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# Eco-efficiency and industrial symbiosis – a counterfactual analysis of a mining community

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## Abstract

Complex utilization, a production model analogous to those described by industrial symbiosis, was planned at the Russian Kola Science Center in mid-1980. The model integrates the waste streams of mining industries in the Kola Peninsula in such a way that waste from one industrial operator becomes raw material for another. Using a counterfactual method, this article determines the eco-efficiency of the model between the years 1985 and 2005. A parallel study of the eco-efficiency of the actual system, i.e. in the absence of complex utilization, is then performed for the same time period. The study shows that complex utilization would indeed have yielded increased eco-efficiency, even though not all environmentally harmful emissions would have decreased. As a result of market collapse and the use of upstream pollution prevention together with traditional end-of-pipe technologies, however, the actual system shows net emission reductions similar to those modeled in complex utilization. It is suggested that in systems like the mining industry of the Kola Peninsula, with high production volumes and poorly developed environmental technologies, upstream pollution prevention together with traditional end-of-pipe technologies may prove more attractive than industrial symbiosis, despite the substantial increases in eco-efficiency of the latter.

*Keywords:* Industrial symbiosis; Eco-efficiency; Counterfactual analysis; Mining

## 1. Introduction

Industrial symbiosis (IS) has been defined as the synergistic exchange of material and energy between industrial organizations in a locality or region or even in a virtual community [1–3]. Within studies of industrial ecology, IS is sometimes used interchangeably with concepts such as eco-industrial parks [4] and industrial ecosystems [5]. A common denominator for these concepts is that they all attempt to describe changes in a set of individual systems, each processing its own material flows into a system whereby there is an integration of the material flows from the companies of the system. This change is expected to contribute to increased eco-efficiency [6–8], as has been the case in the benchmark of IS, Kalundborg [2,9–13]. Given the link between IS and eco-efficiency, it comes as a surprise that long-term empirical studies of this link are rare. A number of symbiotic industrial systems have been recognized in the history of the industrial era and it is instructive to turn to such industrial symbioses for signs of improvements in overall eco-efficiency [14].

The objective of this paper is to test the link between IS and eco-efficiency improvement in a case study of five mining operations in the Kola Peninsula in Northwest Russia (Fig. 1). In this region, a concept analogous to IS was suggested in the 1980s. The concept, known as complex utilization, promised an increase in welfare and a decrease in pollution produced by the mining industry of the region. As a result of the collapse of the Soviet Union, complex utilization was never implemented in full scale. The operational complex utilization plan, however, fits well into the framework of IS and offers a chance for modeling the development path of an IS, and comparing it to the actual development path of the mining

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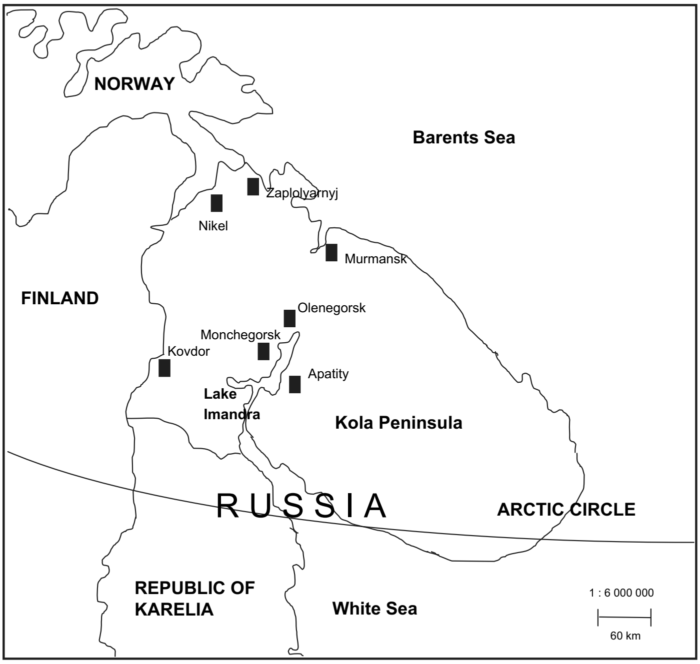

Fig. 1. Mining-industrial cities of the Kola Peninsula and the region's capital, Murmansk. One of the five case companies, Pechenganikel, operates both in Nikel and Zapolyarnyj.

industry in the Kola Peninsula. This way of estimating the present effects of hypothetical changes in a system's history is commonly called counterfactual or what-if analysis in cognitive and social psychology [15]. In the environmental field, counterfactual analysis has emerged in recent years in the baseline calculations for country-specific carbon dioxide quotas [16]. In a different vein, eco-industrial planners have used what-if analyses to estimate the future feasibility of industrial ecosystems and IS [10,12,17].

In this paper, eco-efficiency indicators based on input-output analyses are created on the basis of a counterfactual question: How would an IS have changed the eco-efficiency of the Kola Peninsula mining-industrial system relative to actual changes in the system's eco-efficiency? First, the construction of eco-efficiency indicators is explained in more detail. Second, the development paths of the complex utilization model and of the actual system are analyzed in terms of eco-efficiency and absolute pollution volumes. The article concludes with a discussion of the limitations of eco-efficiency indicators, the counterfactual method, and the significance of case studies for IS.

## 2. Materials and methods

The raw materials, products, by-products, wastes and emissions of the five major mining businesses still in operation in the Kola Peninsula are presented in brief in Table 1. Based on stakeholder interviews and literature, it was concluded that pollution from mining and minerals processing in the Kola Peninsula is clearly dominated by sulfur dioxide, heavy metals and apatite-nepheline tailings. The emissions of sulfur dioxide and heavy metals are primarily related to the sulfur content of the raw material and to the processing conditions of the cupro-nickel industry (Severonikel and Pechenganikel). Therefore, an indicator of raw material efficiency (output volume divided by input volume) would not be able to indicate performance changes resulting from, for instance, raw material substitution.

By dividing production volume by specific pollutant volumes, an indicator is obtained that better approximates to the eco-efficiency of the cupro-nickel industry. In Eq. (1), an eco-efficiency indicator ($\eta_{\mathrm{em}}$) is obtained by dividing a ton of a company's net production ($m_{\mathrm{prod}}$) by a ton of the company's specific emission ($m_{\mathrm{em}}$).

$$\eta_{\mathrm{em}} = m_{\mathrm{prod}} / m_{\mathrm{em}} \tag{1}$$

Regarding emissions from the Apatit company, the case is different. The risk of dust storms is related to the amount of tailings produced in the apatite-nepheline plant. Therefore, the eco-efficiency of Apatit is indicated by the raw material efficiency ($\eta_{\mathrm{rm}}$) of the company. This is expressed by Eq. (2), in which a ton of the company's net production ($m_{\mathrm{prod}}$) is divided by a ton of material input ($m_{\mathrm{rm}}$).

$$\eta_{\mathrm{rm}} = m_{\mathrm{prod}} / m_{\mathrm{rm}} \tag{2}$$

A material flow analysis was conducted on the five case companies with an aim to retrieve data for Eqs. (1) and (2) for the period 1980−2003. Actual production and emission

Table 1
The production chains of the Kola Peninsula mining industries

| | Raw materials | Products | By-products | Wastes | Emissions |
|---|---|---|---|---|---|
| Severonikel | Cu-Ni matte and other non-ferrous concentrates from the Kola Peninsula, Norilsk (Siberia) and other sources | Copper (0.6% of world production[a]), nickel (8.5% of world production[a]), cobalt, gold, platinum-group metals | Sulfuric acid | Dry tailings deposits, sulfur | Sulfur dioxide and heavy metals into the atmosphere, process effluents containing heavy metals into Lake Imandra |
| Pechenganikel | Cu-Ni ore from the Kola Peninsula, Norilsk (Siberia) and other sources | Cu-Ni matte to Severonikel | Sulfuric acid | Dry tailings deposits, sulfur | Sulfur dioxide and heavy metals into the atmosphere |
| Apatit | Apatite-nepheline ore from the Kola Peninsula | Apatite concentrate (6.1% of world production[a]), nepheline concentrate (46% of world production[a]) | Sphene, titanomagnetite, Al-coagulants, aegirine | Wet and dry tailings deposits | Process effluents containing phosphorus into Lake Imandra, dust from dry tailings |
| Kovdor | Baddeleyite-apatite-magnetite ore from the Kola Peninsula | Iron ore concentrate (0.35% of world production[a]) apatite concentrate (1.3% of world production[a]), baddeleyite concentrate (100% of world production[a]) | Gravel | Wet and dry tailings deposits | Process effluents containing phosphorus and heavy metals into local reservoirs, dust from dry tailings |
| Olenegorsk | Magnetite ore from the Kola Peninsula Silicates | Iron ore concentrate (0.35% of world production[a]) | Gravel | Wet and dry tailings | Process effluents containing metals into local reservoirs, dust from dry tailings |

[a] In 2002.

data were collected directly from the case companies. The data for complex utilization were retrieved by modifying the original model (Fig. 2) in a spreadsheet to yield the required material and emission data for 1980–2005. The original model [18], as outlined in Decree 338 of the Central Committee of the Communist Party [19], describes how the Kola Peninsula was to counter the decreased production efficiency and poor ecosystem conditions:

> “At the same time there are serious shortcomings in the development of the Murmansk region. Growth rates and production efficiency have decreased in many branches. Disproportions between the extension of the mining of the primary raw materials and the development of the processing industry have arisen. In a number of districts the ecological situation is unfavorable.” [19]

Ultimately, complex utilization was to solve the environmental problems caused by sulfur dioxide and tailings by feeding these back into the region’s production system. This feedback would require new processes that would add value to the region’s products and broaden the product mix. In the model (Fig. 2), nine production units are combined into a single Kola Peninsula Mining-Industrial Complex, consisting of 20 waste material or by-product flows between the production units. In addition, 18 new and 7 traditional product material flows lead out of the system. It should be noted that the model used in this study is a simplified version of the original model. Production units in the original model that do not contribute to the specified emissions (sulfur dioxide, heavy metal, and apatite-nepheline tailings) have been excluded from this study. The five companies analyzed here would all have taken part in complex utilization but the connections would have emerged gradually over the time period between 1985 and 2005. Due to limited space, the chemistry of the unit processes will not be described in detail.

The focal element of the complex utilization model is here called the Kola Chemical Plant, which produces alumina, Portland cement, calcinated soda, potash, saltpeter variants, amorphous silicates, and phosphorus-potassium fertilizers. This plant would be located on the coast of the White Sea and it would run entirely on waste flows such as nepheline from Apatit, commodity slag from Pechenganikel, and calcium carbonate from Kovdor. The process itself is well known: it has been suggested for IS elsewhere [20] and it is partially in use at the Pikalevo aluminum plant [21]. As the process turns all components of the raw material into products, the amount of secondary waste is negligible in theory. The large amount of Portland cement, however, might be a problem if no immediate consumers are present. In the complex utilization model, saltpeter, potash, and phosphorus-potassium fertilizers are let out of the system but a great part of the output from the focal element is redirected inside the Kola Peninsula:

- Calcinated soda enters the Severonikel desalination process and the Kovdor apatite process.
- Portland cement supplies the expansion of industrial infrastructure and dwellings.
- Alumina enters the existing Kandalaksha aluminum plant that previously used raw material from elsewhere.
- Potassium silicate enters a new plant for smelted phosphorus-magnesium fertilizers, located in Kovdor.

The operations of the other units used in the eco-efficiency calculations from the complex utilization model are summarized

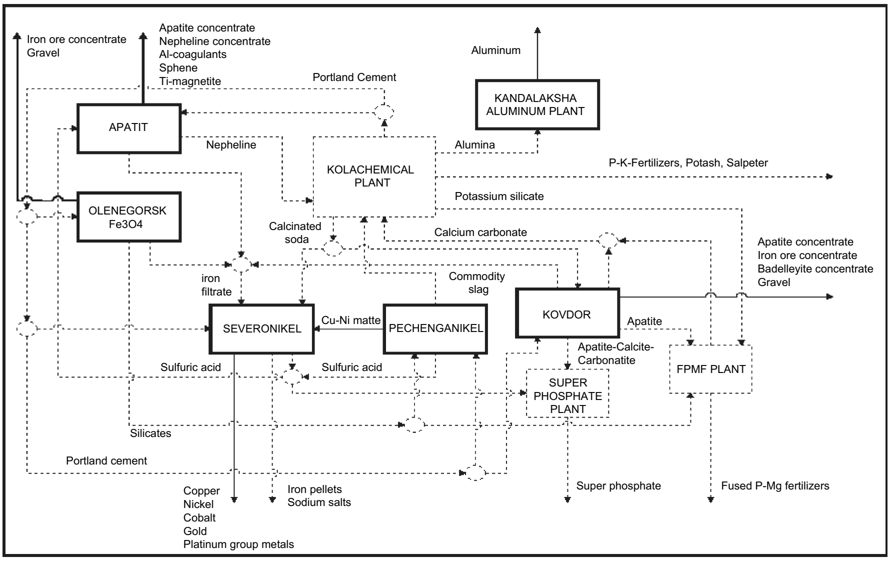

Fig. 2. Kola Peninsula Mining-Industrial Complex, modified from [18]. Operational plants and material flows as of 2005 are drawn with solid lines, modeled plants and material flows are drawn with dashed lines.

in Table 2. In addition, Table 2 presents the operations from which the actual eco-efficiencies of the case companies were calculated. It should be noted that although the production volumes of each company have decreased, the core business of the industries has not changed significantly during the past 30 years. Thus, the current operations provide a suitable basis for calculations of the actual development of eco-efficiency.

The model uses the real material flows from the year 1985 as a starting point. After that, the production data change with an unknown rate of technological change. Therefore, it was assumed that the model contains at the minimum the same technological development that has occurred in real life. For instance, if no detailed information on a process in the complex utilization model was given, conversion rates from a real-life corresponding process were assumed on a three-year moving average. In case a modeled process does not exist in the current Kola Peninsula industries, conversion rates were assessed from a corresponding process given in the literature.

## 3. Results

Figs. 3–8 depict the changes in the eco-efficiencies and the specified emission flows of the Kola Peninsula mining companies. Each figure presents two curves: changes in the modeled complex utilization eco-efficiencies and emissions are drawn with dashed lines and changes in the actual eco-efficiencies and emissions are drawn with solid lines.

### *3.1. Cupro-nickel industry*

The eco-efficiency of the cupro-nickel industry as regards sulfur dioxide emissions (Eq. (1)) is an aggregate of the Severonikel and Pechenganikel operations (Fig. 3). These two plants participate in the complex utilization model with 17 connections. The model gives an increase in eco-efficiency from 0.99 t product to 20.31 t product per 1 t $SO_2$ between 1985 and 2003. The actual development in turn shows an increase in eco-efficiency from 0.99 t product to 1.51 t product per 1 t $SO_2$ during the same time period. In respect of emissions of heavy metals (Eq. (1)), the model gives an increase in eco-efficiency from 130.6 t product to 492.3 t product per 1 t heavy metals (copper, nickel and cobalt) between 1990 and 2002, while the actual data yield a fluctuating development over that time from 107.5 t product to 88.2 t product per 1 t heavy metals between 1990 and 2002 (Fig. 4). As a result of inconsistent data for Pechenganikel, only emissions of heavy metals from Severonikel were included in the study. Moreover, the lack of heavy metal emission data prevented an analysis of the period prior to 1990 and post 2002.

Looking at the absolute sulfur dioxide and heavy metals emissions in Figs. 5 and 6, it can be seen that the complex utilization model would have yielded significant reductions. Emissions of $SO_2$ would have been reduced from 586.3 t to 98.0 t between 1985 and 2003. This reduction and the increased eco-efficiency in Fig. 3 result mainly from the planned total desulphurization of the Pechenganikel plant, which would have required increased extraction of local ore on one hand and conversion of lean sulfur dioxide into sulfuric acid on the other. The first strategy, enhancing the utilization of local sulfur-poor ore, would have reduced the company's dependence on imported sulfur-rich ore from the Krasnoyarsk region in Siberia, thus helping the company to reduce its $SO_2$ emissions [22]. The second strategy, increasing sulfuric acid production from sulfur dioxide captured at the end of the pipe,

Table 2
Main mass flows of the five case companies, and the hypothetical Kola Chemical Plant, as used in the eco-efficiency calculations

| | | Complex utilization | | Actual development | |
|---|---|---|---|---|---|
| | | Supplier/consumer within the Kola Peninsula | Supplier/consumer outside the Kola Peninsula | Supplier/consumer within the Kola Peninsula | Supplier/consumer outside the Kola Peninsula |
| Severonikel | Supplies: | Iron pellets, sodium salts, sulfuric acid | Copper, nickel, cobalt, sulfuric acid | Sulfuric acid | Copper, nickel, cobalt, sulfuric acid |
| | Consumes: | Virgin ore, Cu-Ni matte, iron filtrate, calcinated soda, Portland cement | Cu-Ni matte | Cu-Ni matte | Cu-Ni matte |
| Pechenganikel | Supplies: | Cu-Ni matte, sulfuric acid, commodity slag | | Cu-Ni matte, sulfuric acid | Cu-Ni matte, sulfuric acid |
| | Consumes: | Cu-Ni ore, silicates, Portland cement | Cu-Ni ore | Cu-Ni ore | Cu-Ni ore |
| Apatit | Supplies: | Nepheline concentrate, iron filtrate | Apatite concentrate, nepheline concentrate, sphene, titanomagnetite, Al-coagulants, Na-K-Ca-saltpeter, Amorphous silicates, P-K fertilizers | Sphene, titanomagnetite, Al-coagulants | Apatite concentrate, nepheline concentrate, aegirine |
| | Consumes: | Virgin ore, sulfuric acid, Portland cement | Flotation reagents | Virgin ore, sulfuric acid | Flotation reagents |
| Kovdor (with super phosphate and FPMF plants) | Supplies: | Calcium carbonate, iron filtrate | Iron ore concentrate, apatite concentrate, baddeleyite concentrate, super phosphate, FPMF | | Iron ore concentrate, apatite concentrate, baddeleyite concentrate |
| | Consumes: | Virgin ore, tailings, calcinated soda, silicates, sulfuric acid, Portland cement | | Virgin ore, tailings | |
| Olenegorsk | Supplies: | Silicates, iron filtrate, gravel, sand | Iron ore concentrate, iron ore super concentrate, gravel, sand | Gravel | Iron ore concentrate, gravel |
| | Consumes: | Virgin ore, Portland cement | | Virgin ore | |
| Kola Chemical Plant | Supplies: | Alumina, Portland cement, calcinated soda, potassium silicate | P-K fertilizers, potash, saltpeter | | |
| | Consumes: | Nepheline, calcium carbonate, commodity slag | | | |

The columns under the title Complex utilization describe the mass flows used in the calculation of eco-efficiency from the complex utilization model. The columns under the title Actual development describe the mass flows included in the calculation of eco-efficiency from the actual development data of the case companies.

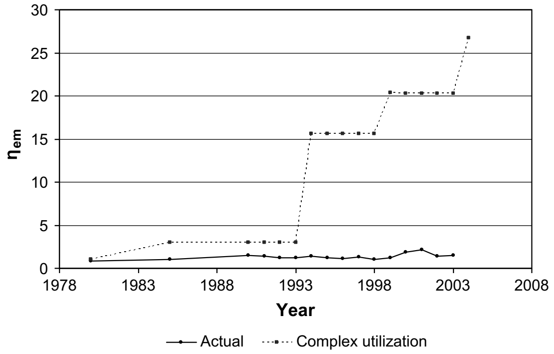

Fig. 3. Modeled and actual eco-efficiencies of the Kola Peninsula cupro-nickel industry in respect of sulfur dioxide emissions. The significant increase in the modeled eco-efficiency (dashed line) is a result of raw material substitution and increased production of sulfuric acid. The same actions have been taken in smaller scale in real life, which is indicated by the exiguous increase of the actual eco-efficiency (solid line).

would have been feasible as the other industries within the Peninsula could have consumed the excessive amounts of acid. For instance, at Severonikel sulfuric acid production would have increased from 236.2 kt (kilotons) to 649.7 kt between 1985 and 2005. The recipients for the acid would have been the planned Kovdor super phosphate plant, and the increased aluminum coagulant and titanium pigment production at Apatit [23–26]. It should be noted, however, that without any recirculation of sulfuric acid in the consumers' processes the regional acid consumption would have roughly matched the regional production. This means that sulfur-containing wastes such as ferrous sulfate from secondary production, omitted in this study, would have posed a considerable environmental threat had they not been treated properly.

The collapse of the Soviet system in 1993 led to dramatic reductions in industrial production volumes and, consequently, to reductions in environmental emissions throughout Russia. Accordingly, sulfur dioxide and heavy metals emissions from the Kola Peninsula cupro-nickel industries (solid curves in Figs. 5 and 6) fell in the 1990s. However, while Severonikel did experience a decrease from 223.0 kt to 135.2 kt in its total production between 1990 and 1993, the production of cupro-nickel matte at Pechenganikel has remained rather stable. That is, the cupro-nickel industry has substituted some of the Siberian sulfur-rich ore with local sulfur-poor ore. In addition, sulfuric acid production from sulfur dioxide captured at the end of the pipe has been increased both at Severonikel and Pechenganikel.[1] As a result, $SO_2$ emissions from the cupro-nickel industry fell from 586.3 t to 257.5 t between 1985 and 2003 (Fig. 5). This also explains the slight increase in eco-efficiency for the actual production with respect to $SO_2$ (Fig. 3). While the volume of sulfuric acid production in the cupro-nickel industry has been smaller than it would have been in the case of complex utilization, the two strategies for $SO_2$ reduction are very similar both in reality and in the complex utilization model.

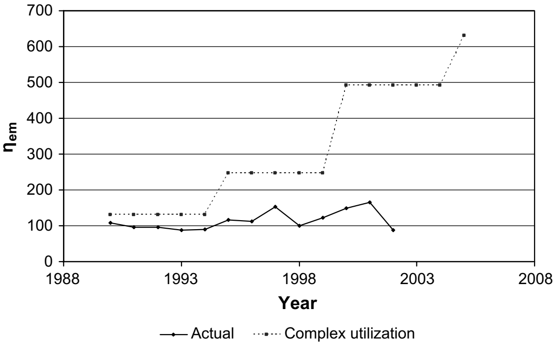

Fig. 4. Modeled and actual eco-efficiencies of the Severonikel metallurgical plant in respect of heavy metals (copper, nickel and cobalt). The increase in the modeled eco-efficiency (dashed line) is a result of increased flue gas treatment.

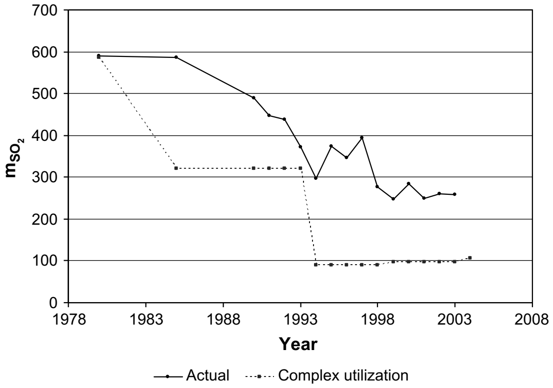

Fig. 5. Modeled and actual absolute sulfur dioxide emissions from the cupro-nickel industry, in thousand tons. The reduced sulfur dioxide emissions in the model (dashed line) result from raw material substitution and increased production of sulfuric acid. Those that have occurred in real life (solid line) result from reduced production volumes, raw material substitution and increased production of sulfuric acid.

### 3.2. Apatite industry

Dust from dry tailings and the amount of phosphorus waste water are the dominant emissions from the apatite industry in this study. These emissions are related to production through input-output efficiency (Eq. (2)). In the complex utilization model, Apatit would have initiated the conversion of waste nepheline into aluminum coagulants in 1995, and would have started to ship 1 Mt nepheline annually to the Kola Chemical Plant in 2000. As Apatit would have redirected the flow of nepheline from landfills to the beginning of a new production chain (Fig. 2), the need to contain dust from tailings at the end of the pipe would have been reduced.

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[1] Environmental Manager, Severonikel, personal communication, 19 May 2005.

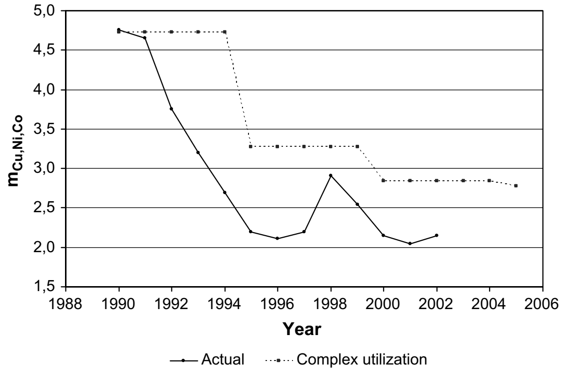

Fig. 6. Modeled and actual absolute heavy metal emissions (copper, nickel and cobalt) from the Severonikel metallurgical plant, in thousand tons. The reduced heavy metal emissions in the model (dashed line) result from flue gas treatment. Those that have occurred in real life (solid line) result from reduced production volumes and flue gas treatment.

The complex utilization model gives an increase in eco-efficiency for Apatit from 0.39 t product to 0.42 t product per 1 t extracted ore between 1985 and 2003 (Fig. 7). At this point, however, the apatite industry differs from the cupro-nickel industry in one important sense: despite the increase in eco-efficiency in the complex utilization model, the absolute volume of tailings would increase and remain higher than the initial values throughout the analysis period (Fig. 8). Thus, complex utilization would hardly have solved the dust and effluent problems, as was intended. This is explained mainly by the large volumes of apatite concentrate that the model expects to be maintained: the modeled apatite concentrate production for 2005 is 16.8 Mt (megatons) and the modeled nepheline production for the same year is 11 Mt. As the Khibiny apatite-nepheline ore contains 43.2% apatite and 40.0% nepheline [27], the modeled demand for nepheline is well below the amount in the extracted ore. Thus, the remaining nepheline would have been disposed of as tailings.

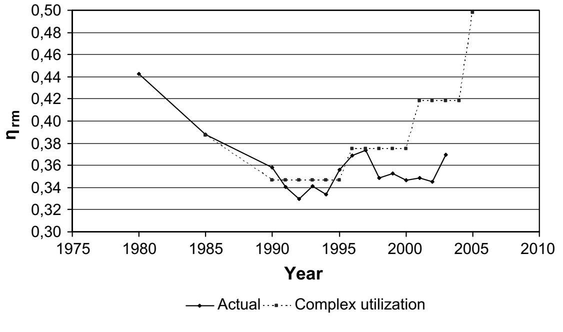

Fig. 7. Modeled and actual eco-efficiencies of Apatit in respect of input-output volumes. The increase in the modeled eco-efficiency (dashed line) result from simultaneous increase in production volumes and utilization of the nepheline by-product. The increase in eco-efficiency in real life (solid line) from 1994 results from process changes in mining and enrichment.

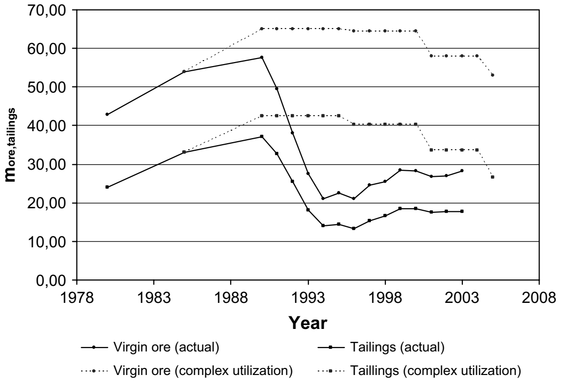

Fig. 8. Modeled and actual absolute ore extraction and tailings volumes of Apatit fertilizer plants, in million tons. The increase in the modeled tailings volumes (dashed line) results from increased apatite production, which counters the utilization of the nepheline by-product. The reduction of virgin ore and tailings volumes in real life (solid line) has been caused by the collapse of the Soviet Union and the consequent decrease in demand for fertilizers.

It is in the case of Apatit that the post-Soviet reductions in production volumes are most striking: production of apatite concentrate fell from 19.3 Mt in 1990 to 6.1 Mt in 1994. But, as depicted in Fig. 6, the production efficiency of Apatit has increased from 0.36 t product to 0.37 t product per 1 t extracted ore between 1990 and 2003. This has been achieved with heavy investments in production and mining technologies, which counter the natural deterioration of the ore base.[2]

On the whole, the analysis is revealing in respect of the relation between IS, end-of-pipe technologies, and upstream pollution prevention. Definitions that characterize IS as an attempt to achieve collective benefits that transcend individual benefits [2], or as raw material optimization among neighboring industries [28] generally do not specify the ways in which the symbiosis should abate pollution. In this paper, IS embodies the outcomes of end-of-pipe technologies, which are typically defined as technologies of control, treatment and disposal of pollution after it has been created [29,30]. Both the sulfuric acid conversion in the cupro-nickel industry and the nepheline landfilling in the apatite industry are results of end-of-pipe technologies. But they are more than that. In the IS model, or the complex utilization model, sulfuric acid and nepheline are constitutive elements of the symbiosis. In addition to end-of-pipe technologies, industries both in the IS model and in real life use upstream pollution prevention — such as raw material substitution and process changes — which aims at reducing pollution before it has been created in the production process [31]. Raw material substitution in the cupro-nickel industry resulted in reduced $SO_2$ emissions and increased eco-efficiency both in the IS model and in real life. Similarly, process changes in the apatite industry have, during the past decade, led to moderate increases in eco-efficiency. Rather than enhancing their end-of-pipe technologies with IS, as the

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[2] Manager, Apatit, personal communication, 28 May 2002.

complex utilization model suggests, the case companies have adopted a combination of end-of-pipe technologies and upstream pollution prevention with modest improvements in eco-efficiency.

## 4. Discussion

The results of the eco-efficiency analysis described in Section 3 are somewhat ambiguous. On one hand, the complex utilization model would have enabled the cupro-nickel industry to achieve increased eco-efficiency with both economic and environmental benefits. On the other hand, the model would have led to a simultaneous increase in the environmental load of the apatite industry. Assuming a sufficient similarity between complex utilization and IS, the case contradicts the purported positive feedback between IS and eco-efficiency presented in the introduction of this paper. This conclusion should be considered carefully, for several reasons.

First, eco-efficiency is a measure that can be increased in two ways: either the nomerator in Eqs. (1) and (2), i.e. value, can be increased, or the denominator, i.e. pollution, can be decreased. The complex utilization model illustrates both of these ways. Below the hyphen, poisonous sulfur and heavy metals emissions from the cupro-nickel industries would have diminished radically but dust storms resulting from apatite production would have continued to occur on a larger scale than ever before. Above the hyphen, production levels would have skyrocketed as a result of vertical integration and the diversification of the product mix. In both cases, eco-efficiency would have increased. However, the transition to a market economy and plant-level technical changes have led to net emission reductions in all of the case companies. While IS may offer a feasible set of tools in systems with well-developed environmental technologies, this is not the case in the Kola Peninsula. Most processes are thoroughly outdated and were not planned for waste reuse from the start. Leapfrogging, i.e. radical improvements in eco-efficiency, would not be possible without radical process changes. What is more, environmental impacts of pollution typically depend on absolute levels of pollutants. Eco-efficiency, being a relative measure, may lack explanatory power in such large-scale systems as the Kola Peninsula Mining Complex.[3]

Second, the counterfactual method used in this study does not allow direct comparison between the model and actual development. Rather, in relation to each other, the modeled and the actual eco-efficiencies should be seen as scenarios in the sense that they are two possible development paths out of many more [32]. A major difference to scenarios is that one of the paths in fact became reality. Thus, given the boundary conditions of this study, it is safe to say that complex utilization would have resulted in higher levels of eco-efficiency than the Kola Peninsula had seen before. In the same way, the radical market collapse and individual process changes have guaranteed a rather stable eco-efficiency throughout the transition period, with reductions in net emissions. But, although the planners of complex utilization arrived in part, at similar emission reductions to those that were actually achieved without complex utilization, the two paths are not readily comparable. This is a limitation of the counterfactual method but it is also inherent in the eco-efficiency indicators. The definition of eco-efficiency allows for a high degree of freedom in exactly how an indicator is designed. This renders eco-efficiency an unstable measure. For instance, many indicators of human-environmental interaction, including eco-efficiency, contain a certain level of aggregation. On one hand, extensive aggregation of environmental indicators may guide researchers to recommend material substitution that may lead to increases in net environmental risk [33]. On the other hand, environmental impacts are usually localized phenomena. This makes the elicitation of impacts in two distant regions unjustifiable and thus, damages the whole notion of a net environmental impact [34]. By not aggregating the indicators above the level of the specific pollutant in a particular region, this study has attempted to incorporate the claim for scale-sensitive generalizations of eco-efficiency indicators and the necessary inclusion of stakeholders' perceptions of their immediate environment.

As the indicators used in this study were based on localized pollution arguments collected from interviews and literature, they reflect something about the relationship between society and the environment on a local level. But the environment also contains a certain interpretative flexibility. That is, people tend not to agree upon what is good or bad for the environment - in particular if environmental well-being is confronted with human well-being. This notion, apparent in the conflicting results of the eco-efficiency calculations in Section 3, leads to a third critical point: IS and its eco-efficiency indicators need to be developed in such a way that they allow the researcher to understand both the physical and the social aspects of a system. In particular, development would be needed in defining exactly how the case study method, typical of IS studies, can contribute to a more general theory. This is a substantial task as it touches upon the divergent foundations of physical and social sciences as regards science's ability to model and predict the future states of systems. When studying the social, IS engages itself in theory building that is different from, for instance, that found in physics. That is, unlike physical objects, society, when subjected to scientific inquiry, reflects upon the results of the inquiry and often, as a result of this reflection, undergoes change. This blurs the distinction between the subject and the object of a scientific study, making it very hard for social scientists to develop predictive methods [35]. For instance, in the present case, stakeholder evaluations of what constitutes an environmental problem become "second-order" information when coupled with physical "first-order" data, such as time series on industrial emissions [36].

If the claim that the social and the physical can be combined in IS studies is to be upheld, the coming theory of IS would have to generalize in part upon information of a second-order type. For the reasons mentioned above, this may be a substantial obstacle on the way to a general theory in

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[3] I would like to thank one of the anonymous reviewers for this point.

IS. The very same obstacle is present in doubts that a Kalundborg-type IS could be found or easily designed anywhere else [37,38]. However, this doubt has not thwarted other IS cases and these cases certainly contain valuable information for IS theory development. In particular, single cases selected so as to maximize the utility of information, e.g. critical cases, would suit well the task of combining the physical and social. Critical cases may embody a number of qualitative and quantitative characteristics of a complex phenomenon, for which a researcher is able to set an upper or lower limit on the basis of the single case [36]. In this way, critical cases allow a specific type of generalization upon single case studies. For IS studies, the strength of the critical case analysis lies in its micro-level approach, which is made sensitive to the rich local-level perceptions of the environment, thus distinguishing it from approaches that reduce the richness by aggregation.

Accordingly, in this paper, complex utilization is a critical case in terms of the magnitude and style of the industries involved: if such a large-scale, centrally planned, rigorously modeled, and, to its constituents, homogenous IS would not have led to increased environmental performance, then it is unlikely that increasing the size of the IS or the rigor of modeling would do so. Increasing scale or rigor would only increase the likelihood of the critics of IS coming up with indicators showing that the environmental benefits gained with IS are questionable. It is probable, however, that in a similar setting to that found in the Kola Peninsula, IS would succeed on a smaller scale. This is indicated by eco-efficiency improvements at Kovdor, where reduced demand for iron-ore concentrate led to financial problems in the early 1990s. The problems were countered by an increase in apatite production, which was made cost-effective by the utilization of old apatite-rich tailings that the company had produced before including apatite in the product mix in the 1970s [39].

## 5. Conclusions

Eco-efficiency indicators offer a practical tool for assessing the environmental and economic benefits from loop-closing in IS. This paper has presented complex utilization as an unfortunate IS that never had the chance to mature. Yet the complex utilization model from Soviet Russia contains process solutions familiar to the developers of IS today. Thus, complex utilization offers a fruitful case for counterfactual analysis of the potential of IS for solving environmental problems, in a non-Western context, as indicated by eco-efficiency. The analysis showed that complex utilization would have led to increases in eco-efficiency and it would have solved some, though not all, of the pressing environmental problems of the Kola Peninsula. On one hand, IS, in the form of complex utilization, would have led to increased eco-efficiency, but the environmental load would not have decreased in all of the case companies. On the other hand, the actual post-Soviet development of the Kola Peninsula has led to stabilized and yet, at times, increased eco-efficiencies and a reduced net environmental load with the use of both end-of-pipe technologies and upstream pollution prevention. This reflects the limits of both eco-efficiency and IS as environmental management guidelines in the former, centrally planned, economies. In particular, when the production volumes of primary products are high and environmental technologies poorly developed, as in the case of the Kola Peninsula, upstream pollution prevention together with traditional end-of-pipe technologies may prove more attractive than IS, despite the substantial eco-efficiency increases offered by the latter.

Similar experiments to complex utilization have been identified in Eastern Europe but typically they also have come to an end with the downfall of the communist regimes [40]. Clearly, the former communist countries provide a rich source of critical IS cases. Further research will be needed to see if the phenomena observed in this paper have occurred in other ex-communist countries and, above all, to see what kinds of boundary conditions new and carefully chosen case studies reveal for IS in such non-Western industrialized nations.

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