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Towards a model predicting freight transport from material flows

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Abstract

Material flow analysis generates highly aggregated indicators for the material „scale" of national economies. Similarly, transport statistics operate with indicators for the scale of freight transport. This paper presents a model that seeks to predict this scale of freight transport from material flows. The model is developed conceptually and put to two preliminary quantitative trials. First, it is used to predict the change in freight transport in the United Kingdom during the last six decades from material flows; second, it is tested for its ability to explain the 135-fold increase in freight transport worldwide during the twentieth century.

Introduction

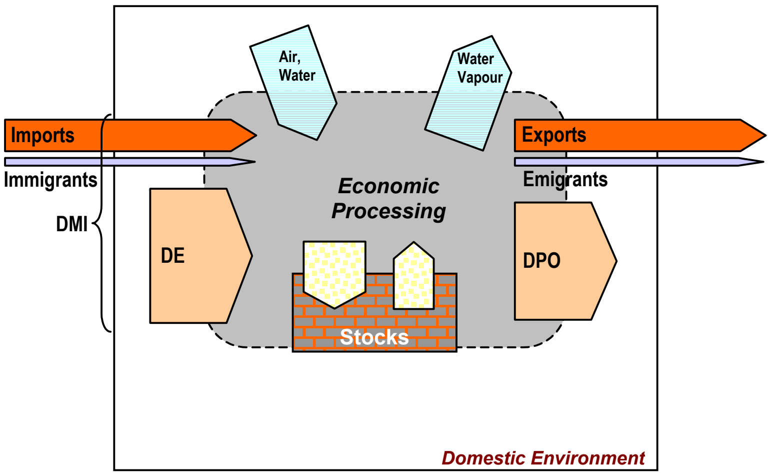
The question asked in most literature on freight transport is the question HOW. How is freight to be transported, by which mode, which infrastructural networks, which vehicles, at what risks and at what cost (Owen 1987). This also holds for most literature on transport and environment: environmental pressures are primarily associated with the modes of transport; analyses performed and solutions sought focus on how to produce less environmental damage with a given volume of freight transport (Grübler and Nakicenovic 1991; van Veen-Groot and Nijkamp 2001; Feitelson and Verhoef 2001; OECD 1993). In contrast, the model presented here asks a different question: it seeks to explain the volume, the scale, of freight to be transported. For such an explanation, material flow analysis has something to offer.

Material flow analysis generates highly aggregated indicators for the material "scale" of national economies. Such indicators now exist in a methodologically standardized way (Eurostat 2001) for all countries in the European Union and for quite a few beyond (Matthews et al. 2000; Eurostat 2002). What I am attempting here is to link those material flows to a socio-economic activity of outstanding environmental relevance: freight transport. The environmental relevance of freight transport is at least twofold: on the one hand, it constitutes an environmental burden wherever it takes place (across territories, oceans and in the atmosphere) in various respects, from pollution to noise to health hazards. On the other hand, freight transport is a biophysical / technical prerequisite for the ability to use distant territories (their resources, their production platforms, their purchasing power...), inextricably linked to the ability to spatially re-distribute environmental loads (Muradian and Martinez-Alier 2001). Whatever consequences one wishes to bring into focus, it is out of question that freight transport matters environmentally. I will make an attempt to demonstrate material flow analysis to provide key variables driving freight transport.

Relating “Freight Lifted” to the Direct Material Input of national economies

How is the volume of freight transport related to material flows? By common sense reasoning, it should be expected that an increase in material input into a country’s economy (such as reflected in Direct Material Input [DMI][1], one of the standard core indicators of material flow analysis) should boost the volume of freight transport within this country. DMI comprises the total volume of materials extracted from the domestic environment to enter economic processing, plus the total volume of imports from other countries, expressed in tons per year (Eurostat 2001).

figure 1: The material metabolism of a national economy



DE: Domestic extraction
DMI: Direct material input = DE + Imports
DPO: Domestic processed output

Source: (Matthews et al. 2000), slightly modified.

How is this total amount of materials processed in an economy, and what is the role of transport? Each ton enters the domestic economy either by primary extraction within the country (such as agricultural produce, timber, mineral ores, sand and gravel for construction or fossil energy carriers), or through the customs at a border as imports from other economies. The material will then be processed through several stages, from the extracting primary sector to manufacture, from manufacture to commerce, from commerce to consumers, and from consumers to waste deposits; or, alternately, it will be exported to another country. What does this mean for freight transport?

Let us first look at one of the common macro indicators for transport: “Freight Lifted” (FL). This indicator expresses the volume of freight loaded on transport vehicles for a haul in tons per year. Each time goods are loaded for transportation (irrespective of the distance

[1] It is called “direct” material input to make aware that there exists also “indirect” material input that does not enter the production chain of the focal economy, but has been part of the production chain of those economies that produced imports to the focal economy (Eurostat 2001).

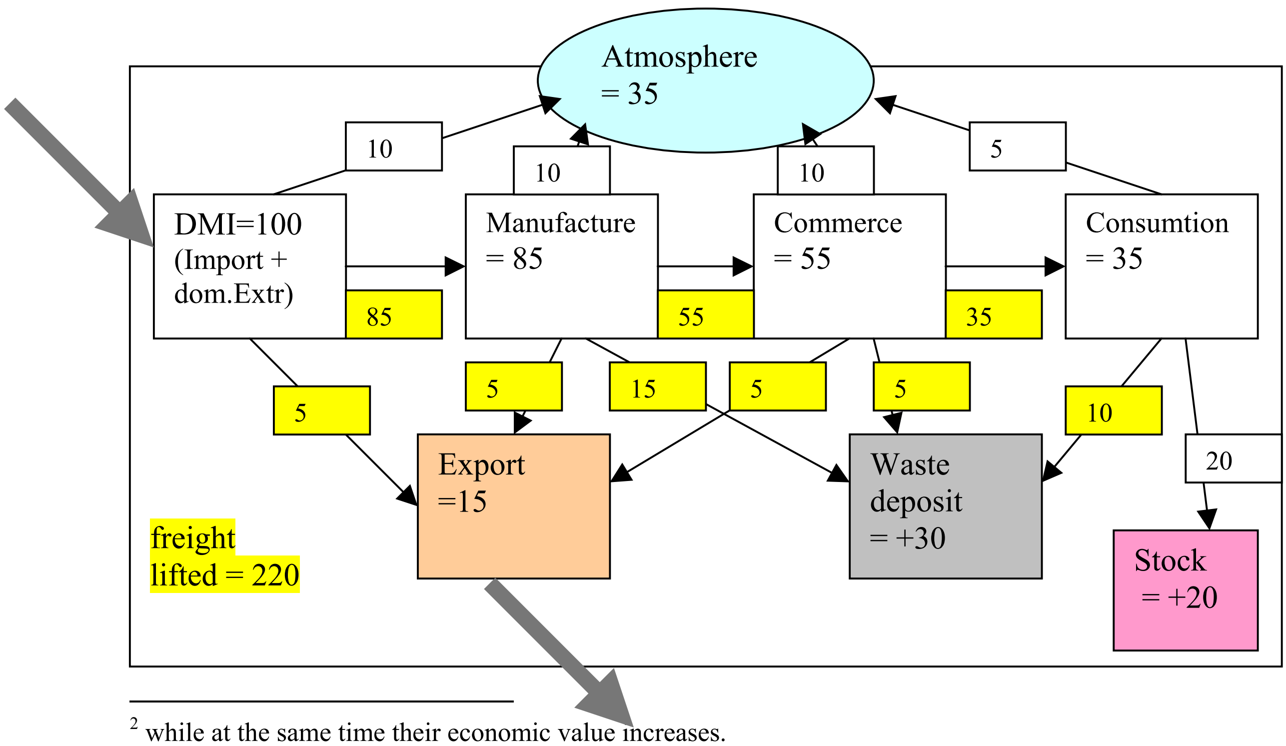
they are going to be transported), their weight is counted. Let us now suppose – however implausible – that *all* material inputs into the national economy would be directly delivered to their final destination: then Freight Lifted (FL) would be equal to direct material input, DMI. This would be the case irrespective of the number of final destinations to which it would be delivered – many customers would only mean that the volume is divided into small portions that are then added up again for the indicator. It would make a difference, though, if these customers were ordered sequentially, and the same tons were lifted for a haul several times – which is exactly what we have to expect in a production-consumption chain.

What we can deduct from this reasoning is that Freight Lifted is a simple function of DMI and the number of (spatially differentiated) stages of processing, in other words, the length of the production-consumption-disposal chain.

[1] Freight Lifted (FL) = Direct Material Input (DMI) * Chain Length

We have to consider, though, what can be learned from material flow analysis: While for the total economy it holds that Input = Output + Stock Change, the amount of materials that are handed down the chain from extraction to consumption decreases from stage to stage[2]. This is because at each stage, wastes and emissions are generated that either dissipate into the atmosphere (such as the remains from energy carriers when burnt or digested), and therefore don't have to be transported at all any more, or have to be transported to a waste deposit only.[3] Taking into account the knowledge we have from studies analyzing material input and output on the level of national economies, we can construct a first approximation to estimating Freight Lifted from DMI (see figure 2).

Figure 2: A first approximation for how DMI translates into Freight Lifted



[2] while at the same time their economic value increases.
[3] On top of this, there are also emissions to water that do not have to be transported, but their volume is so small that we disregard them for simplicity (Matthews et al. 2000).

Figure 2 describes, for a model DMI of 100 tons, the material flows within the economy in the most simple way that is still roughly comparable in proportions to what we know from MFA studies on industrial countries (such as Matthews et al. 2000)[4]. In this figure, transfers between boxes that require bulk transport have been shaded. If we add up all the numbers in the shaded fields, we arrive at a "Freight Lifted" of 220 tons per year, that is the 2.2 fold of DMI. This factor 2.2 can be interpreted as the average number of stages each tonne of DMI undergoes, or the average number of times each tonne is loaded to a transport vehicle.

From this model, we can also estimate what "Freight Lifted" for example would be like if the transfer from commerce to consumers, and the transfer from consumers to waste deposits were not part of freight transport (because it would be done by walking/carrying, or by private car transportation)[5]: then the factor would amount to roughly 1.7. On the other hand, we can guess what would happen if the chain of manufacture or commerce became more differentiated: each additional stage would increase this factor. This increase would always amount to less than 1 (because there always are losses in weight from one stage to the next). According to our model as sketched in figure 2, if we introduced a distinction between wholesale and retail trade, we would increase the factor by roughly 0.4[6]. If we introduced another stage of manufacturing, the increase would be higher: it may come close to 0.85[7].
So we should expect for industrial countries "Freight Lifted" to amount to something between a little above DMI (in case there is a substantial subsistence sector that feeds directly from extraction to consumption) to up to maybe the threefold of DMI. So theoretically, even if we know very little about a county's economy, DMI should be a fairly good predictor of freight transport.

The quality of this prediction, of course, depends on knowledge about the composition of DMI. In relation to freight transport, the standard large fractions of DMI - fossil fuels, biomass and construction minerals – have a different profile. By the knowledge of the amount and composition of fossil fuels (that usually make up about a third of DMI or more), for example, you could tell the impact upon freight transport. While coal tends to be delivered by train and then be reloaded to trucks, gas by contrast is delivered by pipeline to the end user and counts only once for "Freight Lifted", therefore. Most fossil fuels get burnt, so they end up as emissions to the atmosphere rather than be transported to waste deposits. Biomass, on the other hand, if broken down to major fractions, can also be traced

[4] One simplification employed is that we do not make a difference between "waste disposal" and "dissipative use" (such as with fertilizers in agriculture). So the numbers for waste disposal include dissipative uses. Another simplification was to express all numbers in multiples of 5 tons – I did not wish to suggest a numerical refinement beyond that.
[5] what is statistically counted as "freight transport" is confined to what also is called "bulk transport", thus distinguishing it from "diffusion transport" (Clark 1998). It makes sense to think of persons carrying goods, be it on foot, by bicycle or private car, as "diffusion transport". This, at least, is the way it is dealt with in transportation statistics.
[6] We arrive at this number by assuming wholesale trade to receive, as in figure 2 above, 55 tons from manufacture, to produce 5 tons of atmospheric emissions, 5 tons of waste and 5 tons of exports. Then it will deliver 40 tons to retail trade, which will produce another 5 tons of emissions to air and deliver 35 tons to consumers. Everything is equal except for the extra delivery 40 tons that add to freight lifted.
[7] Since manufacturing, according to the model in figure 2, receives 85 tons from the primary stage, it is bound to deliver less than that to a second stage of manufacturing, since every production process involves some kinds of waste. If we allow for manufacturers on stage 1 also to deliver directly to commerce (without an in-between manufacturing stage 2), then the additional stage may increase freight lifted by less than the 55 tons finally delivered from manufacture to commerce.

well. The amounts grazed will, to a high extent, immediately end up as atmospheric emissions; so will a large proportion of animal feed. Raw materials for human food will typically undergo a long chain of manufacture, whole-sale and retail trade. So, as a research program, it probably would make sense to look into the fractions of DMI, and thereby specify and refine the above equation [1].

Another path towards refinement would be based upon a better representation of economic sectors and their specific consumption patterns. From their fuel input, for example, it can be predicted what part of their consumption will end up as emissions to air (and never as a weight for freight), and the above chain can be adjusted to more realistic values. Methodologically, there is a lot of promise in this direction through so-called PIOTs (physical input-output models of national economies) that deliver exactly the kind of data needed.

So the issue of how to relate the standard transport indicator "Freight Lifted" to the core indicator from MFA, "direct material input", seems to be settled – at least theoretically.

Relating "Freight Moved" to some aggregate biophysical, technical and economic parameters

But what about the second major macro indicator, "Freight Moved"? Technically, the following equation holds:

[2] Freight Moved = Freight Lifted * Length of Haul[8]

How can we relate the (average) Length of Haul, that is the distance the freight, once hauled, will be transported, to other biophysical variables? I will discuss four possible candidates. The first candidate is a geographical one: (1) the spatial distance between the actors involved; the second candidate is a matter of economic organization: (2) the number of deliveries (actors * frequency) required; the third candidate is of a technological nature: (3) the tonnage of the vehicles used for transport (and the modal split between them); finally, the fourth candidate is strictly economic: (4) transportation cost per ton kilometer (tkm).

(1) the spatial distance between resources and actors, and among actors.

One very simple determinant of spatial distance, if we are analyzing the amount of freight transport within a given territory, is the size of this territory. The distances of transportation should relate to the square root of the surface area (maybe with some corrections for the deviation from a square form: rectangular territories, stripes, for geometrical reasons have larger distances relative to their surface area). For resources that are more or less evenly distributed over the area, and that have to be collected and concentrated at the centers of human settlements (such as agricultural produce), the assumption average distances corresponding to something like 2/3 of the radius of the territory of this settlement might be appropriate. For each group of resources, one would

[8] Physically speaking, "Freight Lifted" is proportional to mass, while "Freight moved" is related to work, respectively to energy. Why this is so, can be argued as follows: force = mass * acceleration. Acceleration in our case (lifting freight) is determined by gravity and can, therefore, be supposed to be constant. Energy = force * distance. Here, not just gravity, but also speed and technical conversion factors play a major role.

have to consider distances separately. Construction materials, like sand and gravel, probably are taken from vicinity, more or less. In all cases, considering the composition of DMI by major groups of materials will help to make realistic assumptions about transport distances. For the distances between actors (such as primary extractors, manufacture, retail and consumers) there is also a role for settlement patterns, and for the spatial distribution of economic activities. As a research strategy here, I would suggest to review various indicators from regional planning and test them for their validity in representing the average geographical distance between actors. The focus should be on how far from each other they may be located, across the whole territory.[9]

(2) The number of deliveries required (frequency of delivery per time period)

Technically, the number of deliveries equals the number of actors times the frequency of delivery – in other words: how many times do the existing distances have to be overcome? Let us first take a look at the number of actors. The difficulty to be resolved here lies in the interdependence of numbers of actors and distances: on a given territory, we may either expect few actors far apart (such as, for example, large supermarkets), or many actors in close distances (small groceries). If we now think of actors on the same functional level of the production-consumption chain, we should assume deliveries to occur in one sequence (e.g. bread to many groceries, or waste collection from all households in an area). Thus, for distances to be traveled, many dense locations might amount to roughly the same as fewer, less dense locations. So let us, for simplicity, ignore the number of actors on each functional level. What remains important, though, is the number of functionally different stages: You cannot expect to deliver to a secondary producer and a supermarket in one and the same trip. But this variable, as we have seen, is already included in the indicator "Freight Lifted" as discussed above. So there is no reason to include it here a second time. The conclusion from all this, for a first approximation, seems to be that one may disregard the number of actors for this variable altogether, and just consider the question of frequencies of delivery. How could this be approached?

There has been a lot of discussion on "just-in-time" delivery, saving cost for reloading and storage. "Just-in-time" delivery makes it more difficult for the transport company to serve several customers on one roundtrip and will, therefore, increase the number of rides, while the freight loaded per ride will decrease. So increasing flexibility should have no effect on "Freight Lifted" (for Freight Lifted it makes no difference whether you have 10 rides with one ton each, or one ride with ten tons), but a substantial impact on distances traveled. Thus, with an increasing demand on flexibility, we should expect the frequencies with which given distances are covered, to rise.

(3) The tonnage of the vehicles used (distribution across whole fleet)

In as far as transport companies may be expected to behave economically, they will seek to a) invest into vehicles they can use best, that is buy vehicles that have an appropriate tonnage, and b) seek to maximize the load factor of the existing fleet. Thus, although this may occur with a certain time lag, the tonnage of the fleet (or of the transport containers) represents the expectation of transport companies of how much weight they should haul at

[9] The question gets more complicated once you do not take the whole territory as the given spatial unit ("container") for interconnected economic actors, but consider that there may be a (socially and economically evolved) regional structure that leads to strong interconnections within but fewer between regions. In this case, you would have to work with network models to generate an indicator for distances.

a time. This, somehow, should correspond to the inverse of frequencies of delivery, for a given volume.

[3] Frequency = Freight Lifted / average tons per haul

The charm of this indicator is twofold: On the one hand, it introduces an independent information (that is usually statistically available) to check on the other interrelations and bring the model away from tautology. On the other hand, because of time lags, it might be helpful for anticipating trends in the future. If DMI, like in Europe during the last decade, stagnates, and the fleet decreases in tonnage per vehicle, then we may expect frequencies to increase, but not distances per haul.[10]

While all biophysical indicators discussed so far constitute something like functional framework conditions or technical options, one major driver for dynamics still remains to be named: transportation cost.

(4) Transportation cost per ton kilometer

Under pre-industrial conditions, as everything almost entirely depends on the same energy source (namely: biomass as food and feed, converted by endosomatic metabolism), the economics of the distances for bulk goods to be overcome by transport is determined energetically: if the drivers of the carriage plus the draught animal consume more energy for a certain distance than it can load at the start of the journey, than the trip is obviously uneconomical. Thus, depending on geomorphology and transport infrastructure, the still-economical distances for land transport tend to be very small.[11] Today, such a technical energetic limit may still be relevant for interstellar transport, but not on earth territory. What always mattered and still does is the relation between the locality-specific price variations and the cost per unit transport (tkm). If, for the same commodity, source A is 100 km away, and source B just around the corner, the 100 km-transport will only happen if the offer from A is so much cheaper that the difference covers at least the transportation cost. With transportation cost being subsidized by public infrastructure, and with cheap fuels, the economic radius will expand. On top of this, a self-reinforcing process will evolve: with low transportation costs prevailing, producers and sellers can specialize, and so the radius for the availability of a particular commodity will increase. Customers increasingly will not find a producer/trader of the same commodity but in quite a distance. And this dynamics should hold on any scale level of territory.

Because of these considerations, and because prices for transportation have been growing slower than GDP during the last decades, I would expect the average distance hauled to increase, and to do this at about the difference of growth rates of transportation cost to GDP-growth. This, admittedly, is a wild hypothesis, the outline for a research effort still to undertake.

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[10] All this gets more complicated once multimodal freight transport is considered, with all the technical interdependencies this implies (Organization for Economic Cooperation and Development 1997), and the time-lags that come with these interdependencies.

[11] Boserup (1981) named 7.5 km as a typical radius for land transport in rural agrarian systems. We have attempted to do some more detailed model calculations on the basis of historical data (see Fischer-Kowalski, Krausmann & Smetschka, 2004).

Checking for plausibility: Material Flows and transport in the United Kingdom in the past seventy years

There is some evidence to be gained from research recently done by (Schandl and Schulz 2002) on society's metabolism and Schulz (Schulz 2003) on transport of the UK. Approaching the problem from a material and energy flow perspective, Schulz calculated several of the indicators discussed here for the 60-year time period from 1937 to 1997. I wish to discuss some of the interrelations that have been stated theoretically above.

The clearest relation can be established with what I had termed "chain length": this factor, expressing the relation between Freight Lifted and Direct Material Input (FL/DMI), is indeed in the expected range: it varies between 1.8 (for 1937) and 2.75 (1965). It could have been any other numbers – but, fortunately for me, the empirical data for the UK comply exactly to the order of magnitude I had been predicting with my model visualized in figure 2. But, on the other hand, by my very general considerations I am unable to explain the ups and downs in the factor for the period from 1965 to 1995 (a period of substantial restructuring of the British economy). The fact that the numbers have been lower in the pre-war period I interpret as a lower degree of differentiation/specialization of producers, which seems quite plausible.

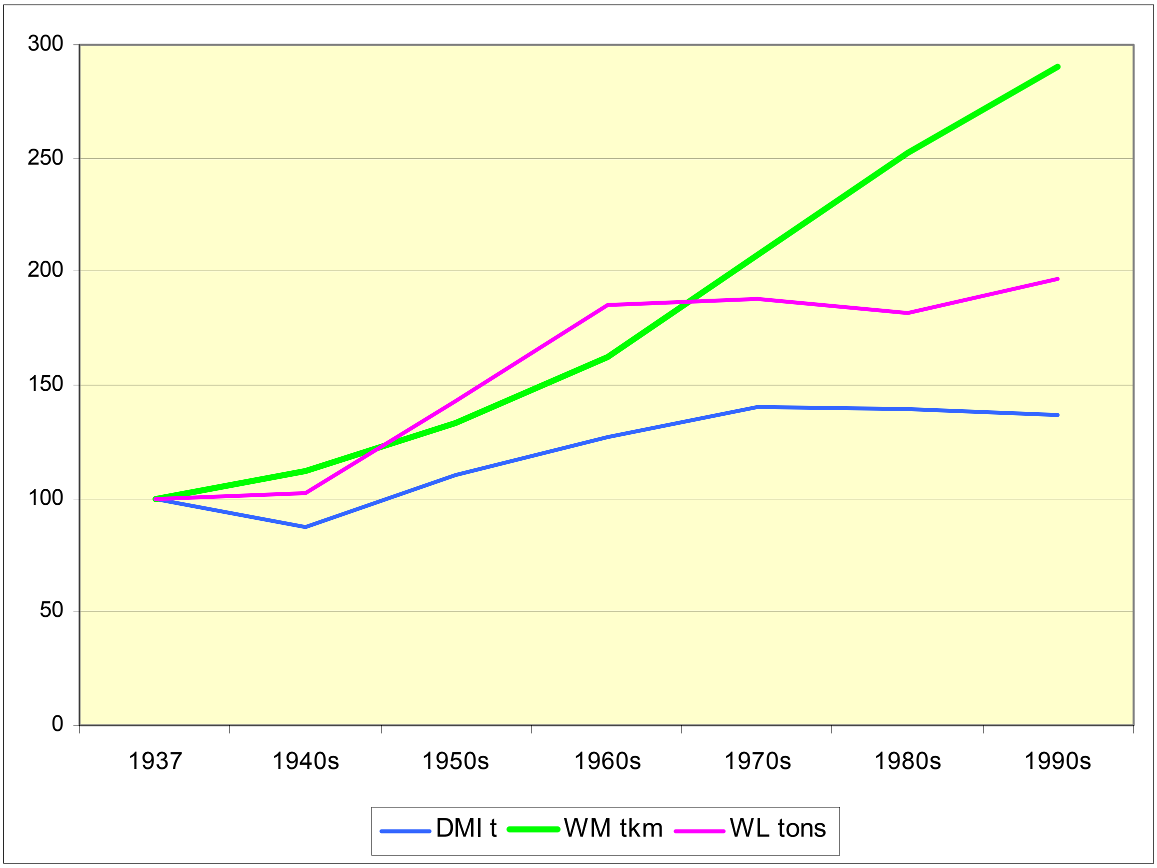
Of course, such a result for just one country tells not yet anything about the validity of the theoretical considerations – but it certainly is reassuring to find data not to contradict the theoretical assumptions.

Table 1: Some indicators for material flows and freight transport for the UK, 1937-1997

YEAR		1937	1945	1955	1965	1975	1985	1995
DMI mio t		490	390	600	710	780	790	830
Freight Lifted mio t (FL)		880	750	1350	1950	1900	1850	2150
chain length (FL/DMI)		1.8	1.9	2.25	2.75	2.4	2.3	2.6
Freight Moved bio tkm (FM)		65	75	95	130	155	190	235
distance hauled per lift km (FM/FL)		74	100	70	67	82	103	109
each ton is hauled for ...km (FM/DMI)		133	190	158	184	197	237	283

source: own calculations from (Schulz 2003)

Figure 3: The dynamics of DMI, freight lifted and freight moved for the UK, 1937-1997

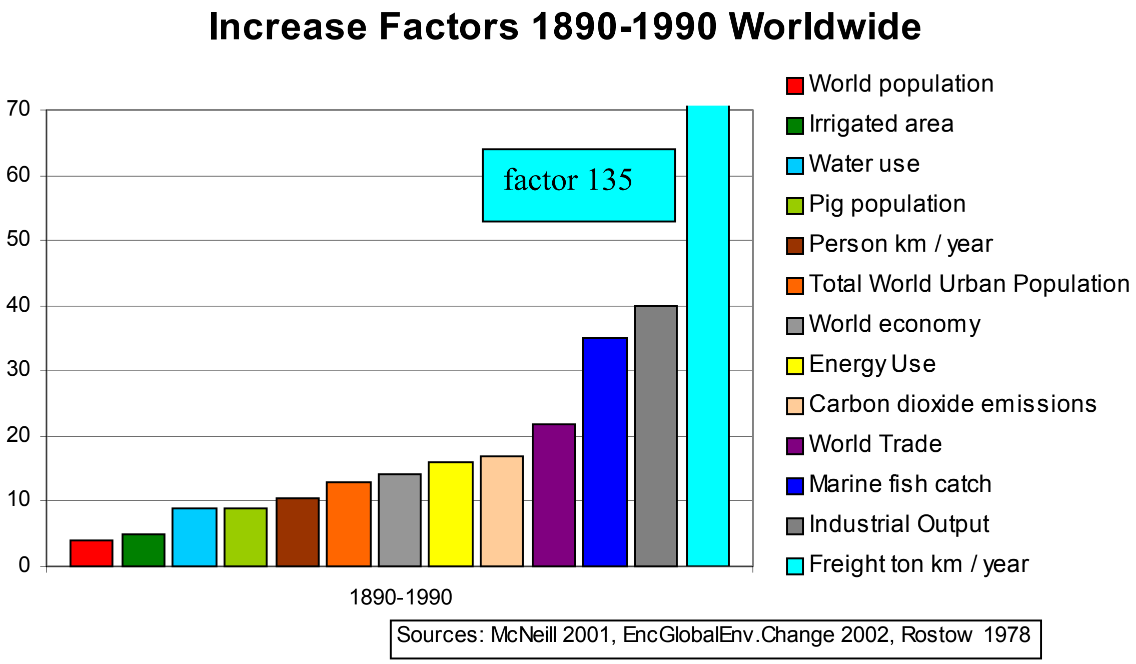


For the distance hauled (per lift), my assumptions cannot be checked with the data from Schulz, since he does not give numbers for tonnage nor transportation cost. What is interesting to note, though, is that the distance hauled per lift had remained pretty constant until the mid-Sixties, and then rose very rapidly. As a result from both an increase in chain length from extraction to consumption and deposition, and an increase in average distance per haul, each ton of input into the British economy travels much farther now than it did decades ago; while it used to travel 133 km before the War, it already was transported 200 km in the mid-Seventies, and now its journey is approaching 300km. This, be aware, is only the distance it travels within the UK, and does not include distances covered by international trade. The UK has not changed the size of its territory in that period, and it has become more densely populated, so actors should in principle be closer to one-another. Nevertheless, transport distances keep growing substantially. Whatever the magic of globalization, according to my considerations above, one should look for transportation cost per ton kilometer as an explanation: my hypothesis is they rose markedly less than GDP.

Plausibility check 2: Can the model explain why freight transport worldwide is exploding?

Indicators for freight transport in the twentieth century show a dynamics more explosive than any other symptom of growth and globalisation. (McNeill 2000; Tolba 2002). As we know from other sources, the transition from an agrarian socio-metabolic regime to an industrial socio-metabolic regime involves a three- to fourfold increase in per capita resource consumption (DMI/cap) (Sieferle 2003; Weisz et al. 2001). During the same period, the human world population has increased about fourfold. If we, for simplicity's sake, assume that all of the world's population has switched from an agrarian to an industrial mode during the last century, we arrive at a roughly twelvefold increase of material input to human economies (DMI). In a next step, we may assume – in accordance with empirical analysis presented elsewhere (Fischer-Kowalski, Krausmann & Smetschka, 2004) – the transition from the agrarian to the industrial mode to imply at least a doubling of stages in the chain from extraction to deposition. Thus we would expect Freight Lifted (FL) to have increased about thirty fold. If Freight Moved (FM) increased by a higher rate, this would have to be attributed to an increase in transport distances (per haul).

Figure 4: "Explosions" in the 20th century



According to the Encyclopedia of Global Environmental Change, we find an increase in worldwide freight transport (Freight Moved) by a factor of 135! (Tolba 2002, see figure 4). So we are – after this very rough and dirty calculation – left with an "unexplained" increase by factor 4-5. Have freight transport distances (per haul), on the average, undergone a four to fivefold increase during the past century? This is not completely out of frame, since ocean transport grew twice as much as all freight transport (FM; see Tolba 2002), and of course it covers the largest distances. So I feel this model might be adequate to explain such huge long-term increases.

These swift intellectual exercises though, of course, provide with no more than a little reassurance to move ahead with further, more in-depth inquiry.

Conclusion: What can be learned from this model?

Whatever the – still fairly vague – numerical details, a few conclusions can be clearly drawn. The most important of these conclusions is that the direct material input of an economy, multiplied by a factor somewhere between 1 and 3, determines the volume of freight to be transported (FL). With a given division of labour, you cannot reduce the freight to be transported without reducing direct material input. Put the other way round, this means that any "dematerialization policy" within a given economic structure will, as a probably welcome side effect, reduce transportation. Since reducing transport also means saving on energy, there will be an extra bonus of reduction. Moreover, this effect of dematerialization policy on transport should, according to the model presented here, occur irrespective of transport cost. Inversely, it is hard to imagine how such a reduction of transport could be achieved only by increasing transportation costs, for example by road pricing. The transportation cost factor should be most effective in influencing the "distance-multiplier" that translates Freight Lifted (FL) into Freight Moved (FM). But here relations get more complex: both cost and environmental impact depend upon infrastructure, modal split, intermodal coordination and many more factors extensively discussed in literature on transport. This to me seems an area where material flow analysis does not have much more to contribute. But for transportation volumes (FL) material flow analysis delivers exactly the kind of information required.

Acknowledgement
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