given result. In everyday life, we would not expect that users would produce exactly the same output after switching over to new IT equipment. It is self-evident, for instance, that the appearance of documents produced on PCs has varied considerably during the 25 years of 'PC evolution'. Variability in output quality creates space for a specific case of the rebound effect known as 'goal displacement':

'...studies of individuals using word processors have noted that instead of using the technology to produce more documents in a given length of time, employees make five times as many corrections as previously. They also pay more attention to fonts, graphics and so on. In other words, at this individual level, there is a displacement from the goal of increasing throughput productivity to the goal of enhancement of quality and appearance.' (Attewell 1993, p. 4).

Viewed together, the rebound effects on the side of the software developers and the goal displacement effects on the users' side could help explain why IT investments do not seem to have a positive impact on productivity. This so-called 'IT productivity paradox' has been discussed in economics and management literature for a long time. Robert Solow, the 1987 Nobel laureate in economics, initiated the debate by stating that 'we see the computer age everywhere except in the productivity statistics' (Solow 1987). The subsequent controversy motivated a range of interesting research on the question of how IT affects the productivity of organizations, and how productivity on the organizational level aggregates to productivity on the macrolevel.

3 Organizational productivity

Productivity is the amount of output of a production process per unit of an input. If any given process is seen as production (which is always possible in principle), efficiency and productivity are the same.

The inputs to production are called *factors* in economics. If we consider only one individual factor of production, for example, labour, then we talk about *factor productivity*, in this specific case *labour productivity*. The attempt to consider all factors is called *total factor productivity*. Both input and output are usually not measured in physical units, but represented by their economic value.

The IT productivity paradox is a phenomenon attributed to the service sector.[1] In today's service sector, most production is done by people aided by computers. The employees of banks, insurance companies, travel agents, law firms, publishers, research institutes—just to mention a few—typically spend most of their time using a PC, even during face-to-face meetings. Also those service industries which are not dominated by deskwork, such as medical services, logistics or gastronomy are obviously being pervaded by computers, for example, specifically designed hand-held devices.

The productivity of a typical service organization is therefore an aggregate of the productivity of humans using computers, which coincides with the work efficiency discussed above.

The fact that there is no straightforward relationship between using a PC and *individual* work efficiency is, therefore, one possible explanation for the IT productivity paradox. Beyond that, there are explanations referring to unintended effects on the *organizational* level. We will briefly discuss two of them in the following subsections.

3.1 The information work rebound effect

Although our experiment described above casts doubt on whether IT progress increases the efficiency with which people use *previously available* functionality, it can still increase overall individual work efficiency by providing *new functions*. Desktop publishing, the use of e-mail, access to the World Wide Web and its search engines, groupware and virtual private networks are examples of additional functionality that has had a radical influence on what people are doing with computers. The outcome of these changes is difficult to measure. However, we will assume that the goal displacement rebound effect is clearly below 100%, so that the productivity of an individual doing desk work is still being improved.

What effect do such improvements have at the organizational level? They decrease the company-internal price of information work, because the individual effort to access or exchange information is lower than before. As the unit cost of

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[1] It is an undisputed fact that IT contributed to productivity improvements through the automation of manufacturing and other physical production processes.

a good falls, demand for the good increases. This is also true for an organization's internal market, even if the processes are not explicitly organized in a market framework. It is not surprising, though, what Attewell has observed: 'Thus even as the unit cost of computer-related work has fallen (due to productivity improvements), the demand for that work within the corporation has increased. With a price elasticity of demand greater than one, the total amount of information processing work after computerization and its cost can be greater than the volume and cost of information work prior to computerization, (Attewell 1993, pp. 4–5).

For example, the demand for internal reporting has increased with the development of IT infrastructure in many organizations to a degree that affects the productivity of the organization. As early as the 1970 s, Weizenbaum made the point that the growth of bureaucracy would have encountered limits, if the computer had not been invented in time to expand those limits (Weizenbaum 1976). His point was then that the computer had reinforced government bureaucracy, but it is just as true today for the administration of large commercial organizations.

3.2 Technological determinism

Macdonald (2002) suggests another solution to the IT productivity paradox, which is not a specific case of the rebound effect, but is nevertheless essential in our context. In his view, the expectation that IT would increase the productivity of an organization is taking the wrong view of things. It is not the IT, but rather management methods that can increase the productivity of an organization. Using an adequate management method is, therefore, of primary importance, and the requirements placed on the IT infrastructure should be derived from it. In fact, exactly the opposite has been happening over the last decades of business information systems. Consultants have been very successful in selling management methods inspired more by the capabilities of IT than by the requirements of the organization. An observation supporting this view is the trend towards measuring and quantification in management:

'The mantra of "what gets measured gets managed" is stronger than ever in these days of management method with the result that management is focused on what can be measured most easily and neglects what is less easy to measure. The IT has allowed much performance to be quantified very easily...but has trouble with the qualitative.' (Macdonald 2002, p. 20)

Another example is 'knowledge management', a management method that became popular during the late 1990 s. At least the simplistic forms of knowledge management are based on the assumption that knowledge can be separated from humans and managed externally, in particular with the aid of database systems. This type of knowledge management is actually a revival of naïve ideas from the early days of Artificial Intelligence (AI): in the late 1970 s, AI researchers believed that it would be possible to 'milk' knowledge from experts by interviewing them or by letting them interact with the 'knowledge acquisition component' of the expert system. It turned out later that this belief was based on a drastic underestimation of the role of tacit knowledge in expert performance: most of the knowledge that distinguishes experts from beginners cannot be stated explicitly by them (see, e.g. Dreyfus 1992 for a critical discussion of early

AI). It seems that even obsolete ideas from the IT world find their way to management methods, where they are resurrected in new guises.

Macdonald's main conclusion is that the technological determinism of the last decades is at the heart of the IT productivity paradox. If he is right, the best advice that should be followed by a manager who wants to improve the productivity of his organization is not to let IT determine management methods. The IT infrastructure of an organization should be shaped by the requirements of the organization, not vice versa.

4 Global sustainability

Among the different factor productivities, labour productivity is not posing a problem at the global scale, because labour is not a scarce production factor. There are enough people willing to work.

In contrast to this, resource productivity *is* a problem, because natural resources *are* scarce. The earth's crust provides only a limited amount of each element of the periodic system, and limited amounts of valuable compounds such as fossil fuels. It follows that the extraction and (practically irreversible) dissipation of material resources cannot continue forever, that is, is not sustainable.

Sustainable development as a political idea has its origins in the Brundtland report issued by the World Commission on Environment and Development (WCED 1987). According to the notion of sustainability in that report, the aim of economic development should be both

- *intra*generational and
- *inter*generational solidarity.

In other words, the needs of people living today must be met throughout the world without this being to the detriment of future generations.

Under present technological conditions, the goal of sustainable development leads to a dilemma: if the lifestyle of the OECD countries is to be applied across the whole globe, a great burden would be put on future generations because of the accelerated dissipation of material resources that would be caused by global affluence.

As long as there is non-negative growth in world population, the only way to solve this dilemma is through an 'efficiency revolution' in terms of material resources. This idea became very popular during the 1990 s (Schmidt-Bleek 1993; Weizsäcker et al. 1995).

Whenever the resource efficiency of a process is dramatically increased, the change comprises 'dematerialization'. Dematerialization is a far-reaching reduction in the material and energy intensity of any economic process (production, transport, consumption and waste disposal). The need for dematerialization was recognized in the late 1980 s, when—after *micrograms* of toxic substances—the *megatonnes* of the regular, non-toxic mass flows became the focus for environmental protection: 'Considering the fact that for every person in the United States we mobilize 10 t of materials..., it is clearly important to gain a better understanding of the potential forces for dematerialization. Such understanding is essential for devising strategies to maintain and enhance environmental quality, especially in a nation and a world where population and the desire for economic growth are ever increasing.' (Herman et al. 1990, p. 346)

Since the early 1990 s, estimates have been discussed according to which the material intensity per service unit would have to be reduced by a factor of 4 to 10, if the lifestyle of the rich North is to be applied at a global scale (Schmidt-Bleek 1993; Weizsäcker et al. 1995).

For quite a long time, the 'dematerialization community' failed to adequately consider what was going on in the IT field, with few exceptions (Arnfalk 1999; Forseback and Johnston 2000; Heiskanen et al. 2001; Hilty and Ruddy 2001). What is the role of IT with regard to the sustainability dilemma?

First, the IT sector is a perfect example of the 'efficiency revolution' or the 'dematerialization' that would be needed in (almost) all sectors to solve the sustainability dilemma. What is dematerialization if not the reduction of an ENIAC weighing 30 t, covering an area of 140 m^2 and making 5,000 additions or subtractions per second to a single microchip, which carries out some hundred million floating point instructions per second?

Second, IT is a strong agent for change in almost every economic process. As can be learned from the 'IT productivity paradox' debate, the relationship between IT investments and (labour or total factor) productivity is not straightforward and depends on many aspects—the impact of IT on *resource* productivity would be worth at least as much study. Such analyses would provide basic knowledge for the design of policies intended to harness IT for the purposes of sustainability.

Third, there is already sobering evidence for the existence of a perfect rebound effect in both of the first cases:

1. Despite the dematerialization of IT hardware 'from a Rolls-Royce to a promotional gift', as mentioned in 'Introduction' section, the use of scarce materials induced by the production of IT has at the global scale reached a level that bears watching and is increasing rapidly.
2. Despite the high potential of IT to dematerialize production in industries other than IT and even consumption, the overall material throughput of the industrial economies has dramatically increased over the last three decades of IT's progress and diffusion—this could be called the 'IT resource productivity paradox'.

We will elaborate on both claims in the following two subsections in providing empirical evidence and potential explanations.

4.1 The case of electronic waste

The amount of electronic waste (or 'e-waste' for short) that is processed and its material composition can be used as indicators of the material resources spent on electronics. Although the global figures on e-waste are alarming in themselves, e-waste is an 'optimistic' indicator that tends to underestimate resource flows, because most materials used in the production of electronics do not become part of the final product. For example, the production of a microchip (32 MB DRAM) requires at least 1.6 kg of chemicals and fossil fuels, which is about 630 times its physical mass (Williams et al. 2002).

Looking at IT-induced resource flows from the end of their life cycles, we get the following situation.

In 2004, an estimated 100 million obsolete PCs entered waste streams. In the same year, more than 180 million new PCs were sold. The PCs comprise only a fraction of all e-waste. It is estimated that in 2005 approximately 130 million mobile phones will be scrapped. Similar quantities of waste are expected for all kinds of portable electronic devices such as PDAs, MP3 players, computer games and peripherals (Widmer et al. 2005).

In EU15 (the 15 countries constituting the EU before May 2004) the amount of waste electrical and electronic equipment per capita today is between 14 and 20 kg/a. As a general rule, about half of such waste consists of information, communication and entertainment equipment, the other half being household appliances (such as refrigerators) of which only a small percentage by mass is comprised by electronics and thus is not considered here (Widmer et al. 2005).

Electronic waste contains considerable quantities of valuable materials such as precious metals. Early-generation PCs used to contain up to 4 g of gold each; however this has decreased to about 1 g today. The ordinary metal content is also very high: 1 t of e-waste contains up to 200 kg of copper, which can be sold for about 500 Euros at the current world price. Recycling e-waste has the potential, therefore, to be an attractive business, and more organized players are investing in the area such as Boliden (Sweden), WEEE AS (Norway) and Citiraya (United Kingdom).

Electronics also contains small amounts of exotic raw materials that are usually not recycled and could become a limiting factor for future electronics production. The temporary shortage of tantalum that occurred in 1999–2001 demonstrated this problem. Only two companies extract tantalum from the mineral coltan, one in the Democratic Republic of Congo and the other in Australia. This scarcity appreciably slowed the growth of the IT industry, for example, in the mobile phone and games console segments (Horvath 2002).

4.2 E-waste recycling in developing countries

Electronic waste recycling is both an opportunity and a high risk for the people in developing or transitional countries. Although the per capita waste production in populous countries such as China and India is still relatively small, and estimated to be less than 1 kg per capita per year, the total *absolute* volume of e-waste generated in these countries is huge. Additionally, some developing and industrializing countries import considerable quantities of e-waste (Fig. 3), even though the Basel Convention restricts transboundary trade of it.

When e-waste is disposed of, recycled, or put into a landfill with domestic waste without any safety measures, there are predictable negative consequences for the environment and human health. E-waste contains more than 1,000 different substances, many of which are toxic, such as lead, mercury, arsenic, cadmium, selenium, hexavalent chromium and flame retardants that create dioxin-like emissions when burned. About 70% of the heavy metals mercury and cadmium in US landfills come from e-waste. Consumer electronics make up 40% of the lead in landfills. These toxins can cause brain damage, allergic

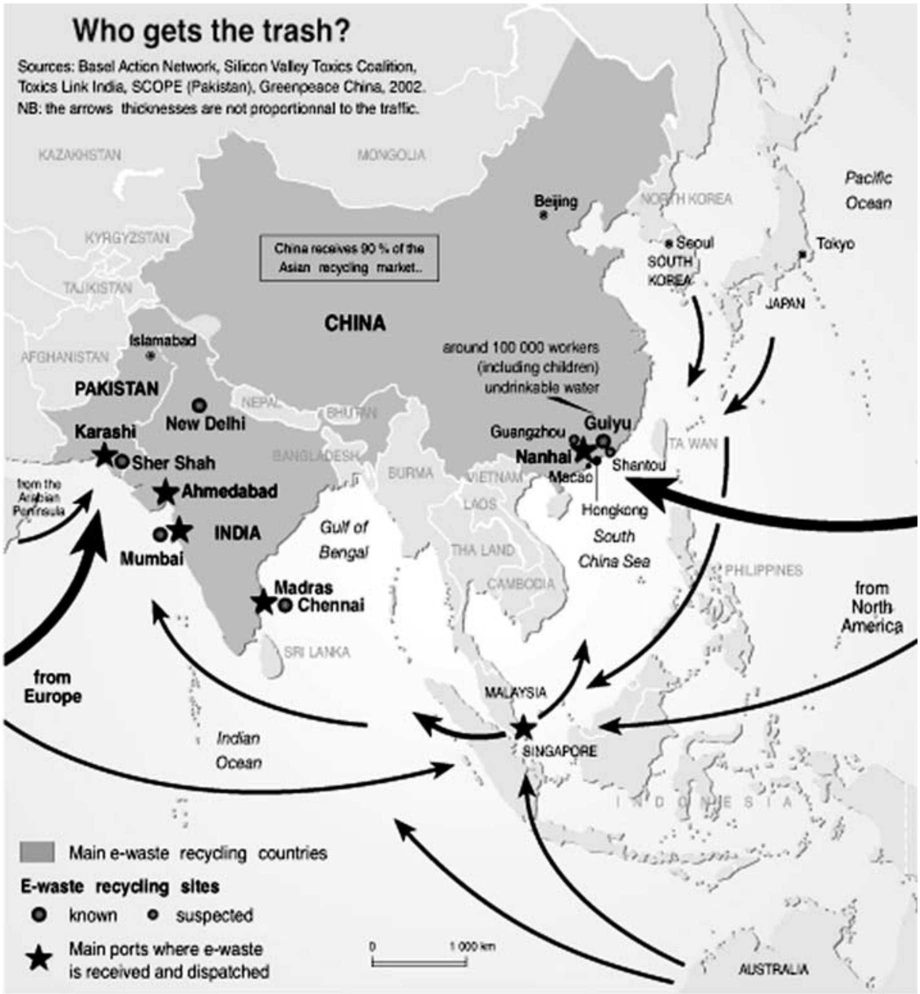

Fig. 3 Asian e-waste traffic. *Source* Schwarzer et al. (2005)

reactions and cancer.

From Empa's own investigations in New Delhi in 2004 it can be estimated that around 10,000 people generate their income by backyard recycling of e-waste in the capital. Other urban areas of India are under investigation. In the region of Guiyu in China, it has been known for several years that at least 100,000 people are working in the informal e-waste recycling business and that these activities polluted the groundwater (Puckett and Smith 2002).

As an example, Fig. 4 shows the copper extraction process as it is performed in countless small backyard companies.

From a sustainability perspective, these activities are necessary to prevent us from dissipating our most valuable resources with the distribution of electronic devices. The recovery processes do not seem to be very efficient, but compared to primary production of raw materials, they are. In order to produce 1 g of gold,

Fig. 4 Extraction of copper from printed wiring boards (PWBs): (1) manually removing varnish, (2) recovering copper-sulphate after submerging PWBs for 12 h into sulphuric acid by boiling off H_2O using PWB residues as a fuel, (3) manually segregating the copper layer and glass fibres after burning multi-layer PWBs (as they are resistant to the acid), (4) scrap iron is added to the remaining liquid to react with the dissolved copper, (5) fallen out copper slime is a third product bringing the total to 1–2 t of copper per month, (6) such an enterprise creates about 12 jobs, however at high-external costs. *Source* Widmer et al. (2005)

roughly 1 t of rock has to be moved and processed. It seems much easier to boil some printed wiring boards from a scrapped PC in sulphuric acid to recover the same amount of gold. This informal industry also creates jobs and, therefore, reduces poverty. However, these manual processes have considerable side effects on health and the environment. It is therefore imperative to find ways to prevent the side effects without destroying the positive effects of e-waste recycling. This is the aim of the project ‘Knowledge partnerships in e-waste recycling’ which Empa is carrying out together with partners in India, China and South Africa (Empa 2005).

Will continuing miniaturization solve the problem?

One could assume that the ‘self-dematerialization’ of IT will solve any resource or waste problems associated with the hardware.

Thus far however, miniaturization of IT devices has always been counteracted by the growing numbers of devices produced. The price per functional unit has always fallen and triggered greater demand, which has compensated—or even over-compensated—for the miniaturization effect in terms of mass flow.

For example, the considerable reduction in the average physical mass of a mobile phone from over 350 g (1990) to about 80 g (2005), which corresponds to

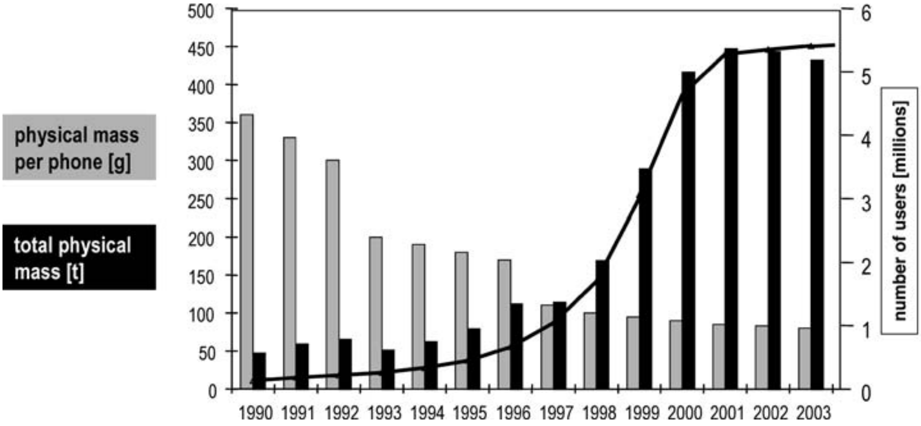

Fig. 5 Development of the physical mass of mobile phones sold in Switzerland. The *bars* denote the mass per phone in grammes and the total mass in metric tons, respectively. The *line* shows the number of users in million persons. *Source* Hilty et al. (2005a)

a reduction by a factor of 4.4, was accompanied by an increase in the number of subscribers, which in turn led to a rise in total mass by a factor of 8.0 (data for Switzerland, see Fig. 5).

There is no evidence that this rebound effect of miniaturization will no longer apply if the visions called ‘pervasive computing’, ‘ubiquitous computing’ or ‘ambient intelligence’ become real. Quite the contrary, IBM expects that in the next 5–10 years about one billion (10^9) people will be using more than a trillion (10^{12}) networked objects across the world. This would mean that there would be an average of 1,000 ‘smart objects’ per person in the richer part of the world, each containing a processor and some communication module. If we assume that the average mass of an electronic component used to make an object ‘smart’ is about 10 g and that such a component were in service for about 1 year, the resulting per capita flow of e-waste would amount to 10 kg/a. This value is on the same order of magnitude as today’s e-waste in industrialized countries, as mentioned above.

Taking other technological visions literally can even lead to dramatic results. One example is the vision of ‘e-grains’, very small processors that are envisioned to be used as ‘intelligent wall paint’, turning walls into large-scale displays and rooms into distributed computers. In a study for the Swiss Center for Technology Assessment (Hilty et al. 2005a), we hypothetically assumed that this technology would be applied to give every inhabitant of Western Europe, North America and Japan one ‘intelligent room’. Assuming further that nickel will still be used as a constituent of e-grains, it was estimated that more than 40% of the world’s annual nickel production (1.2 million metric tonnes in the year 2000), would be required to produce the wall paint, among other materials that would be needed.

Another trend is that the borderlines between ‘classic’ *electrical* equipment (such as refrigerators) and *electronic* equipment are becoming blurred. One can already see today that more and more objects that used to be considered purely ‘electrical’ are now equipped with computer chips, and thus have turned into 'electronic' objects. Today more than 98% of all programmable microprocessors are embedded in commodities that are usually not perceived as computers, for example, household appliances and toys. Even more relevant from an environmental point of view, many commodities that until recently were considered 'non-electric', are now being equipped with microprocessors for extended functionality, or with Radio Frequency Identification (RFID) transponders for contactless identification (Hilty et al. 2005a; Oertel et al. 2005).

There is little hope that the resources used to produce these billions of embedded components will ever be recovered, not even in the backyards of Asia. Given the more-than-100% rebound effect of miniaturization that we have to acknowledge thus far, it is likely that the dissipation of valuable and toxic materials due to the distribution and disposal of electronics will continue at a higher rate than today, unless effective counter-measures are taken.

4.3 Second- and third-order effects of IT

In the study on the impacts of IT on sustainability, the impacts of the *hardware life cycle* from production, distribution and use to waste disposal are called 'first-order' or 'primary' effects. These are effects of the physical existence of IT. The impacts of e-waste recycling we have sketched in the preceding subsection are first-order effects. We speak of second-order effects of IT when its application has consequences for *other processes* (e.g. production, transport), whose effects relevant for sustainability are then modified positively or negatively. For example, IT applications can support dematerialization. Since every change of processes can lead to adaptation of behaviour as well as organizational and economic structures, these *third-order effects* also have to be taken into account (e.g. changes in consumption patterns, new forms of work organization). The rebound effect is a special type of third-order effect (see EITO 2002; Köhler and Erdmann 2004; Hilty et al. 2005a for this classification of IT effects).

It is often useful to think of a second-order effect as a *potential* (the maximum impact that can in principle occur) and of a third-order effect as the interaction of such potentials with the surrounding system, which can either enable or inhibit the realization of these potentials, compensate for them by seeking an equilibrium, etc.

An assessment of the overall outcome of second- and third-order IT effects in a given framework must be based on models that account for the dynamics of the (socio-economic) system in which IT is applied. In the project 'The future impact of ICT on environmental sustainability' we developed such a model, using the most 'classical' approach to modelling socio-economic systems, System Dynamics.

The model was designed to assess the second- and third-order IT effects in the areas of

1. e-business,
2. virtual mobility,
3. virtual goods,
4. waste management,
5. intelligent transport systems,
6. energy supply,

7. facility management,
8. production process management.

The assessment was done with regard to the following environmental sustainability indicators that were developed in response to the conclusions of the European Council in Gothenburg and reported to the Spring European Council in March 2002 (see also Ruddy 2005):

1. greenhouse gas emissions,
2. energy intensity of the economy,
3. volume of transport to gross domestic product,
4. modal split of transport,
5. urban air quality,
6. municipal waste landfilled or incinerated.

The model combined all available knowledge about the environmental impacts of IT, life cycle assessment (LCA) data on the application fields, and economic elasticities on relevant goods and services. The result of this modeling process was an equation system that related more than 2,000 variables to each other. The model was then used to simulate a series of policy scenarios with the time horizon 2020. A sensitivity analysis was performed to detect which results were the strongest and most robust ones, given the high uncertainty of some parameters.

The three most important findings were,

1. There is a great potential for IT to rationalize energy use in housing or other facilities, because space heating is a process that is far from being optimally controlled today and somewhat ‘under-informed’. For example, heating systems usually have no information about which rooms are in use. Since space heating comprises a large part of total energy consumption (about 30% under European conditions), small efficiency increases can add up to considerable savings. Whether this potential can be realized and if there will be a rebound effect depends on parameters such energy prices.
2. There is a similarly great potential for IT to support a product-to-service shift in the economy. Selling and buying just services instead of goods is in many cases the most effective way to dematerialize. In many cases where this shift has been inhibited by the high-transaction costs of selling a service so far, IT can solve this problem, for example, by enabling efficient ‘microbilling’. Whether this potential will be realized is also a cultural issue and exploring it would go beyond our model.
3. Passenger transport, which accounts for roughly ¼ of total energy consumption, is a field where any future IT application increasing time efficiency (‘intelligent’ cars and roads) will be counteracted by a full rebound effect. In all our scenarios, applying IT to make traffic more efficient caused an *increase* in traffic volume. This result is not surprising, given the historic truth that any timesavings in travel have been transformed into additional travel so far. Passenger traffic does not seem to be a field where sustainability can be approached by IT applications that make the system more efficient. However, a surprising detail of our simulation study was that IT progress stimulates the growth of public transport more than the growth of private car transport. This

is a consequence of the time-use submodel we incorporated, combined with the assumption that progress in IT increases the share of work that can be done while travelling: if people want to use this increasing potential for mobile work, it results in a competitive advantage of public transport systems, in particular, railways.

To sum up, there are two main fields where there is an opportunity to use IT in the near future to save relevant quantities of resources: heating and services.

One general observation that can be made from our project is that the impact of IT is roughly between −20 and + 30% across the range of chosen indicators. It can be concluded, therefore, that the impact of IT on the environmental indicators is relevant and should be taken into account by policymakers. However, the positive and negative effects tend to cancel one another out, so that in a 'business as usual' case of IT no significant effect is expected with regard to sustainable development. Instead policies are needed that can deal with the various effects of IT à *la carte*, that is, can create conditions such that the negative ones are inhibited and the positive ones can develop. Under the most favourable conditions we estimate that 20% of environmental impact over the next one to two decades could be avoided through IT applications. Policy has, therefore, an important role to play in realizing the positive environmental outcomes obtainable with IT applications, and, at the same time, in suppressing rebound effects.

For a synopsis of the project results see the final report (Erdmann et al. 2004); details on the methodology and data can be found in the fourth interim report (Hilty et al. 2004).

5 Conclusions

The observation that progress in IT efficiency does not necessarily translate into individual work efficiency, organizational productivity or socio-economic sustainability can be explained on different levels by the following effects:

1. Software design and implementation rebound effects on the part of software developers.
2. Goal displacement on the part of the user.
3. The information work rebound effect within an organization.
4. Technological determinism on the part of managers and their consultants.
5. The miniaturization rebound effect.
6. A lack of policies which take a differentiated view of IT's effects and systematically use IT for sustainable development.

The astounding efficiency progress in IT has enriched us with opportunities. However, we fail to use these opportunities creatively: instead we let IT dictate to us how we are to work and manage organizations. We even accept accelerated resource depletion and pollution for the questionable progress that such an approach to IT gives us. The IT offers great potential to solve real problems—in order to exploit that potential, the requirements placed on IT must be derived from society's needs, not from the capabilities of the technology.

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