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Industrial ecology: a new perspective on the future of the industrial system[1]

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Industrial ecology? A surprising, intriguing expression that immediately draws our attention. The spontaneous reaction is that "industrial ecology" is a contradiction in terms, something of an oxymoron, like "obscure clarity" or "burning ice".

Why this reflex? Probably because we are accustomed to considering the industrial system as isolated from the Biosphere, with factories and cities on one side and nature on the other, as well as the recurrent problem of trying to minimise the impact of the industrial system on what is "beyond" it: its surroundings, the "environment". As early as the 1950's, this end-of-pipe angle was the one adopted by ecologists, whose first serious studies focused on the consequences of the various forms of pollution on nature. In this perspective on the industrial system, human industrial activity as such remained outside the field of research.

Industrial ecology explores the opposite assumption: The industrial system can be seen as a certain kind of ecosystem. After all, the industrial system, just as natural ecosystems, can be described as a particular distribution of materials, energy, and information flows. Furthermore, the entire industrial system relies on resources and services provided by the Biosphere, from which it cannot be dissociated. (It should be specified that "industrial", in the context of industrial ecology, refers to all human activities occurring within modern technological society. Thus, tourism, housing, medical services, transportation, agriculture, etc. are part of the industrial system.)

Besides its rigorous scientific conceptual framework (scientific ecology), industrial ecology can also be seen as a practical approach to sustainability. It is an attempt to address the question, "How can the concept of sustainable development be made operational in an economically feasible way?" Industrial ecology represents precisely one of the paths that could provide concrete solutions.

Governments have traditionally approached development and environmental issues in a fragmented and compartmentalised way. This is illustrated in the classical end-of-pipe strategy for the treatment of pollution, which has proven to be quite useful, but not adequate to make an efficient use of limited resources, in the context of a growing population with increasing economic aspirations. Thus, industrial ecology emerges at a time when it is becoming increasingly clear that the traditional pollution treatment approach (end-of-pipe) is not only insufficient to solve environmental problems, but also too costly in the long run.

Industrial ecology in a nutshell

So far, there is no standard definition of industrial ecology. However, in order to avoid any confusion, we would like to specify what is meant here by "industrial metabolism" and "industrial ecology".

– "Industrial metabolism" refers to the materials and energy flows of the industrial system. It is studied with an essentially analytical and descriptive approach (basically an application of materials-balance principles), aimed at understanding the circulation of the materials and energy flows (and stocks) linked to human activity, from their initial extraction to their inevitable re-integration, sooner or later, into the overall bio-geochemical cycles [1–5].
– Industrial ecology goes further: the idea is first to understand how the industrial system works, how it is regulated, and its interactions with the Biosphere; then, on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function [6–10].

Whatever the definitions may be, all authors more or less agree on at least three key elements of the industrial ecology perspective:

a) it is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the Biosphere.
b) it emphasises the biophysical substratum of human activities, ie, the complex patterns of material flows within and outside the industrial system, in contrast with current approaches which mostly consider the economy in terms of abstract monetary units, or alternatively on energy flows.
c) it considers technological dynamics, ie, the long-term evolution (technological trajecto-

[1] "President's lecture", Assemblée annuelle de la Société Suisse de Pneumologie, Geneva, March 30, 2001

ries) of clusters of key technologies as a crucial (but not exclusive) element for the transition from the current unsustainable industrial system to a viable industrial ecosystem of the future.

In short, industrial ecology aims at looking at the industrial system as a whole. Industrial ecology does not address just issues of pollution and environment, but considers as equally important, technologies, process economics, the inter-relationships of businesses, financing, overall government policy and the entire spectrum of issues that are involved in the management of commercial enterprises. As such, industrial ecology can provide a conceptual framework and an important tool for the process of planning economic development, particularly at the regional level [11–15]. Also, industrial ecology may offer options, which are not only effective for protecting the environment but also for optimising the use of scarce resources. Thus, industrial ecology is especially relevant in the context of developing countries, where growing populations with increasing economic aspirations should make the best use of limited resources [16].

Industrial ecology: earlier attempts

Industrial ecology has been manifest intuitively for a very long time. There is little doubt that the concept of industrial ecology existed well before the expression, which began to appear sporadically in the literature of the 1970's. In fact, and not surprisingly, scientific ecologists had for a very long time intuitively regarded the industrial system as a subsystem of the Biosphere. This line of thought has, however, never been actively investigated. Several attempts to launch this new field have been made in the last couple of decades, with very limited success. The industrial ecology concept was indisputably in its very early stages of development in the mid-1970's, in the context of the flurry of intellectual activity that marked the early years of the United Nations Environment Program (UNEP).

The expression re-emerged in the early 1990's, at first among a number of industrial engineers connected with the National Academy of Engineering in the United States. Every year in September, the popular scientific monthly *Scientific American* publishes an issue on a single topic. In September 1989, the special issue was on "Managing Planet Earth". The issue featured an article by Robert Frosch and Nicholas Gallopoulos, both then at General Motors, called "Strategies for Manufacturing" [16–18].

In their article, the two authors offered the idea that it should be possible to develop industrial production methods that would have considerably less impact on the environment. This hypothesis led them to introduce the notion of the "industrial ecosystem". Projections regarding resources and population trends "lead to the recognition that the traditional model of industrial activity – in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of – should be transformed into a more integrated model: an industrial ecosystem. (...) The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesise nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialised world is to maintain its standard of living – and the developing nations are to raise theirs to a similar level – without adversely affecting the environment." (p. 106)

However, as Robert Frosch indicated during his lecture, "Towards an Industrial Ecology", presented before the United Kingdom Fellowship of Engineering in 1990: "The analogy between the industrial ecosystem concept and the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogy." (p. 272) [19].

In contrast to preceding attempts, Frosch and Gallopoulos's article sparked off strong interest. There are many reasons for this: the prestige and wide readership of *Scientific American*, Frosch's reputation in governmental, engineering and business circles, the weight carried by the authors because of their affiliation with General Motors, and the general context, which had become favourable to environment issues with, among other features, discussions around the report of the United Nations World Commission on Environment and Development (the "Brundtland Commission"), published in 1987. The article manifestly played a catalytic role, as if crystallising a latent intuition in many people, especially those in circles associated with industrial production, who were increasingly seeking new strategies to adopt with regard to the environment. Although the ideas presented in Frosch and Gallopoulos's article were not, strictly speaking, original, the *Scientific American* article can be seen as the source of the current development of industrial ecology (for details, see: [20]).

Today, industrial ecology is being pursued with unprecedented vigour. It is gaining recognition not only in business communities, but in academic and government circles as well. In 1997, the Journal of Industrial Ecology (MIT Press) was launched, and in early 2001, the International Society for Industrial Ecology was founded [21, 22].

The industrial ecology agenda

From a practical point of view, one of the first analogies that comes to mind is of an "industrial food chain". Just as in natural ecosystems, where certain species feed on the waste or organisms of other species, one can imagine a similar process of waste recovery between various economic entities. Thus, the concept of "eco-industrial parks" (EIP) was born in the early 90s. EIPs are areas in which companies co-operate to make the most of resource use, namely by mutually recovering the waste they generate (the waste produced by one enterprise is used as raw material by another).

However, the notion of "park" should not be considered in the sense of a geographically confined area: an eco-industrial park can very well encompass a neighbouring city, even a remote enterprise, especially if the latter is the only one around capable of recovering a rare type of waste impossible to process at other factory sites. Hence the new term, "eco-industrial networks", where parks represent a particular case, is appropriate. The notion of eco-industrial parks (or networks) is quite different from traditional waste exchange programs. Indeed, it involves a systematic recovery process of overall resources in a given region. It does not merely recycle waste on an ad hoc basis. Around 50 eco-industrial parks projects are presently under way in various parts of the world, mostly in North America, Western Europe and Asia [23–29].

One idea that fits in with the notion of eco-industrial parks is that of "industrial biocoenoses". In biology, the concept of "biocoenosis" refers to the fact that, in ecosystems, various species of organisms always meet according to characteristic patterns of association. Just as in natural ecosystems, there are "key species" in industrial biocoenoses. Power plants, for instance, are an obvious "key species". All kinds of different eco-industrial complexes could develop around power plants (coal, oil, gas, nuclear), given the degree of flow of matter involved and the enormous quantity of energy wasted as heat.

Once the best possible associations are determined, including the most appropriate combinations of various industrial activities, the concept can then be extended to industrial complexes. Instead of building an isolated sugar cane production unit, one should attempt, from the outset, to plan an integrated complex whose objective is to use all the flows of matter and energy linked to sugar cane processing in the best possible way. In this instance, a number of units could be attached – a paper mill, a distillery, a thermal power station – in order to recover all the different by-products of sugar cane. A variety of possibilities come to mind: "pulp-paper" complexes, "fertiliser-cement" ventures, "steelworks-fertiliser-concrete" partnerships, etc. Granted, there are examples of partial and spontaneous complexes that have been around for a long time. However, the main focus now should be on developing these complexes in a more explicit and systematic way [30].

Therefore, the main challenge is to reorganise the industrial system in depth, in order to help the system evolve toward a sustainable long-term operating mode compatible with the Biosphere. In concrete terms, four challenges must be met within the framework of industrial ecology:

1) Waste and by-products must systematically be exploited:

Just as in the food chain processes of natural ecosystems, we must create networks of resource and waste use in industrial ecosystems, so that all the residues become resources for other enterprises or economic entities (through eco-industrial networks). Traditional recycling is only one aspect in a series of matter flow recovery strategies.

2) Loss caused by dispersion must be minimised:

In industrial countries today, human consumption and use often cause more pollution than actual manufacturing does. Products such as fertilisers, pesticides, tyres, solvents, etc., are entirely or partially dispersed into the environment as they are used. Therefore, new products and services must be designed that minimise dispersion or at least eliminate its harmful effects.

3) The economy must be dematerialised:

The objective here is to minimise total matter (and energy) flows while making sure equivalent services are provided. Technical progress makes it possible to obtain a greater amount of service from a smaller amount of matter, namely by producing lighter objects or by replacing matter (a few kilos of fibre optics allows for more telecommunications throughput than a ton of copper cable). However, dematerialisation is not as simple as it may seem: less massive products may also have shorter life spans and will therefore ultimately consume more resources and generate more waste. Furthermore, dematerialisation does not necessarily apply to consumption goods only, but also in large part to the industrial system's heavy infrastructure, such as buildings, roads, transportation networks, etc. [31–36].

Two possible dematerialisation strategies are currently being debated:

a) relative dematerialisation, which makes it possible to obtain more services and goods from a given quantity of matter (also referred to as resource increased productivity);
b) absolute dematerialisation, which strives to reduce the flow of matter circulating within the industrial system in absolute terms (the latter challenge is much more daunting than relative dematerialisation).

Recently, there has been a surge of interest on the issue of dematerialisation in the context of the so-called "New Economy", or "Internet based economy". There have been many claims that the Internet and associated emerging information technologies contribute to the dematerialisation of the economy. However, this is far from proven, in particular because of the well known "rebound effect". The huge number of electric and electronic devices needed to run the information economy place a growing demand on the supply of electricity, which, at least for countries like the US, implies digging more coal. Another example: electronic commerce might diminish the need for shopping malls, but in San Francisco, there has been already an increase in traffic jams linked to the rise in numbers of fast deliveries by courier services. At this stage, in fact, it would be fair to acknowledge our ignorance of the real impact of new information technologies on resource consumption, with serious research in the field just in its infancy [37–40].

Perhaps one of the best ways to dematerialise the economy is to emphasise the service rendered, to market the product's use rather than the product itself. From the Industrial Revolution on, our economic system has been organised in such a way as to maximise production. Within the context of industrial ecology, the objective is to prioritise use, in other words to evolve toward a genuine service-oriented society. The goal involves strategies such as durability (extending the useful life of a product), renting rather than owning, selling use rather than the actual product. To illustrate the point, a manufacturer of photocopiers who sells the "photocopying" service rather than the machine itself, will run a more profitable operation if the photocopier, of which he retains ownership, requires as little matter inputs as possible, has the longest possible useful life, is easily recyclable, etc. (as in the case of Xerox) [41].

4) Energy must rely less on fossil hydrocarbons:

From the beginning of the Industrial Revolution, hydrocarbon compounds from fossil fuels (coal, oil, gas) have been a crucial element, a vital substance in powering the engines of industrial economies. However, carbon-based fossil fuels are also at the root of many problems: increasing greenhouse effect, smog, oil spills, acid rain, etc. Therefore, we must make hydrocarbon consumption less harmful (by recovering carbon gasses emitted by combustion) and encourage the move toward energies that requires less fossil fuels (renewable energy, energy savings). In abstract terms, the "energy" function must be separated from its "fossil carbon" substratum [42, 43].

A concrete example: the Industrial Symbiosis in Kalundborg

As a matter of fact, industrial ecology is already more than a nice theoretical idea: the "Industrial Symbiosis", which has evolved during the last three decades in the small city of Kalundborg, in Denmark, offers the best evidence that such an approach can be very practical and economically viable. Kalundborg, located 100 km. West of Copenhagen, can be seen as a successful example of an industrial complex minimising pollution and optimising the use of various resources.

As summarised by Colin Francis [44], the history of Kalundborg really began in 1961 with a project to use surface water from Lake Tissø for a new oil refinery in order to save the limited supplies of ground water. The city of Kalundborg took the responsibility for building the pipeline while the refinery financed it. Starting from this initial collaboration, a number of other collaborative projects were subsequently introduced and the number of partners gradually increased. By the end of the 1980's, the partners realised that they had effectively "self-organised" into what is probably the best-known example of a working industrial ecosystem, or to use their term – an industrial symbiosis.

This industrial ecosystem today consists of six main partners:

- Asnæs power station – part of SK Power Company and the largest coal-fired plant producing electricity in Denmark.
- Statoil – an oil refinery belonging to the Norwegian State oil company.
- Novo Nordisk – a multi-national biotechnology company that is a leading producer of insulin and industrial enzymes.
- Gyproc – a Swedish company producing plasterboard for the building industry.
- The town of Kalundborg, which receives excess heat from Asnaes for its residential district heating system.
- Bioteknisk Jordrens – a soil remediation company that joined the Symbiosis in 1998.

In addition, several other companies participate as recipients of materials or energy. The status of the industrial symbiosis in 1999 is shown in figure 1.

Thanks to the Symbiosis, the reduction in the use of ground water has been estimated at close to 2 million cubic metres per year. However, in order to reduce overall water consumption by the partners, the Statoil refinery supplies its purified waste water as well as its used cooling water to Asnæs power station, thereby allowing this water to be "used twice" and saving additionally 1 million cubic metres of water per year.

Asnæs power station supplies steam both for

Statoil and Novo Nordisk for heating in their processes and, since it is therefore functioning in a co-generation mode, it is able to increase its efficiency.

Excess gas from the operations at the Statoil refinery is treated to remove sulphur, which is sold as a raw material for the manufacture of Sulphuric acid, and the clean gas is then supplied to Asnæs power station and to Gyproc as an energy source.

In 1993 Asnæs power station installed a desulphurisation unit to remove sulphur from its flue gases, which allows it to produce calcium sulphate (gypsum). This is the main raw material in the manufacture of plasterboard at Gyproc. By purchasing synthetic "waste" gypsum from Asnæs power station, Gyproc has been able to replace the natural gypsum that it used to buy from Spain. In 1998 approximately 190,000 tons per year of synthetic gypsum were available from the power station.

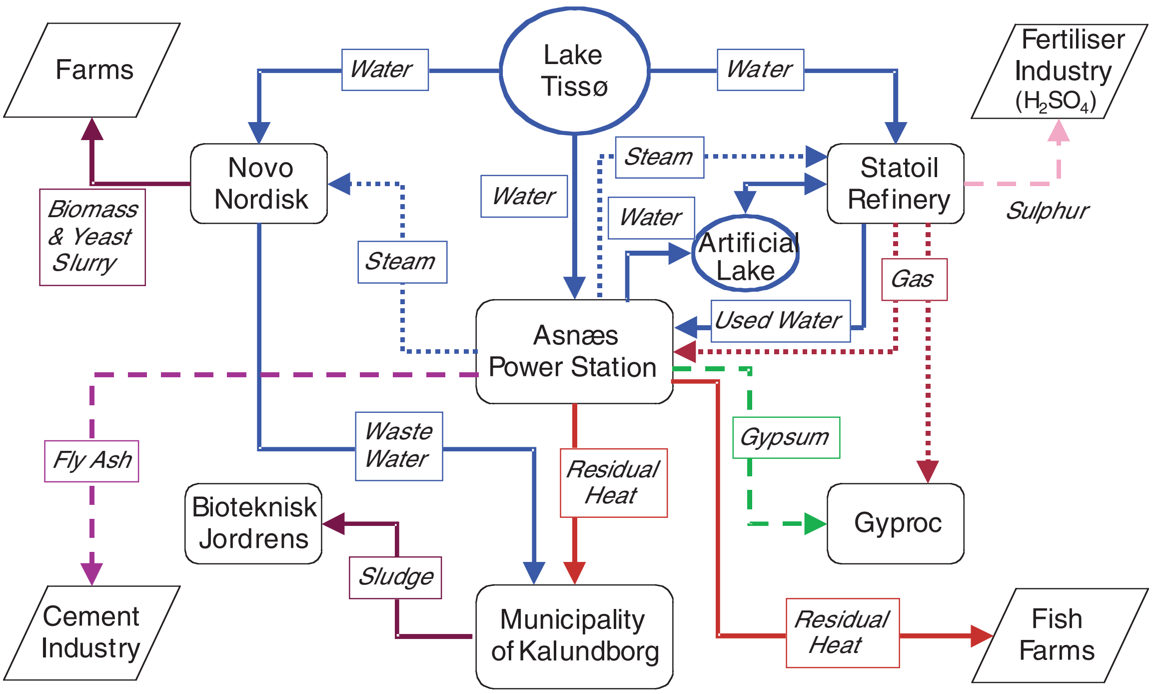
Novo Nordisk creates a large quantity of used bio-mass coming from its synthetic processes and the company has realised that this can be used as a fertiliser since it contains nitrogen, phosphorus and potassium. The local farming communities use more than 800,000 cubic metres of this liquid fertiliser each year as well as over 60,000 tons of a solid form of the fertiliser.

Finally, residual heat is also provided by Asnæs power station to the district heating system of the town. The system functions via heat exchangers so that the industrial water and the district heating water are kept separate.

The investment needed to put the different material and energy exchanges in place has been estimated at $75 million. This is the cost of the 18 projects established up to and including 1998. Keeping in mind that each exchange is based on a separate contract between the two partners involved, revenues can be estimated as coming from selling the waste material and from reduced costs for resources. The partners estimate that they have "saved" $160 million so far. The payback time of a project is less than 5 years on average. Therefore a clear lesson is that a more rational utilisation of resources is not only good for the environment, but it can also save money [45, 46].

Figure 1

Material flows in the Kalundborg industrial ecosystem (status 1999). (Source: Colin Francis, ICAST, adapted from Jørgen Christensen, Symbiosis Institute, 1999.)



A new way of managing companies

Finally, industrial ecology leads to two major consequences for the management of companies.

On the one hand, it challenges the traditional exclusive emphasis on the product alone. Generally, a company's talents and energy are devoted to selling products. Waste management and environmental issues are left to a single, more or less marginal department. Today, waste recovery operations and the improvement of material flows mobilised by the enterprise must be given as much importance as selling goods.

On the other hand, traditional management has turned "competitiveness" into a dogma, especially in highly competitive market environments. Industrial ecology, however, reminds us that in addition to competitive relationships, we need to foster an over-the-fence management system, where enterprises collaborate to ensure optimal resource management. Enhancing overall matter and energy flows should eventually lead to increased performance and heightened competitiveness, a reason why small and medium-sized businesses should seize the opportunity and put industrial ecology into practice. Indeed, industrial ecology is not just for a small number of large companies that can afford the luxury to uphold new practices without raking in immediate profits. Everyone can benefit.

Furthermore, increased performance is one of the central arguments put forward by "eco-efficiency", a term coined in 1992 by Frank Bosshardt, one of the top executives of Anova (the holding company which belongs to the Swiss industrialist Stephan Schmidheiny, initiator of the Business Council for Sustainable Development). Basically, eco-efficiency suggests an approach very similar to that of industrial ecology. The main difference is that eco-efficiency remains centred on an individual enterprise's strategy, whereas industrial ecology also aims for product enhancement and recovery on a larger scale: enterprise networks, regions, and ultimately the entire industrial system [47, 48].

Nanomedicine and the evolving industrial system

Industrial ecology focuses on the long-term evolution of the entire industrial system, and strives to reach its objective by using a dual approach: a rigorous one in terms of theory (scientific ecology) and an operational one (prescribing economically viable concrete steps). Environmental problems, therefore, are only one of the many issues which industrial ecology tries to deal with. Among these issues, the emergence and diffusion of new "pivotal" technologies (as they are sometimes called), deserve particular attention – especially nanotechnology. Potentially, nanotechnology (or rather nanosystems) could profoundly transform the entire economy, including all industrial activities and subsequently their environmental impacts [49–53].

In short, nanotechnology can be defined as the ability to manipulate and control matter at the level of molecules and atoms. The capacity to assemble molecules and atoms in a precise and controlled way could permit the manufacture of objects with almost no "production waste", since only the desired atoms and molecules would be used. Nanotechnology would also make possible a whole range of new "smart" materials with many useful properties, thus preventing the release of pollutants during the use of products (for example, by minimising corrosion and degradation) and at the end of their life as well (such products would be selectively degradable and reusable under specified conditions). Combining nanotechnology and biotechnology would also allow the development of manufacturing processes at ambient temperature and pressure, in contrast with today's high pressure and high temperature industrial processes that consume large quantities of energy and raw materials, usually under dangerous conditions [54]. Benefits of nanosystems for the environment could be very substantial – with, however, new risks also [55, 56].

Nanosystems are likely to transform medicine very significantly, as appears from the few papers published so far in the fast emerging field of nanomedicine [57–64]. Some theoretical speculations clearly offer a flavour of science fiction, for example "respirocytes" proposed by Robert Freitas [65], but the field is receiving growing recognition [66]. Nanomedicine is of outmost importance not only in itself, but in the perspective of industrial ecology as well. Indeed, nanomedicine could have tremendous impacts not only on health, but also on the global environment, for a simple reason: in theory, nanomedicine would allow a growing world population to live much longer – and moreover in good health. This implies a potentially large increase in the consumption of resources and generation of waste, a daunting challenge for the design of future viable industrial ecosystems.

Besides, it should be strongly emphasised that the most crucial aspect of such technological development is not nanotechnology per se, but its convergence with the science and technology of self-replication. This convergence may lead to totally new kinds of artefacts: physical nanosystems, ie, very small "robots" (nanorobots, typically the size of a bacterium or even less), which would be autonomous, self-learning, self-repairing, self-replicating, and self-evolving [67–69].

There is no doubt that the time has come to prepare for the coming era of nanosystems, as acknowledged in the first "Guidelines on Molecular Nanotechnology" recently released by the Foresight Institute [70]. Hopefully, such guidelines will help to ensure that nanosystems (along with other technological developments) will contribute to the ultimate goal of industrial ecology, namely promoting a more sophisticated and "elegant" industrial system, one capable of creating more wealth and better living standards with less harmful impacts on the Biosphere [71].

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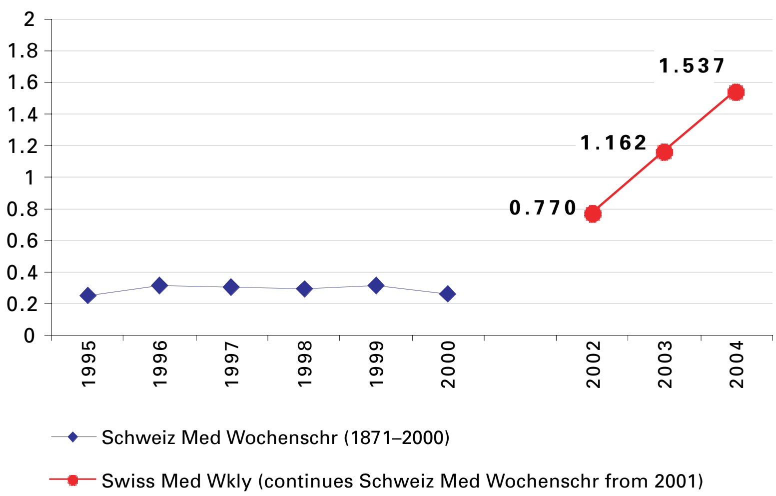

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