Impacts of Information and Communication Technologies on Environmental Sustainability: speculations and evidence

REPORT TO THE OECD

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Summary

This report summarises recent literature on the environmental impact of information and communication technologies (ICTs) and the Internet. Three main types of effects identified are:

- *first order impacts*: direct environmental effects of the production and use of ICTs (resource use and pollution related to the production of ICT infrastructure and devices, electricity consumption of ICT hardware, electronic waste disposal)
- *second order impacts:* indirect environmental impacts related to the effect of ICTs on the structure of the economy, production processes, products and distribution systems; the main types of positive environmental effects are dematerialisation (getting more output for less resource input), virtualisation (the substitution of information goods for tangible goods) and 'demobilisation' (the substitution of communication at a distance for travel)
- *third order impacts*: indirect effects on the environment, mainly through the stimulation of more consumption and higher economic growth by ICTs ('rebound effect'), and through impacts on life styles and value systems.

The report concludes that ICTs are having profound environmental impacts, both positive and negative. While there are large opportunities for environmental and resources gains through the diffusion of ICTs, many of these opportunities will lead to incremental changes over the longer term (general labour, capital and resource productivity improvements). Technological and organisational changes enabled by the Internet and other ICT networks may also have profound environmental impacts, but evidence on the sign and magnitude of these effects is still sparse.

The implications for policy, in particular technology and innovation policy, are manifold. In general, we would expect policy to influence most easily first-order effects by setting technology standards, by encouraging energy pricing taking into account environmental costs, and by facilitating the creation of robust systems for retrieving and recycling equipment at the 'end of life'. The influence of policy on second- and third-order effects is more difficult to foresee. Indeed, some commentators argue that policy can represent a significant obstacle to the efficient diffusion and use of ICTs (and by implication, the realisation of potential environmental benefits). On the 'supply side', there is a role for policy in encouraging innovation that promise real substitutions of information for resources and mobility, and in setting ambitious long-term targets for their widespread adoption. On the 'demand side', there is an important role for government in shaping telecommunications and 'hard' (transport, utilities, buildings, urban form) infrastructures that will determine whether opportunities for radical improvements in resource productivity will arise from the diffusion of ICTs. Government also has a role as a 'consumer' through public procurement of de-materialised 'solutions' and in the delivery of government services. Imaginative use of ICTs also allows governments to associate consumption with their true environmental costs, and to create greater transparency about the relative environmental performance of alternative means of providing a good or a service. Many of the information gaps endemic to environmental policy making can be reduced through the intelligent use of intelligent systems.

I. Introduction

The relationship between the development, diffusion and use of information and communications technologies (ICTs) and the broader social goal of sustainability is not well understood. Large and growing efforts have been made to understand the emergence of ICTs as a 'general purpose' technology, and to analyse their impacts on the economy and on society. Until very recently, these studies have been concerned primarily with a specific range of impacts attributed to the technology: changes in work organisation and worker productivity; job creation and loss; profitability of companies and industrial sectors; structural change in the economy, and ultimately, prospects for economic growth and national security. The rise of communication networks, and especially the advent of the World Wide Web, have produced a flowering of research concerned with the process of 'globalisation' in all its facets; the reshaping of the political and fiscal authority of the nation state; questions of identity, group formation, and new forms of activism; problems about the governance of the Internet and its impacts on democracy; the 'digital divide' and so on. A range of science and technology issues have also been considered: ICT impact on the conduct of scientific activities; the impact of codification of knowledge on technological diffusion; the monitoring of climate change and so on.

Impacts on environmental sustainability have been characterised by a number of authors, but have only very recently become the subject of systematic research.[1] Partly this is because ICTs impacts on the environment appear to be incommensurate with their huge impacts on the economy and more generally on society. Compared to more traditional industries, like energy, transport and manufacturing, the environmental burdens linked to the production and use of ICTs appear to be small. This paper will therefore focus for the most part on indirect impacts. They are to do with the way in which human activities are being changed and reorganised, and what the implications may be for the environment.

Research into the links between ICTs and environmental sustainability is a difficult and uncertain task. Although statistical sources about the diffusion and the economic contribution of ICTs exist (e.g. OECD 2000), they are naturally behind a fast changing reality. Medium and long-term forecasts concerning, for example, the number of households connected to the Internet, or the number and value of retail and supply chain e-commerce vary greatly, sometimes by several orders of magnitude. Research into the likely future effects of a growing digital economy are currently based on hypothetical or case study-based analysis generating results that are preliminary and contingent. This is particularly true for the literature dealing with more mediated and long-term effects, e.g. through structural change. Much of the discussion here is therefore speculative and will be subject to revision as the structure of digital economy continues to unfold and as more rigorous academic research is completed.

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[1] For example: iMP Information Impacts, October 1999 issue (http://www.cisp.org/imp/october_99/10_99contents.htm); J. Romm (1999); Leadbeater (2000); Hilty and Ruddy (2000); Wilsdon (2001). While most of this research focuses on e-commerce in a narrower sense (defined broadly as economic transactions over the Internet) this paper looks at impacts from the use of ICTs more broadly. It includes the use of ICTs in product design, production processes, distribution and logistics as well as seller-buyer relationships.

II. Sketching the relationship between ICTs and sustainability

Economically, ICTs are believed to be the main driving force behind a major transformation in the global economy (OECD, 2000). What are the implications for environmental sustainability of what has been termed the 'information revolution'?

At first sight, the environmental effects of ICTs appear to be exclusively positive because 'information' is generally considered to be quick distinct from the material aspects of the natural environment. Often information is thought to substitute for, or at least improve, the use of energy and materials. There are many who go further and argue that the knowledge economy is 'weightless' and 'frictionless'. In an October 1996 speech, Alan Greenspan said,

> '…Virtually unimaginable a half century ago was the extent to which concepts and ideas would substitute for physical resources and human brawn in the production of goods and services. In 1948 radios were still being powered by vacuum tubes. Today, transistors deliver far higher quality with a mere fraction of the bulk. Fiber-optics has replaced huge tonnages of copper wire, and advances in architectural and engineering design have made possible the construction of buildings with much greater floor space but significantly less physical material than the buildings erected just after World War II. *Accordingly, while the weight of current economic output is probably only modestly higher than it was a half century ago, value added, adjusted for price change, has risen well over threefold.'* (cited in Romm, 1999)

Coyle has argued that the digital world is about as close to weightless as is possible, allowing 'nearly costless reproduction.' (Coyle, 1998) Nicholas Negroponte has argued that '…the information superhighway is about the global movement of weightless bits at the speed of light' (Negroponte, 1996). Leadbeater (1999) talks of 'living on thin air'. If economic value is increasingly generated by the intangible and the weightless, then perhaps post-industrial economies are liberating themselves from the awkward and difficult imperatives of extracting and manipulating materials. 'Frictionless' refers to the reduced transaction costs, for example to the consumer in getting information about products and purchasing them that are enabled through use of ICTs and the Internet in buying. Friction is equated with the loss of energy and materials, and hence a lack of friction is seen as environmentally beneficial.

More recently a more balanced position has begun to emerge that seeks to test some of these predictions and assumptions. This may partly be explained by a generally more cautious attitude towards all aspects of the 'new economy'. But it is mainly the result of more systematic research into the complex, two-way and fuzzy link between information technologies and environmental sustainability. ICTs are pervasive in the economy, they can affect the natural environment in many ways and at various levels.

The debate has also become more politically urgent over the past 2 to 3 years as electronic commerce has been recognised as a potentially important new feature of economic activity. Any discussion of ICTs and sustainability must therefore include a discussion of e-commerce.

To bring some clarity to the claims that are made, it is useful first to draw a distinction between first, second and third order effects of ICTs and e-commerce (see Table 1).

	Positive impacts	**Negative impacts**
First order effects	environmental ICT applications	environmental impacts of

	e.g. environmental monitoring	production and use of ICTs *e.g. electronic waste*
Second order effects	dematerialisation structural change *e.g. electronic directories*	incomplete substitution *e.g. 'white vans' in addition to private shopping trips*
Third order effects	life style changes *e.g. green consumerism*	'rebound effect' *e.g. growth of long distance travel*

Table 1: ICT impacts on the environment

1) *First order effects of ICTs*: Direct negative environmental effects stem from the production, use and disposal of hardware such as computers, screens, network cables etc. They are not radically different from the environmental effects of many other products, but pose a number of specific environmental problems. Positive direct impacts include the use of ICTs for environmental protection purposes, e.g. through electronic monitoring of toxic emissions, remote sensing, electronic controls, generally improved 'transparency' about the use of environmental services, the potential to delineate environmental property rights more cheaply (Esty, 2001).

2) *Second order effects of ICTs*: Second order effects are expected to be largely positive. Many authors expect ICTs to facilitate a decoupling of economic growth and environmental damage. Two main causes are put forward. First, the value added generated by the use of information technology in the economy has been characterised as being mainly concerned with the manipulation of ideas rather than energy and materials (Kelly, 1999). More than 40% of US investment in new equipment over the past decade has been in the form of information devices - communications, computers, fax machines and other appliances. And between 1995-98 about 35% of economic growth resulted from the IT business (USDOC, 1999). Information technologies contribute to a structural change in the economy away from energy and materials intensive activity and towards information-intensive activities. These investment and structural effects on the economy are clearly of major significance for the environmental performance in aggregate, even if measuring these effects has proven elusive.

Second, and perhaps more importantly, information technology is changing the way in which virtually every product and service in the economy is designed, produced, distributed and operated. The economy is therefore seen as growing not through the addition of more resources, but by the more intelligent use of resources to produce greater value. Indeed, entirely intangible assets are in many industries critical components of the value they create. There is strong evidence that information technologies have raised labour productivity (David, 1999; Schreyer, 2000), but sharp increases in the capital and resource productivity are also proposed. Such efficiencies are being achieved through changes affecting a range of activities:

- *intelligent production processes*: through careful computer-aided design of production facilities, and precise control of operations during production made possible by extensive sensors and automated controls.
- *intelligent design and operation of products*: enabled by computer-aided simulations of product performance result in 'lighter' products that use less material to make products that operate more efficiently; efficient sensors and controls ensure services/functions are delivered efficiently when and where they are required

- *reorganisation of supply chains and business organisation*: e-commerce leads to the closure of retail outlets, more efficient inventory and supply chain management, the rise of 'teleworking'
- *intelligent logistics and distribution*: using communications and computer-based management and tracking systems improves both the flexibility (just-in-time) and efficiency of distribution systems.
- *the process of 'e-materalisation'*: the substitution of tangible goods for intangible services (for instance, the purchase of software over the Internet directly rather than on a disk, the development of 'electronic paper')
- *networking effects facilitated by diffusion of codified information*: the use of computers and digital communications and networks may facilitate more rapid codification and routinisation of many economic activities bringing integration and efficiency gains (with consequent environmental gains as well).

But this inventory of potential positive impacts is matched by uncertainty about whether they will be realised. Good empirical evidence from which generalisable lessons can be drawn is sparse. Research on the 'productivity paradox' (the longstanding debate about the absence of evidence of a relationship between labour productivity and investment in ICTs) is repeated in the problems faced by analysts in drawing strong inferences about the links between ICTs and environmental/resource productivity. What evidence that does exist seems to confound an optimistic reading.

- *resource productivity gains are slow*: ICTs have become integrated into production processes and new products over a long period (over 20 years). Evidence in most sectors is that resource productivity improvements tend to be slow, and only a proportion can be explained by the diffusion of ICTs. Dematerialisation is a long-standing historical trend.
- *the scope for e-materialisation may be limited*: The substitution of 'bytes for bits' may in some cases be complete (MP3, e-books), but the number of goods and services where this can be achieved may be limited. For most goods, IT is integrated in the delivery of a good or a service, but it does not substitute for it. Indeed, the use of electronics may lead to greater environmental burdens associated with the use of a product (the rapid diffusion of batteries to power intelligent functions in consumer goods is an example).
- *incomplete substitutions*: Many of the goods and services that are ICT or web-enabled will come 'in addition to' existing goods and services, especially during an initial transition phase.
- *The interrelationship between the virtual and the material economy*: The virtual economy is intimately embedded in the real, material economy. Growth in the virtual economy is likely to lead to change and growth in the material economy. For instance, e-commerce is likely to depend on the evolution of faster, more flexible transport infrastructures with greater capacity.

The most important negative second order effect could be the incomplete substitution of existing structures and activities, leading to more environmental damage. The case of the 'paperless office' can serve as an example. The use of computers in business administration did not replace conventional paperwork but supplemented it, and the promise of an environmentally friendly 'paperless office' did not materialise. Similarly, new logistic systems for retail e-commerce could result in additional transport if they are not integrated with existing systems or if consumers do not significantly reduce the number of individual shopping trips.

3) *Third order effects of ICTs*: Third order effects relate to feedback processes that can have counter-intuitive outcomes. They are potentially most profound effects, but also difficult to assess. A well-known feedback mechanism is the so-called 'rebound effect', often observed in the transport and energy sector. It occurs when efficiency gains (directly or indirectly) stimulate new demand, which balance (or even overcompensate for) positive environmental effects. Sceptics fear that the economic development stimulated by ICTs could offset the environmental gains described above. Whether the dematerialisation of the economy can keep up with the increased rate of GDP growth stimulated by the widespread diffusion of ICTs depends mainly on the collective choices of consumers. Will the money and time freed through the use of ICTs be spent in the consumption of environmentally damaging goods and services, or through demand for less tangible services? Anecdotal evidence so far suggests that the rebound effect is a real threat to incremental efficiency gains. For example, there seems to be a positive correlation between the use of e-mail and business travel, one spurring the other. Telling a similar story is the observation that, after software, the second largest e-commerce market is on-line ticketing for transport services. A process of social and cultural globalisation could constitute another third order effect. If global communication technologies (satellite television, Internet, email) bring together different cultures this is likely to result in more material exchanges as well, especially through trade and long distance travel.

III. First-order environmental effects of ICTs

The main immediate environmental effects of ICTs are predominantly related to the following four factors:

- manufacture of ICT equipment
- the transport of components and products
- use of ICT equipment
- disposal of ICT equipment.

Other, less significant environmental effects are related to packaging.

III.1 Manufacture

Current ICT systems rely on a variety of different products with heterogeneous environmental characteristics. These include product groups such as personal computers, net servers, mobile phones, cables, satellites, peripheral devices (screens, printers, scanners etc.) etc. The sector is still expanding and now represents a significant part of the GDP in most industrialised countries. In 1997, OECD countries produced ICT goods worth more than 720 billion USD (OECD 2000).

Most products consist of a large number of different components, e.g. micro-chips, semiconductors, printed wiring boards, cathode ray tubes, and batteries. The manufacture of many of these components has important environmental effects. The production of semiconductors, for example, causes significant amounts of air emissions (acid fumes, volatile organic compounds and doping gases), water emissions (solvents, cleaning solutions, acids, metals) and wastes (silicon, solvents). (EPA 1995). The production of other components is equally a matter of environmental concern. The use of process controls and new materials, however, has reduced the scale of the problem. For example, toxic solvents once used to clean circuit boards have largely been eliminated by quality control processes. Overall, the manufacture of ICT equipment results in emissions of acids, metals, volatile organic compounds, chlorinated solvents and other substances. It is energy intensive and uses large amounts of water for cooling and rinsing.[2] Matthews also shows that across a variety of dimensions of environmental performance (waste, energy, greenhouse gas emissions), computer manufacture is creating greater environmental burdens (Matthews, 2001). With regard to waste, it has been found that 98% of the material used in PC production goes into the waste stream and only 2% becomes part of the product (Hilty and Ruddy, 2000).

III.2 Supply chain

ICTs are produced through global supply chains. A typical personal computer contains 1500-2000 components sourced from around the world, and typically transported by air. The complexity and scale of the global electronics sector means that the aggregate environmental impacts of these supply chains are large. E-commerce may have the effect both of 'shrinking' the supply chain (by enabling greater control and reducing the number of steps) thus bringing environmental gains, but it may also have the opposite effect, allowing supply chains to become more 'globalised' and segmented.

III.3 Use

ICT devices typically use a large amount of electricity. A typical medium-sized PC consumes about 150W per hour. But residential energy use is also growing through the integration of ICTs into all products and even commodities. These include advanced television and audio equipment, mobile phones, playstations, handheld personal digital assistants and many other information appliances. Set-top boxes (integrated receiver decoders) are projected to add some 6,000 GWh of power demand in the UK by 2010 (and 0.8 million tonnes of carbon emissions).[3] Standby losses associated with electronic consumer goods in the home are another major source of power use. These devices provide "instant on" capability, and account for 5-15 percent of residential energy use (IEA, 1998).

Computers, information technologies, and other information devices are also the largest source of growth in electricity demand in commercial buildings. Unlike privately owned personal computers, many professional workstations and network servers tend to operate on a 24-hour basis. The scale of the problem was revealed last year, when the construction of vast "server farms"—warehouses full of computers and their attendant cooling systems—has contributed to the overloading of the electrical power network that has caused brown-outs in Silicon Valley (Economist, 2000). In comparison, the energy use of networks seems to be relatively small, although this is a matter of debate in the literature.

There are numerous attempts to reduce the electricity use of ICT equipment. PCs and especially laptops often have advanced power management systems that reduce the electricity consumption by introducing various 'low power modes' after certain time of inactivity. However, increasing performance and, more importantly, larger screens have in the past been balanced off or overcompensated these efficiency gains.

[2] A recent study estimated that the production of a PC generated 130 kg of greenhouse gases and 30 kg of total waste (Atlantic Consulting, 1998).
[3] www.mtprog.com

III.4 Disposal

According to Moore's Law the performance of ICT doubles every 18 months. This observation has shown to be relatively accurate, not only with regard to processor speed but also memory capacity and data transmission speed (Hilty and Ruddy, 2000). Extremely rapid innovation cycles have led to a high turnover of hardware and software. As a result, the fast increasing stream of electrical and electronic waste (at present 4% of municipal waste in the EU) has appeared as an important issue on the environmental policy agenda.

The main area of concern for disposal is the metal content of electronic waste. ICT devices typically contain significant amounts of copper, lead and mercury. Current product design does not allow the separation and recycling of these metals without further treatment. A number of other materials such as flame retardants and plastic softeners are also a cause environmental risks (van Drunen and Olsthoorn, 1999). At present, only a small minority of ICT hardware is recycled. Increasing the rates of recycling and recovery is one of the main aims of a new EU directive (COM (2000)347) proposed by the European Commission. The proposed directive would also restrict the use of certain hazardous substances, such as brominated flame retardants in new equipment.

Although important data gaps and the fast changing technology do not allow a reliable overall assessment of these effects, it it is widely recognised that production, use and disposal of ICTs have become a serious environmental policy issue. Matthews reports that in the US some 4% of municipal waste is now accounted for by 'waste from electrical and electronic equipment' (WEEE) and that this proportion is set to grow (Matthews, 2001). Much of this material could be economically recycled if effective collection and processing systems were in place. These direct effects may, however, be less significant than the potentially much wider and deeper *indirect effects* of information and communication technology.

IV. Second-order effects of ICTs

Information technologies are seen to provide a large potential to reduce the use of energy and materials. They play a key role in the debates about resource efficiency, often held under the label 'Factor 4/Factor 10'. The proponents of this concept claim that advanced technologies can improve the eco-efficiency of many products and processes by several hundred per cent, allowing a decoupling of the economic growth curve and the environmental damage curve (von Weizsäcker et al, 1998). Although other technologies and structural changes are also considered to be important, highest expectations are placed on dematerialisation through electronic communication.

Significant evidence to support this argument has been produced in a study into the impacts of the US Internet economy on global warming (Romm, 1999). Romm argues that in 1997 and 1998, aggregate energy productivity in the US economy improved by more than 3 percent, reversing a trend of slow declines in the previous decade. Similarly, Kelly (1999) argues that while US gross domestic product grew by 8 percent between 1996 and 1998, energy use grew by less than one percent. This is seen as a break with past trends that corresponds to the first evidence of widespread positive environmental impacts of ICTs.

IV.1 Efficiency gains through ICT use

The development, production and distribution of products and services involve highly complex processes in which information technologies are playing an increasingly important part. ICTs are used in various ways to optimise the input of labour, capital and natural resources. Although driven by the need to reduce costs, the optimisation of processes through ICTs has, by and large, benefited the environment. This is not only because many environmental resources need to be paid for (most industrialised countries have charges for water, waste water, waste, electricity) but also because efficient processes tend to be less polluting. The positive environmental effects of ICTs affect many different aspects of the production process.

IV.1.1 Intelligent production processes

ICTs allow the simulation of complex production systems in order to test and review costs, material use, and environmental emissions of design options before systems are purchased. Once in operation, low cost sensors throughout a plant, coupled with communication networks and computer-assisted controls, can ensure efficient and flexible operation. Modern production systems can have tens of thousands of individual microprocessors embedded in them, controlling valves, measuring temperatures, sensing the colour of fluids, and performing other tasks (Kelly, 1999). These devices are increasingly networked together, improving quality, safety and reducing waste. Today up to 40% of the value of a new manufacturing process (in the pulp and paper industry, for instance) is accounted for by control systems. Precise electronic control is essential for minimising emissions. Improved controls mean, for example, that material is not wasted because a chemical process is not completed or because errors go undetected producing batches of unusable product. Waste is usually an indicator of inefficiency and poor process design and operation. Resource productivity improvements of this type have been achieved consistently in industry since computers were first introduced into manufacturing over 30 years ago. In this sense they are not new at all, and historical trends suggest that they lead to productivity improvements of 1-2 percent per annum (Berkhout et al. 2000).

IV.1.2 Intelligent design and operation of products and services

Better design

The use of design software and simulation tools leads to a reduction in waste (in production and operation), generates products that are more 'fit for use' and less wasteful, and products that embody more innovation, including innovations that are environmentally beneficial. Computer Aided Design (CAD) has been a feature of design for products and processes for some 20 years, and it is by now pervasive. Concepts such as 'design for the environment' and 'design for recycling' can be integrated more readily into innovation processes using these design and simulation tools. Specific effects are difficult to measure and the relative significance of design software is difficult to disentangle from other developments, such as advances in new materials and metallurgy.

Well-worn examples of this design-driven dematerialisation include reductions in the weight of drinks cans. Drinks cans today use some 50 percent less aluminium than they did in 1972 (CMA, 1999), while reductions in the weight of steel cans have been equally dramatic. Similarly, it has been estimated that the Sears tower in Chicago could be built today with 35 percent less steel than it was in 1974 (AISI, 1999). Other examples include better design of aircraft engines and airframes that can provide 20% fuel savings by 2010 and 50% savings by 2050.

Controls in products

Many complex products (cars, consumer durables) contain microprocessor controls that enable them to respond to changing conditions of performance and environmental conditions. Embedded controls improve the functionality of the product, but also influence their environmental performance. All consumer goods, and in future also less complex products like windows, embody microprocessors to control their behaviour under variable conditions. Amongst other things, they control emissions to the environment, and the use of heat, water and other inputs. Modern engine control systems have been essential for meeting car engine emission standards for the past decade at least. Advanced control systems are also critical for managing the sophisticated new hybrid and fuel-cell technologies being developed to improve the fuel efficiency of cars (Kelly, 1999). These new systems will need to control the charging and discharging of batteries and new energy storage systems, recovering energy from brakes, controlling electronic transmissions, optimising power from electric motors and fuel-burning engines and other operations.

Other examples come from the service industries, many of whose environmental impacts result from the energy used in buildings. Together, residential and commercial buildings use about a third of all US energy and more than two thirds of all electricity. Information systems provide key tools for improving the efficiency of buildings and building components. Improved heating and cooling controls can ensure that buildings are more comfortable for each occupant, they can also lead to major energy savings. Simple control systems can provide 10-15% savings, but this is only a beginning. Likewise, windows are considered low technology but, coupled with intelligent controls, they can have a major impact on energy use. Artificial lighting can be cut through control systems when outdoor light is adequate and automated dimmers when there is little ambient light.

Virtualisation

Beyond efficiency gains, substitutions of information for materials and energy has also been proposed as leading to environmental benefits. Substitutions may be partial (dematerialisation) or complete (virtualisation). The clearest cases of these effects are of substitutions of digital information for 'traditional' media (paper, CDs, answering machines, etc.). More broadly, the argument is made that personal computers and other devices will increase the ease with which information can be assimilated and communicated, thereby reducing transaction costs and eliminating many of the environmental costs associated with paper-based transactions.

Print: Paper-based catalogues, directories, dictionaries, encyclopedias, newspapers and magazines are all believed to be under pressure from cheaper, more accessible and more easily retrieved and updated sources of information on the Internet. The Boston Consulting Group (BCG 1999) produced a comprehensive review of impacts of electronic media on paper use in the US. They investigated impacts on different segments of the paper market, finding that in most cases there would be either direct or indirect pressures tending to lead to a reduction in demand. For instance, they found that newspapers were vulnerable to electronic substitution by the Internet on grounds of cost and accessibility. It appears that people have become more comfortable reading text in electronic form, and this is likely to be a growing trend in future (Romm, 1999). On-line newspaper and magazines are cheaper because they do not have to support three of the major expenses of the print business: newsprint, distribution and printing costs. The BCG study also detected an indirect effect on newspapers through pressure on advertising revenues, a proportion of which will now be taken by the Internet. On the other hand, these higher costs and declining revenues will to some extent be counterbalanced by cost savings that are introduced through the increasing digitalisation of print processes. All of these factors are predicted to play a major role in a decline in paper-based catalogues, directories and information-based books. BCG predicts that the contrary trend – the greater use of office papers to print out information from the Web on desktop printers – will be outweighed by substitution effects.

Audio: The consumption of music offers a significant potential for virtualisation. Downloading of music in digital format (for example MP3) is one of the most popular uses of the Internet. Although a fast Internet connection and sufficient memory capacity are required, a large number of people exchange digital music files via specialised Internet sites. Digital music can be played with freely available software and does not require any devices or other tangible media. Once again, a critical unanswered question is how far these new technologies will substitute for existing media (and therefore have environmental benfits), or whether they may stimulate a greater demand for new devices such as MP3 players, mini disk players or CD writers (each embodying new environmental impacts in production, use and disposal).

Photo/video: The substitution of chemically processed photographic images by digitally processed images is another example of dematerialisation. Digital photography for amateur, professional and medical/industrial uses avoids the environmental impacts of film manufacturing and processing (Nevin, 1999). Digital cameras record and store photographic images in electronic form, rather than chemically on paper. Transmission of pictures and photographic materials would also be avoided. For professional uses, digital images are easier to manipulate and record, and may lead to resource savings. A recent study suggested that digitisation of radiography would lead to savings in X-ray film, and reductions in the use of developer and fixer (IST, 2000).

IV.1.3 Intelligent distribution and logistics[4]

Increasing supply chain efficiency

Increased codification of knowledge and co-ordination enabled by information technology has helped to make supply chains more efficient. In the US, for example, the average stock turn[5] was 8 a year in 1995 but reached 13.2 in 2000. The net effect of this was a fall in inventory to sales ratio to a record low of 1.32 (WERC, 2000). Reduced and faster moving inventory translates into significant, albeit one-off, reductions in wastage levels. Market pressures could also drive further improvements. Electronic business to business (B2B) procurement exchanges and reverse auctions seek to reduce costs, inventory and wastage within the supply chain and increase utilisation of existing capacity. The two latter factors create direct environmental benefits through resource productivity gains – reduced energy and materials use and wastage. However, some efficiency gains could be offset by demand for high speed and just-in-time delivery, which would tend to lower rates of vehicle utilisation. Which of these trends prevails, depends to some extent on price structures and transport systems.

[4] This section draws heavily on P. Hopkinson and P. James, *Virtual Traffic*, University of Bradford, 2000.

[5] Average stock turn is a measure of the rate at which products are sold through retail outlets. A higher stock turn denotes a more efficient operation.

Home shopping
Shopping accounts for a substantial part of personal travel (e.g. 20% in Britain). Complete replacement of car-based shopping trips by Internet ordering and van-based delivery could reduce distance travelled – by 70 to 80% according to one simulation (Cairns 1999). However, complete replacement is highly unlikely. The retail sector also has a strong interest, and new techniques, to divert time and cost savings into further shopping. People shop not only to buy specific goods, but for a variety of other reasons such as social interaction, excitement and creating and maintaining personal identity. Many forecasters predict that future stores will place more emphasis on the 'experience' of shopping, rather than simply providing the market context for purchasing. The limited survey evidence of consumer responses to home shopping has found that they reported less use of cars (Cairns 1999). Against this, evidence from dedicated grocery picking centres in the UK indicates that, in the first phase of operations, fleet and vehicle utilisation were very low due to lower than expected demand and a consequent lower drop density.

A business model which consigned low margin staples to Internet ordering and delivery, and replaced them on the shelves with more interesting, higher margin, goods would be highly profitable for current retail chains. It is also possible that the Internet might produce an 'unbundling' of multiple orders which, for convenience, were previously made from a single location. This could mean that a single car trip is replaced by a number of van deliveries, leading to a major increase in delivery units (Marker and Goulias 1999).

The transport implications of retail e-commerce will depend on the details of logistics and transport systems. These are still in an experimental phase because business to consumer e-commerce is, in *absolute* terms, still a very small market (less then 1% of retail sales in the US in 2000). The environmental outcomes remain, therefore, highly speculative. Cairns (1999) has identified six key factors which are likely to influence the environmental impacts of home shopping:

> Returns – which create the need for additional journeys and delivery of replacements (and are potentially higher with home shopping because of the absence of any physical contact with goods before purchase and many vendor's commitment to easy return).
>
> Cost structures – at a general level, whether these reflect the full environmental costs of transport used, and more specifically, whether they encourage deliveries of small value and weight and encourage deliveries at non-congested times
>
> Delivery locations – with the possibility that home storage units, local pick-up points and shared distribution channels could reduce returns and/or movements of delivery vehicles
>
> Vehicle use – the mode used and, for road vehicles, the extent to which they use conventional or alternative fuels, have advanced engines and emission control systems, are well driven and maintained

Routing and scheduling optimisation – based on sophisticated software systems and accurate global positioning system (GPS) data to track actual vehicle locations

Load consolidation – sharing of distribution facilities and delivery vehicles to increase utilisation and reduce the amount of vehicle movements and warehouse space required.

Recent studies in this area (TLN 2000, IST 2000, NERA 2000, Matthews et al 2001indicate the sensitivity of the outcomes to the assumptions made. Until there is more empirical evidence on how customers respond to home shopping, and what delivery patterns suppliers use, it is impossible to validate or disprove claims made about net impacts.

Alternative distribution structures
E-business creates an opportunity for a more community-based distribution structure and a reversal of the move to 'out-of-town' development, which has occurred over recent decades. The high cost of distributing goods to homes – both because of low drop-off densities in residential areas, and high levels of returns - is the Achilles heel of B2C e-commerce (Jackson 2000, Jones 2000). One response could be networks of drop-off points, to be used when people are not at home and/or as the primary distribution point (with the incentive being lower charges) (Granda 2000).

There are a number of options for this network. For existing premises, these include superstores, shopping centres and other retail centres, CTNs (confectionery, tobacco and news outlets), convenience stores, village stores, public transport nodes, village stores, community halls and schools. It has also been suggested that purpose-designed facilities could be built on business parks, at major employment sites, drive-in shopping centres, park and ride schemes and warehouse sites.

One striking feature of many of the discussions of collection to date is that car access is a primary criterion. While this is obviously important, especially for bulky goods, no equivalent attention is paid to cycling or walking as alternative means of collection. Neither has there been much discussion of 'community distribution models', aimed at minimising vehicle movements, particularly in residential areas. One possibility is that they become local meeting places which provide an alternative means of meeting some of the psychological requirements of shopping, such as social interaction.

Geographic extension of supply patterns
The increased ordering options which e-business provides to both business and consumers will result in more geographically extended supply patterns, and therefore higher transport intensity of goods. There is considerable evidence that this is happening at a global scale. The best objective indicator is the high rate of growth of air freight (currently 4.5% per year), which is being partially driven by e-business (Lobo and Zairi 1999). The growing sophistication of specialised supply chain management by both importers and exporters, and the creation of on-line markets in most sectors, is likely to strengthen this trend.

E-business driven trade would be less transport intensive if more goods could be shipped by sea and rail rather than air and road. However, e-commerce usually demands fast and highly flexible supply chains, whereas rail and sea transport are the slowest and least flexible modes, with high infrastructure costs and a reliance on regular volume shipments. This inherent disadvantage is compounded by the slower penetration of e-business within the rail and maritime sectors.

Fragmented supply base

On-line ordering will increase the number of suppliers and decrease average order sizes, making it harder to allocate environmental responsibility to chain members. Over the last decade, the general trend in supply chains has been to work with fewer suppliers, especially for key 'first tier' suppliers (who often co-ordinate the inputs of 'second tier' suppliers). However, the development of B2B e-commerce 'platforms' makes it easier to source from a larger number, and wider geographic range, of suppliers. This is especially true of the maintenance, repair and operating items, and commodities which form the bulk of B2B purchases by value. The main driver is a search for lower transaction costs in sourcing items and contracting for their purchase.

The organisational and personal ties between customers and suppliers may be weakened by B2B exchanges, making it difficult for individual customers to exert informal pressure for improvement. The best means of overcoming these forces is likely to be pre-qualification procedures for environmental and social performance. An alternative or complementary option would be to require buyers to provide environmental and social information about the goods they are selling, perhaps based on standardised parameters. However, the cost-reduction focus of exchanges, and the dangers of violating free trade regulations, may require some kind of policy intervention to achieve it.

IV.1.4 Changing seller-buyer relationships

Mass customisation

"Mass customisation" – production systems that manufacture products for individual consumers – has been proposed as a future organising principle of business, just as mass production by assembly line was the organising business principle under Fordism. In the mass production model, businesses maintain a "one-to-many" relationship with consumers. Consumer demand is predicted and a limited number of product lines are developed to meet that demand. Through branding and advertising, consumers are encouraged to buy goods that have already been manufactured and are stocked on store shelves. In stable, commoditised markets this model works well. But there are many opportunities for inefficiency: new product lines that don't sell; overproduction due to shifts in taste or the economy; new technologies that render products obsolete (Nevin, 1999).

ICTs and the Internet make mass customisation possible because they enable a rich exchange of information between companies and individual customers (whether private or commercial). The primary effect can be to dramatically reduce inventories. As Dell computers has shown, in fast moving industries like electronics, where the value of computer chips and other components depreciates day by day, there are clear business benefits to reducing stockpiles of soon-to-be obsolescent equipment and machines.

Several environmental benefits have been proposed for mass customisation. First, production can be matched more tightly to consumer demand, reducing the energy associated with warehousing products. Second, excess inventories and the waste embodied in them would be reduced. Third, products and services could be designed to fit the functionality desired by the consumer more accurately, so improving the environmental efficiency with which it is used. Fourth, the producer could be transformed into a provider of services to the final consumer, offering new business opportunities while also creating the conditions for ownership (and responsibility) for products delivering services to remain with the service provider. Some authors have suggested that this may presage the development of 'closed loop' product and service systems in which producers have incentives to reduce the resource cost and environmental burden of the services they provide.

IV.1.5 Work organisation

Telecommuting and teleworking
The major hypothesised environmental benefits of telecommuting and teleworking (T&T) are the reduced need for office space, leading to energy savings, and a reduced number of journeys to work, producing energy savings, reduced air pollution and reductions in congestion. While these savings may be achieved in some cases, there is also evidence that employees may be becoming more peripatetic in some service sectors. In general, studies have shown that the potential for environmental savings from T&T are likely to be small. A Japanese study estimated that T&T would produce savings of about 2 million tonnes of carbon a year (or 2% of the reduction needed under the country's commitments under the Kyoto protocol) (MPT, 1998, cited in Matthews, 2001).

IV.2 Critical issues

IV.2.1 The problem of 'incomplete substitution'

While ICT and Internet enabled services may substitute for some tangible goods and services, substitution is rarely complete. Incomplete substitution may indeed lead to new demand and investment in goods and infrastructures, and therefore result in more resource use and pollution.

This phenomenon is likely to arise in the area of logistics. Increased online shopping is currently creating new transport structures. For example, a number of retail chains have started large e-commerce operations requiring new (or the development of existing) call centres, warehouses, pick and pack centres, delivery vehicles and so on. This new infrastructure, intelligently managed through ICTs, has the potential to be more efficient than the large number of individual shopping trips, especially if they replace journeys to out-of-town shopping centres. However, environmental benefits will only occur if these new infrastructures lead to expected substitution effects.

This need not always be the case. Some consumers might choose to do a part of their shopping online (e.g. heavy or low value goods) but still drive into the town centre to buy other goods. Similar phenomena can be expected in other areas. These unstable patterns of substitution will be most apparent during the period of transition (and overlap) between traditional and an ICT-based system. But as in the case of the 'paperless office' a transition period can extend over many years because consumer behaviour does not always correspond to the expectations of those who predict the virtualisation of the economy. Claims of substitution effects need to be carefully evaluated. Many remain speculative.

IV.2.2 Re-materialisation

Information technologies can, in some instances, lead to a 're-materialisation' of economic activities. Although many digital devices (PCs, cellular phones) have been substantially miniaturised and 'de-materialised', they have also vastly increased the capacity of the final consumer to consume. By intensifying competition, integrating markets and driving down prices these devices provide new opportunities to consume both tangible and intangible goods and services. In particular, the Internet increases the 'reach' of consumers in terms of choice and geographically. One concrete example of rematerialisation is document access through the web, allowing for a printed paper copy in just a few mouse clicks.

E-commerce can also provide easier access to markets for suppliers in remote locations, and to goods for disadvantaged consumers. Although this phenomenon might have socially beneficial effects, transport implications are problematic. These effects are now identifiable globally. For example, Indian farmers have used the Internet to check prices in regional markets, which can be much higher than those offered by local merchants (Lloyd 2000). They are now bypassing these and transporting their produce directly to regional market. Although this has meant longer hauls - up to 700km - the prices they can obtain are sometimes 50% higher than locally.

V. Third order effects of ICTs

ICTs and the Internet are profoundly affecting the structure of economies, both in changing the relative size and importance of industrial sectors and sub-sectors, but also on the size and demography (birth, survival, death) of firms. At first sight, these changes seem likely to have positive impacts on environmental sustainability, especially through the growth of 'light' services at the expense of 'heavy' manufacturing. But the net effect of these structural changes will depend on the balance between the relative balance of these 'lightening' effects, and the counter influences of economic growth (which still leads to net growth in the demand for material resources), and the physical investments that are generated to enable and motivate the Internet economy.

V.1 Structural change and resource use

At the macro-economic level, the notion of dematerialisation (or 'intensity of use' hypothesis) was first discussed in the 1970s, and produced the 'Environmental Kuznets Curve' (EKC) hypothesis. Broadly, this argues that during the process of industrialisation economies use material resources (steel, cement, energy carriers) more intensively, until a threshold is reached after which structural changes in the economy (the decline of manufacturing and the rise of services) leads to progressively less intensive materials use.

ICTs contribute significantly to structural changes that reduce the relative resource intensity of the economy. This occurs through the growth of IT-related services (e.g. software development, Internet services, new advertising and marketing services etc.), and through the growth of traditional services (e.g. financial services). Service sectors are supported by material infrastructures and transactions (transport services, for instance), and are not as 'clean' as sometimes presented. However, they tend to generate higher value added with lower environmental impact.

There is evidence that the rapid diffusion of ICTs speeds up this ongoing structural change and therefore contributes to incremental improvements in *relative* resource efficiency. But empirical evidence also shows that in *absolute* terms these economies are still 'materialising' (i.e. getting heavier) (Berkhout, 1998; WRI, 2000). An over-optimistic assessment would also be inappropriate because structural change has failed to address a number of important environmental problems such as biodiversity loss, land use, waste and climate change. These seem to be closely related to the overall economic activity rather than specific sectoral developments.

ICTs also contribute to structural change at the global level. They are believed to be at the heart of the economic, political, social and cultural processes termed 'globalisation'. Closed communications networks connect financial and other global markets, and enable the management of global supply chains. The growth in trade generated by the extension of markets has been a focus of academic (and political) dispute for over a decade. Advocates of liberalisation of markets and international trade argue that these will result in faster economic growth, moving countries more rapidly through the threshold of materials intensity, and providing them with a level of welfare that enables these countries to impose comprehensive regimes to regulate their environment. Critics have argued that unfettered trade may only lead to a shift of 'dirty industries' to 'pollution havens' in which producers in industrialised countries relocate production to less developed countries with lower environmental standards (and lower costs) so as to re-export to northern more developed countries' markets. Here again, evidence is inconclusive, with a variety of studies finding support for both positions (Gossart, 2000).

V.2 The rebound effect

The term 'rebound effect' is used to describe a number of, often counter-intuitive, feedback effects that compensate or over-compensate increases in environmental efficiency. These effects have been observed for example in the transport sector where successful measures to reduce traffic led to freer roads, which in turn stimulated new traffic and a growth in congestion. The rebound effect can be caused by two main effects: falling prices and increased capacity.

As all the described mechanisms (and more competitive open global markets) contribute to a more efficient use of natural resources, the prices of raw materials and other production inputs (electricity, gas, metals, etc.) will tend to fall. Cost pressures, one of the main drivers of eco-efficiency improvements, reduce and the increase in resource efficiency could slow down. The producers of materials for which demand falls suffer economic losses, and they will undertake efforts to find new market opportunities. Because many materials have a potential for substitution, windows can be made from wood, plastic and aluminium for example, new markets for environmentally damaging materials can be accessed.

The second mechanism is the generation of new capacity. Many ICT applications allow a better management of time, money, labour, transport infrastructure, and so on. This leads to new capacity that will inevitably be filled. The key question is whether the time and money gained through the use of ICTs is spent in more or less environmentally damaging ways. For example, some US teleworking studies found that initial reductions in car travel are partially offset over time by stimulation of new driving (Hopkinson, James and Selwyn 1999). This includes living further away from the workplace which no longer has to be attended five days a week, or making short trips from home to shops or other locations during more fragmented work days. Similarly, the presence of online bookseller such as Amazon and Books on Line seems to have expanded the overall market for books. Providing easy access to a larger number of products at lower prices, they have increased book sales.

V.3 Life style changes

Finally, new information technologies are likely to have wider impact on social values, life styles and culture. Although these changes and their impact on the environment remain highly speculative, it should be noted that a lively debate is currently developing.

One of the widely discussed trends is the possible emergence of a new green consumerism based on the new possibilities of information technologies. Richer societies are generally expected to shift towards post-materialist values. ICT systems could allow consumers and civil society to translate these values into purchasing and other decisions. For example, new online information services could provide consumers with more information abut the 'ethical' performance of competing products, and offer them the chance to take on more responsibility for less environmentally burdensome lifestyles and habits. Enabled to make informed choices about products on the basis of environmental criteria, consumers could stimulate more environmentally responsible production and innovation.

On the other hand, the fact that ICT networks decrease the importance of geographical distance could also lead to a re-mobilisation, not only of goods, but also of labour and leisure. The greater connectivity between people provided by email and the Internet, will almost certainly stimulate the desire to meet directly, to share material goods and to experience the specificity of places. Transport and travel are almost always linked to negative environmental effects.

VI. Conclusions

1. ICTs are having major economic impacts, and from these flow a wide range of both positive and negative impacts on the environment. In general, second order effects on the design and operation of products and services has a positive environmental impact. However, there is great uncertainty about the third order effects on consumer behaviour, aggregate demand and the composition of economic growth (whether growth is substantially de-materialised or not). It seems highly likely, though currently impossible to confirm, that there will be a mismatch between opportunities for greater environmental efficiency at the micro-level and resource use and environmental impacts in the aggregate. Many of the substitution effects posited in the literature are either of limited environmental significance, only partial, or may stimulate new forms of consumption, which generate new environmental burdens. There is even the possibility of what might be termed a process of 're-materialisation' of the New Economy as prices for raw materials fall and consumers become increasingly distanced from the environmental consequences of their consumption.
2. Most of the literature on the link between ICTs and the environment is highly positivistic, identifying opportunities and building from case study evidence. There is now the emergence of a more systematic analysis of the full complexity of the relationship, but the evidence base from which to draw conclusions is still thin. Another problem is that most studies are 'future oriented', speculating

about the impacts of technological and market changes that have not yet occurred and that are still highly uncertain.

3. Methods of impact assessment include qualitative accounts, highly simplified conceptual modelling of possible benefits (if X is substituted with Y, this will lead to Z savings). In general, they are unable to handle feedback effects due to responses in market demand and consumer behaviour.
4. There is a need for much better monitoring and evaluation of the links between ICT-driven productivity gains (labour, capital and environmental) and the actual environmental performance of industrialised economies. The OECD could play a major role in generating a framework for monitoring and analysing these changes, providing much-needed empirical evidence and providing an international perspective. It seems likely that many of the impacts of ICTs will be nationally, regionally and location-specific. This differentiation must also be considered in developing policy responses.

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