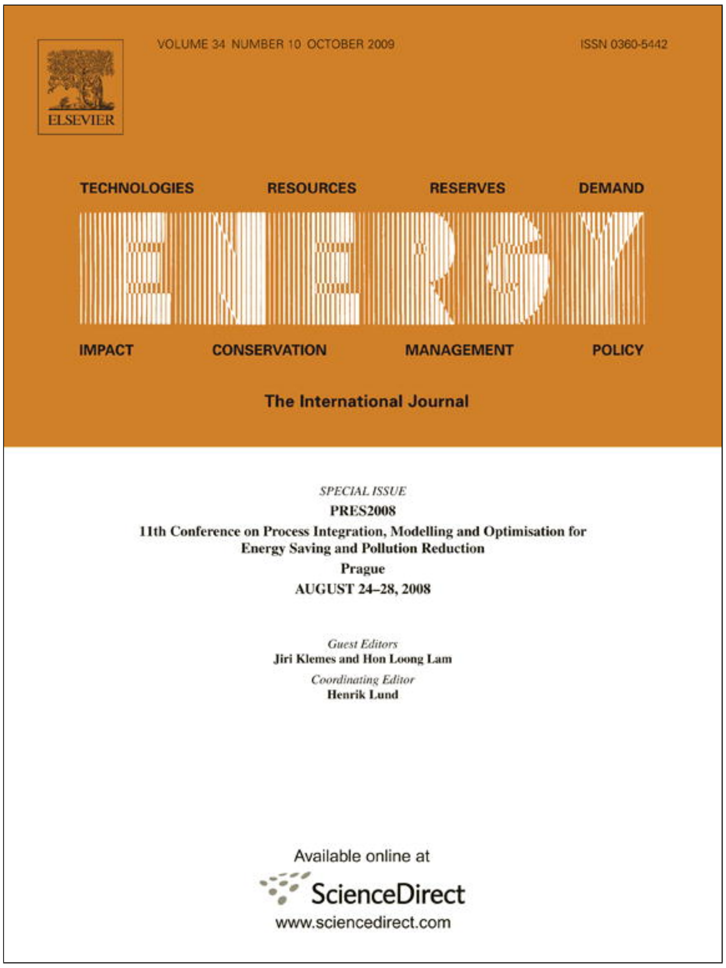
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Erratum

Erratum to ''Assessing the suitability of Input-Output analysis for enhancing our understanding of potential effects of Peak-Oil'' [Energy (2008) 34: 284–290]

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Due to a typesetting error, several errors throughout the article were not corrected properly. For the reader's convenience, the article follows, in its entirety, in the format in which it was intended to appear.

The publisher deeply regrets this error.

Assessing the suitability of input–output analysis for enhancing our understanding of potential economic effects of Peak Oil

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A B S T R A C T

Given recent developments on energy markets and skyrocketing oil prices, we argue for an urgent need to study the potential effects of world oil production reaching a maximum (Peak Oil) in order to facilitate the development of adaptation policies. We consider input–output (IO) modelling as a powerful tool for this purpose. However, the standard Leontief type model implicitly assumes that all necessary inputs to satisfy a given demand can and will be supplied. This is problematic if the availability of certain key inputs becomes restricted and it is therefore only of limited usefulness for the study of the phenomenon of Peak Oil. Hence this paper firstly reviews two alternative modelling tools within the IO framework: supply-driven and mixed models. The former has been severely criticised for its problematic assumption of perfect factor substitution and perfect elasticity of demand as revealed by Oosterhaven [Oosterhaven J. On the plausibility of the supply-driven IO model. J Reg Sci 1988; 28:203–17. [1]]. The supply-constrained model on the other hand proved well suited to analyse the quantity dimension of Peak Oil and is therefore applied empirically in the second part of the paper, using data for the UK, Japanese and Chilean economy. Results show how differences in net-oil exporting and net-oil importing countries are clearly visible in terms of final demand. Industries, most affected in all countries, include transportation, electricity production and financial and trade services.

1. Introduction

Given the potential scale and implication for the world economy the phenomenon of Peak Oil has received very little attention in the media, by policy makers and by academia. Some discussion is taking place around the specific issue of when exactly oil and gas

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production are going to peak (compare World Watch magazine January/February 2006), but these arguments are often of little scientific content and seem motivated by reasons other than to provide an objective public debate. On the one side there are those who argue that Peak Oil is imminent, and urgent action has to be taken as soon as possible to reduce consumption and to prepare ourselves for the radical economic changes that are assumed to be caused by the phenomenon [e.g. 2,3–6]. The group characterised by this more pessimist view is sometimes referred to as the "geologists", because they believe that geology will be the determining factor for the timing of Peak Oil. Colin Campbell, the founder of the Association for the Study of Peak Oil and Gas (ASPO), is at the forefront of this group. On the other side, there are the "optimists" who accuse the former of doomsday politics, of reviving a "recurring myth" [7] or of practicing a "catastrophic cult" [8]. They are known as the "economists" of this debate, because they believe that market mechanisms and human ingenuity will bring about alternative sources of energy to replace energy gained from fossil fuels altogether, before Peak Oil seriously affects economic growth [9].

It is believed here that what lies beneath this optimism is the fact that absolute scarcity of resources does not seem to be accepted by orthodox science and the human society in general. Until now humanity always seems to have found new resources when others became scarce. Technological innovation is believed to solve not only the problem of resource depletion, but also the environmental damage caused by it. Orthodox economics is a major representative of this ideology. It is argued [e.g. 10] that scarcity of matter and energy is only ever relative and not absolute. Relative scarcity means that one resource is only scarce relative to another resource, or the same resource but of a different (lower) quality. It can be overcome by substitution, whereby relatively scarce resources are eventually substituted by relatively abundant ones. Resources are therefore unlimited in total and merely non-homogenous in quality. The price mechanism will automatically make consumption switch from the scarcer resource to an alternative.

Orthodox economists tend to use this rationale to support their claims of unlimited economic growth. Ecological Economics, on the other hand, insists that *ultimate means* in the form of low-entropy matter/energy are scarce in an *absolute* sense, i.e. there are absolute limits beyond which availability is nil [e.g. 11]. A direct result thereof is that economic growth is equally limited. In this study absolute resource (low entropy) scarcity is accepted as a fact. Hence the goal of this study is not to enter the polemic discussion of when Peak Oil is going to occur in time. Fact is that it will occur at some point and that so far there do not seem to be any alternative sources of energy forthcoming, which seem to have the power to replace oil [cf. 12]. History already provides evidence of the dramatic effects of oil and gas shortages: The impacts of the two oil shocks in the late 1970s and early 1980s upon world economies were felt for almost a decade after. Consequently, the urgent need for widespread academic efforts to study the potential impacts of Peak Oil upon world economies is advocated here.

This involves most of all starting to develop and implement policies to reduce resource consumption, not only for the sake of preventing possible economic crises, but also for the sake of reducing environmental impacts of economic activity. A precondition for such an undertaking—and the challenge for science—is to explore, develop and apply tools for enhancing our understanding of the potential effects of Peak Oil. Very little is known about how economies will react once supply of oil and gas becomes physically limited. Surely, one could look at oil and gas consumption balance sheets, to predict which sectors are going to be most affected by Peak Oil. However, such a procedure disregards the complex interdependencies of industries within an economy. It would only be able to show the direct effects but indirect, knock-on or ripple effects are ignored. Input–output (IO) analysis is a framework, which allows capturing inter-industry linkages and to measure the direct and also the indirect effects of external shocks.

Nevertheless, as will be argued in the next section, the traditional demand-driven Leontief model is only of limited suitability for analysing resource constraints, as it assumes unrestricted supply of factor inputs. The same section, therefore, reviews two alternative approaches: the supply-driven and the supply-constrained model. After arriving at the conclusion that a mixed or supply-constrained model would be appropriate for analysing the quantity dimension of Peak Oil, the method is applied to IO tables of the UK, Japan and Chile. The impact of a sudden 10% reduction of output in the "crude oil and natural gas extraction" and "petroleum refining" sectors upon the output of the rest of the economy and upon their own final demands are measured; the results presented in Section 3.1 and its limitations discussed in Section 3.2. Section 4 concludes.

2. Review of methods

Standard IO analysis was developed by Nobel prize laureate Leontief [13,14]. Today, IO tables are being generated on a regular basis for all OECD countries, and the standardization of the framework has been promoted by the United Nations. More recently, it has become a popular tool for ecological–economic analysis (i.e. for studying nature–economy relationships), for Industrial Ecology and for Life Cycle Analysis. The basic IO transaction table consists, firstly, of rows showing "Who gives to whom?" and columns showing "Who receives from whom?" in an economy. The static Leontief model is driven entirely by the final demand matrix [**Y**]. This matrix determines total outputs [**x**], intermediate inputs [**Z**] and primary inputs [**W**] via a set of technical coefficients (see Table 1 for the general outline of an IO table). Usually the question to be answered in demand-side IO modelling is the following: If final demand from one or more of the exogenous sectors (households, government, etc.) is expected to increase or decrease in the future, how would this affect the total output necessary to satisfy this new demand and its ripple effects throughout the economy?

One of the assumptions underlying the demand-driven nature of the standard IO model is that all input requirements for the production of some exogenously given demand will automatically and instantaneously (i.e. within the given statistical year) be met. This is only justifiable, given the existence of unused capacity and very elastic factor–supply curves [15], which usually will not be the case. This feature renders the standard approach unsuitable for the analysis of supply constraints. Intuitively the most attractive alternative to the demand-driven model is the supply-driven IO approach first proposed by Ghosh [16]. The basic idea behind this approach is that if, for example, less of a scarce input (e.g. labour) is fed into the system, the knock-on effects will result in output decreases throughout all economic sectors. Hence it is the supply matrix [**W**], which drives the model and determines the endogenous variables **Z**, **Y** and **x**.

However, on the industry level the model implicitly assumes perfect substitutability between factors. Intuitively this may be regarded plausible as the economy is partly substituting the reduction of available manpower with other inputs. However, this substitution does not respect physical realities and the process does not take into account the properties of the inputs. Moreover, in combination with the assumption of cost minimization, industries would—depending on relative prices—always choose to have only one input (the cheapest) or input combinations would not be unique [17]. At the level of the whole economy the model assumes perfect elasticity of demand, which means that final (households, governments, etc.) and intermediate (inter-industry) demand will adapt smoothly to any changes in supply. It ignores important interdependencies between certain products, such as it is very unlikely that sales of cars, to choose one example, would increase if there was not enough fuel available. Hence we therefore agree with the conclusions made by Oosterhaven [1] in his paper "Plausibility of Supply-Side I-O Models" that the supply-driven model may be unsuitable for both, general descriptions of the working of an economy and for analysing the effects of supply constraints. However, we believe that there may be circumstances, where these problematic assumptions might be less unrealistic and the subject may merit further analysis.

The second model alternative to the traditional Leontief IO model to be reviewed here is the supply-constrained or mixed IO model. So far exogenous variables were either final demand [**Y**] in the demand-driven or value added [**W**] in the supply-driven model. This restricts the scientific efforts to observe the impacts on total output [**x**] of either changes in final demand (due to changing consumer tastes, government spending, etc.) or value added (due to strikes, import embargoes, etc.), respectively. This is particularly restrictive for impact studies of supply shortages such as in the case of Peak Oil. Here it may be desirable to exogenise the sector that is potentially causing the disruption. IO models with mixed exogenous and endogenous variables (therefore the name mixed models) provide a solution to this problem. In the literature they have firstly been described by Stone [18, p. 98]. Instead of estimating changes in sectoral outputs due to changes in final demand (traditional Leontief model) or value added (Ghosh model), mixed models estimate the impacts on unconstrained sectors given some reduced outputs of the supply-constrained sectors. This approach allows the final demand of some sectors and gross output of the remaining sectors to be specified exogenously.

The procedure is well explained in Miller and Blair [19, 330ff] and we will therefore only provide a schematic representation of the model and the underlying equation. The IO system is basically partitioned into supply-constrained and non-supply-constrained sectors. This is illustrated for a simple three sector economy with output restricted energy sectors in Table 1. Using basic matrix algebra for partitioned matrices one can then derive Eq. (2.1) for the general case. The individual variables, vectors and sub-matrices of this equation are explained in Table 2. There are now n total sectors of which one or more are exogenous. The labelling of the sectors indicates that the first k sectors contain the endogenous elements and the last $(n–k)$ sectors the exogenous elements.

$$\begin{bmatrix} \mathbf{x}_{\text{no}} \\ \mathbf{y}_{\text{co}} \end{bmatrix} = \begin{bmatrix} \mathbf{P} & \mathbf{0} \\ \mathbf{R} & -\mathbf{I} \end{bmatrix}^{-1} \times \begin{bmatrix} \mathbf{I} & \mathbf{Q} \\ \mathbf{O} & \mathbf{S} \end{bmatrix} \times \begin{bmatrix} \bar{\mathbf{y}}_{\text{no}} \\ \bar{\mathbf{x}}_{\text{co}} \end{bmatrix} \tag{2.1}$$

The literature holds a number of interesting applications of the supply-constrained model, e.g. [20–25]. All of these studies use the method to incorporate the absolute scarcity of available land in a country. This has been achieved by exogenising the output of the agricultural sector based on available land and assumptions about associated land productivities. In order to measure the potential effects of Peak Oil for an individual economy, one would have to find the sectors that introduce the resource into that economy. The empirical analysis, which follows in this text, uses the two sectors of "petroleum and natural gas extraction" and "petroleum refining" for this purpose.

3. Empirical application of the supply-constrained model

After reviewing the methodology, literature and empirical applications of the supply-constrained IO model it has become evident that it is a prime candidate for analysing sudden output reductions of certain sectors. The methodology is sound and straight forward, the literature does not hold any fundamental criticism of the model and empirical applications have produced very useful results. In order to measure the possible effects of Peak Oil we adopt a simplified scenario, assuming that the phenomenon produces an oil supply reduction to the sectors responsible for its extraction and refining. Hence the use of a static model and the assumption of fixed technical coefficients are justified. Moreover, we only consider the national level. This has foremost two implications: Firstly, we do allow oil-imports from or exports to the rest of the world in the economies we study. Secondly, we are not taking embodied oil in imported goods into account. The same is true for imports of crude oil and refined petroleum products, which are then used as inputs for domestic products (other than refined petroleum products), and crude oil embodied in other imported products.

Two sectors were chosen to reflect the constraints experienced by an economy due to Peak Oil: "crude oil and gas extraction" and "petroleum refining" (referred to as "the oil sectors" in this text). These sectors were subjected to a 10% reduction of total output, which is in the same range as historical reductions of world oil and gas output during past oil shocks: Suez crisis (1956)—10.1%; Arab–Israel war (1973)—7.8%; Iranian Revolution (1978)—8.9%; Iran–Iraq war (1980)—7.2%; Persian Gulf war (1990)—8.8%) [26]. However, the actual percentage of the output reduction is not considered of ultimate importance here. The goal of this study is not to measure the potential extent of damage caused to an economy, when it is facing an oil supply restriction, but to contribute to a deeper understanding of the effects upon the actual economic structure of

Table 1
Partitioning the IO table in constrained and unconstrained sectors.

From (i)	To (j)					Total output ($\mathbf{x}_j$)
	Processing sectors			Purchase sectors final demand (Y)		
	Non-constrained		Constrained			
	Agriculture	Manufacturing	Energy	Households, etc.	Exports ($\mathbf{e}$)	
Processing Sectors (Z) ($I\times J$)						
Non-constrained						
Agriculture	z_{11}	z_{12}	z_{13}	y_1	e_1	x_1
Manufacturing	z_{21}	z_{22}	z_{23}	y_2	e_2	x_2
Constrained						
Energy sectors	z_{31}	z_{32}	z_{33}	y_3	e_3	x_3
Payments sectors ($\mathbf{W}$)						
Value added	w_1	w_2	w_3			
Imports (m)	m_1	m_2	m_3			
Total outlays $\mathbf{x}_i'$	x_1	x_2	x_3			

Table 2
Submatrices of Eq. (2.1).

P	$(k \times k)$ matrix containing the elements from the first k rows and the first k columns in $(\mathbf{I}-\mathbf{A})$. It provides the average expenditure propensities of non-supply-constrained sectors
R	$[(n-k) \times k]$ matrix containing elements from the last $(n-k)$ rows and the first k columns of $(-\mathbf{A})$. It provides average expenditure propensities of non-supply-constrained sectors on supply constrained sector output
$\mathbf{x}_{no}$	k-element column vector with elements x_1 through x_k; representing endogenous total output of non-supply constrained sectors
$\mathbf{y}_{co}$	$(n-k)$-element column vector with elements y_{k+1} through y_n, representing endogenous final demand of supply constrained sectors
Q	$[k \times (n-k)]$ matrix of elements from the last $(n-k)$ rows and first k columns of $(\mathbf{A})$ and represents supply constrained sector expenditure propensities on non-supply constrained sector output
S	$[(n-k) \times (n-k)]$ matrix of elements from the last $(n-k)$ rows and columns of $-(\mathbf{I}-\mathbf{A})$, and represents average expenditure propensities among supply constrained sectors
$\bar{\mathbf{y}}_{no}$	k-element column vector of elements y_1 through y_k, representing exogenous final demand for non-supply constrained sectors
$\bar{\mathbf{x}}_{co}$	$(n-k)$-element column vector of elements x_{k+1} through x_n, representing exogenous total output for supply constrained sectors

Adapted from Ref. [19, p. 332] and Ref. [24, p. 332].

such an economy. For the same reason we are less interested in the actual magnitude of the caused output reduction, than we are in the rankings of the affected sectors. In any case even if the supply shock was more than 10%, the total sectoral output reduction is bound to be very small, given the oil sectors' minor share of total value added: 2.2% (UK—1995); 0.98% (Japan—2000) and 1.63% (Chile—1996).

IO tables for the United Kingdom, Japan and Chile were chosen for this study, with the intention to include economies that would differ in terms of their endowment of oil and gas resources, i.e. of them being either net-oil exporters or importers. In addition, the disaggregation levels of their IO tables proved to be favourable for our purposes. We used a 1995, 138-sector, UK table; a 2000, 104-sector Japanese table and a 1996, 73-sector Chilean table. All tables are commodity-by-commodity. For those sectors that were intuitively expected to be most affected, no further aggregation was imposed. For the remaining sectors an aggregation to a meaningful level in accordance with the industry classification system was chosen and imposed, using the procedure outlined in Ref. [19, p. 174]. As a consequence, the disaggregation level was reduced to 39, 43 and 40 sectors for the UK, Japan and Chile, respectively.

3.1. Results

According to the rationale of the supply-constrained IO approach, the reduction of 10% of output of the oil sectors is distributed throughout the economy: Firstly, the simulated output change of the supply-constrained sector leads to a decrease in final demand of that sector, which is assumed to be mostly due to an increase in imports, for net-oil importers and a decrease in exports for net-oil exporters (here the UK only). The rationale behind this is that adjustments in household consumption would involve changes of household technologies and lifestyles, which are difficult to achieve in the short-run (changes in the transport system from private cars to public transport, installation of energy saving measures in buildings, etc.); equally, unfinished investment projects must be continued and plans for new investment are not yet accounted for, and adjustments in government consumption are also not possible in the short-run when budgets are committed.

Secondly, it modifies the multiplier matrix, which changes the technology structure and thus oil as a factor input. Other non-constrained sectors will show output reductions due to this change in multipliers and the same is true thirdly due to the backward linkages they maintain with the oil sectors. Table 3 summarizes our findings. It shows the 10 most affected sectors for each country in absolute (in the respective currency) and relative terms compared to their original outputs for the 1995—UK, 2000—Japanese and 1996—Chilenien economies. Relative effects are shown because they will be most important for the sector itself in terms of detrimental implications for its continuing profitable operation. Absolute effects, on the other hand, may be significant for the whole economy, as GDP may be reduced substantially. A large percentage decrease of output in a sector that is contributing little to GDP may be less harmful for the whole economy than a small percentage of an "important" sector such as "wholesale and retail trade".

As expected the reduction of endogenous output caused in the non-supply-constrained sectors by the reduction of available oil is rather minor in value terms, both absolute and relative. Relative to total value added (excluding the oil sectors), the UK shows 0.17%, Japan 0.027 and Chile 0.056% additional reduction in output.[1] However, as already mentioned above, it is not so much the magnitude of change itself that is of interest, but to see which sectors are hit more than others when facing a supply restriction of a key resource.

Relatively high impacts can be observed in the following sectors: electricity production, transport, finance/insurance and wholesale/retail. Electricity production is the only sector that shows significant impacts in all three countries both in absolute and in relative terms. Since the sectors' direct backward linkage, to the oil sectors are generally not very strong (e.g. 0 for oil extraction and 0.021 for refining in the UK), this result can probably be attributed to the change of actual factor inputs via modified multipliers. Hence the impact may be due to the electricity sectors' reliance on gas as one of its major direct intermediate inputs in most countries. In Japan it is the sector with the fourth largest decrease in output, while it is on position 7 in the UK and 10 in Chile in relative terms.

Hardly surprising is the relatively strong impact on the different transport sectors given their importance in today's globalised market economy. In Japan water transport is the most affected sector in relative terms and comes third in absolute terms, probably due to the sectors' dependence on overseas oil. Moreover "transport services" and "road transport are also among the ten most affected sectors in that country. In Chile "road freight transport" is the sector with the highest impacts in relative and the second most in absolute terms. Railway and air transport also feature in the 10 most affected sectors in relative terms. In the UK the most affected transport sectors are the railways at position four, before air transport and "ancillary transport and postal services". The high positions of transport by rail in the UK and Chile and by water in Japan could be attributed to their strong backward linkages to the oil sectors.

The merits of using IO analysis for this study are probably most obvious in the case of the "financial and insurance services" sector, where the extent of the inflicted reduction in output will be almost entirely due to indirect effects. The sector occupies position 6 in the UK and 5 in Japan in relative terms and comes first in the UK, second in Japan and seventh in Chile in absolute terms. Finally three very similar sectors namely "wholesale and retail trade" (UK), "commerce" (Japan) and "trade services" (Chile), all feature among the top four affected sectors in absolute terms, as one would expect given their general importance in modern economies. Although considering this sectors, reliance on transport, one would possibly expect even higher positioning, in particular, in relative terms.

Sectors that were expected to show higher impacts were primary sectors such as agriculture. Although its direct backward linkage will be minor, the reduced factor input caused by changes of

[1] These numbers are not reproduced in Table 3.

Table 3
The 10 most affected sectors for the UK, Japan and Chile; absolute and relative.

UK 1995			
Relative sector change	%	Absolute sector change	Mill £
Inorganic chemicals	−0.99	Financial intermediation	425.93
Manufacture—fabricated metal products	−0.39	Construction	147.21
Coal extraction	−0.23	Manufacture—fabricated metal products	89.29
Railway transport	−0.20	Wholesale and retail trade	71.42
Construction	−0.17	Manufactoring (other)	67.50
Financial intermediation	−0.15	Ancilliary transprt, postal services, telecom	54.43
Electricity production and distribution	−0.14	Electricity production and distribution	35.38
Manufacture—iron and steel	−0.14	Manufacture—machinery and applicances	25.48
Air transport	−0.13	Other land transport	22.05
Ancilliary transport, postal services, telecom	−0.10	Other services	17.82
Japan 2000			
Relative sector change	%	Absolute sector change	Mill ¥
Water transport	−0.328	Other services, office supplies, etc.	23,021
Transportation services	−0.142	Financial and insurance	19,590
Coal mining	−0.076	Water transport	13,800
Electricity	−0.073	Commerce	12,525
Financial and insurance	−0.051	Electricity	12,281
Reuse and recycling	−0.041	Transportation services	12,086
Road transport (except by private cars)	−0.025	Education, health and social work	6525
Organic chemicals	−0.023	Communication and broadcasting	4297
Gas, heat and water supply	−0.023	Road transport (except by private cars)	4085
Coal products	−0.020	Misc. manufactured products (1/3)	4049
Chile 1996			
Relative sector change	%	Absolute sector change	Mill. Ptas
Road freight transport services	−0.2513	Real estate, business services and housing	4047.63
Metal products	−0.0937	Road freight transport services	2926.93
Electric and non-electric machinery and equipment	−0.0843	Trade services	1688.74
Basic chemical products	−0.0831	Misc. manufactured products (1/2)	1033.60
Rubber products	−0.0771	Electricity	693.44
Railway transport services	−0.0763	Metal products	627.74
Real estate, business services and housing	−0.0601	Financial and insurance services	429.51
Glass and non-metallic mineral products	−0.0559	Electric and non-electric machinery and equipment	374.13
Air transport services	−0.0554	Hotel and restaurant services	355.30
Electricity	−0.0501	Glass and non-metallic mineral products	353.15

The colour code shows a spectrum from dark (more affected) to light (less affected) in relative terms, which is carried over to the absolute values to facilitate comparison.

the multipliers was expected to be of influence due to its dependence on artificial fertilizers and pesticides, both of which require oil and gas for production. However, surprisingly, even in Chile, where intensive industrial agriculture and fisheries are an important part of the economy (in particular with regard to exports) their combined changes (0.013%) are among the lowest.

Endogenous final demand of the supply-constrained sectors shows rather dramatic relative changes in terms of their original value. Table 4 summarises the respective changes of output and net exports for each country before and after the application of the model. As already mentioned above it is assumed that changes in endogenous final demand for the supply-constrained sectors will be fully met by changes in their net exports (exports—imports).

The differences between the net-oil exporter—UK—and the net-oil importers—Japan and Chile—are clearly reflected in Table 4. Relative reductions in final demands are much higher for Japan and

Table 4
Final demand and net exports of the "oil sectors" before and after the ten percent supply shock (numbers are rounded).

	Final demand ($\mathbf{Y}$) of oil sectors				Net exports ($\mathbf{E}^{net}$)		
	$\mathbf{Y}_{old}$ (before)	$\mathbf{Y}_{new}^{-10\%}$(after)	$\mathbf{Y}_{new}-\mathbf{Y}_{old}$	%	Before	After	%Δ
UK 95 Mill. £							
Crude oil and gas ex.	7630	6470	1160	−15	6200	5040	−19
Petroleum refining	6640	5480	1170	−18	1700	530	−69
Japan 00 Mill. ¥							
Crude oil and gas ex.	−1120	−8723	7603	−679	−7,122,093	−7,129,696	0
Petroleum refining	4,092,724	2,960,189	1,132,535	−28	−1,563,192	−2,695,727	73
Chile 96 Mill. Ptas							
Crude oil and gas ex.	500	−1300	1800	−377	−536,700	−538,500	0
Petroleum refining	201,400	119,400	82,000	−41	−294,500	−376,500	28

Chile than they are for the UK. However, the high percentage change of final demand for crude oil and gas of the net-oil importers (679% Japan, 377% Chile) has to be seen in relation to the fact that for any country deliveries of unrefined oil and gas to final demand are very small. Due to some decreases in stock, Japanese total final demand of crude oil and gas is altogether negative even before the supply shock. The only reason why deliveries are so high in the UK is because of exports. (Recall that final demand **Y** includes household, investment, government and export demand).

Instead of looking at the changes of final demand, it is more revealing to analyse the difference between net exports before and after the supply restriction. Negative figures for net exports on the far right-hand side of Table 4 can be seen as imports, while positive figures are exports. The UK is still a net exporter after the restriction, although its exports of crude oil and gas are reduced by about 20% and exports of refined petroleum by almost 70%. The dramatic reductions of 679% and 377% of final demand for crude oil and gas in Japan and Chile immediately drop to a mere 0,11% and 0.34%, respectively, if seen as an increase of net imports. In terms of refined oil products, however, it becomes evident that Japan will require almost a doubling of its net-imports and Chile an increase by nearly one-third. These are very serious developments, which are bound to change the face of these economies.

3.2. Limitations

The results described above have to be interpreted with caution as several limitations apply. We are aware that we used a static model for a process that is inherently dynamic. However, the purpose of this research was not so much to deliver final quantitative results, but to assess the effects of a sudden shock and its ripple effects throughout the economy during a short time period. For this type of analysis the systems approach of IO analysis (even if static) is very suitable.

Moreover, a further simplification, as already mentioned, is that we did allow imports to increase. If imports were restricted, then the reduction in total final demand would have to be absorbed by all of the different final consumers, either according to their original share, or on the bases of some externally determined preferences (cf. 24]). Thus one may, for example, argue that oil for heating homes should receive priority over government use of fuel for military purposes. In other words the government could impose some kind of rationing system. If this were not sufficient or not adequate, such a rationing system would have to look at reducing intermediate demand. According to certain criteria, some industries could again be given preference in receiving their share of oil and gas supply. Hubacek and Sun [24] in their study applying supply constraints on land have, for example, prioritised sectors according to their creation of value added per unit of land (land allocation according to highest and best use). This strategy favoured the labour intensive service sectors, which received their land share first.

This simplification also implies that we ignore the international perspective of Peak Oil by only looking at one region at a time. Moreover, ripple effects throughout the world economy affecting production and consumption of other countries and thus the import prices and exports of the country under investigation, are not considered. For example, reductions in outputs in the oil sectors of one country would have effects on production of exports for this country to other regions. Thus, a single country approach is likely to underestimate the overall effects. The application of a multi-regional or World IO model could address this limitation but would be very data intensive. However, for future studies this is certainly a matter of interest, and in fact, a number of ongoing studies working on developing global IO models [27,28].

Finally, this study only covers the quantity dimension of the Peak-Oil phenomenon. The authors are aware that there is also a price dimension, which shall be addressed, using the Leontief price model, in future studies. As already mentioned this paper is to be understood as a first venture into this very important topic using the IO framework.

4. Conclusion

As it was argued above, there is an urgent need for the development of methods and models to analyse the possible implications of Peak Oil in particular and resource supply disruptions in general. The input–output framework provides a good base for this purpose. It has long established and refined methods based on real world data provided from most statistical offices which allows for cross-sectional analysis and comparability across countries. However, as one of the assumptions of the demand-driven Leontief model is that supply is perfectly elastic for every input, it is unsuitable for analysing supply constraints. The review of two alternatives showed that the intuitively most attractive supply-driven model is based on very restrictive assumptions. This is unfortunate since it seems perfectly rational to make the industries output dependent on the output of the oil sectors, considering the dependency of world economies on oil and gas.

The supply-constrained or mixed model on the other hand has much more favourable properties. It has been demonstrated that it is a highly promising candidate for analysing the quantity dimension of Peak Oil, which is why it was chosen for a first cautious empirical analysis in this study. Despite the limitations of this first application, there are already some very interesting insights to be gained. The study already allows some conclusions as to which sectors are the most vulnerable to oil supply constraints in the studied countries. For example, while one would expect to find the transport sectors to be highly affected it is very interesting to see the high ranking of the "finance and insurance" sector, whose links with the oil sectors are less visible.

Input–output analysis has frequently been criticised for its constant production coefficients. But this is rather a virtue in the context of this study. Production technologies cannot be replaced instantaneously and thus fixed coefficients allow the evaluation of short-run effects of supply shocks, damages through environmental events or other human-made catastrophes. Thus IO has proven to be very valuable for risk assessments as performed in this study.

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