The Rupture Index *

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*** An informal model of the global fossil fuels supply chain as a scale-free network**

[editor's note, by Dave] Throughout, I will refer to the the **global fossil fuels supply chain** construed as a network by the acronym **GFFSC**. There is only a little math in this post. I will be referring to some pages where they do the math. This is meant to be a "naive", intuitive treatment. The mathematicians among us can take the ball and run with it.

I spend a lot of time worrying about ruptures in the GFFSC and what their effects will be. Standardly, these are called *oil shocks* at TOD. I just picked up the July 1-7 issue of New Scientist and there were two related articles of interest to me, "The Net Reloaded" and "Life is Unpredictable". Sorry, they are both behind a paywall. But I will refer to them in the text below. Ever since Stuart had mentioned Didier Sornette in his excellent post Is Oil In A Price Bubble?, I had also been thinking about so-called *endogenous* versus *exogenous* origins of crises, as Sornette puts it. The latter are forcings from outside the network. In other words, oil shocks. The former are due to the inherent self-organizing nature of the network itself.

Finally, it occurred to me to model the GFFSC as a scale-free network somewhat analogous to the internet and see where that went. I have never seen this kind of analysis done before and thought it would be interesting as a new take on peak oil and our current dilemma.

If you are worried about oil shocks, it is natural to ask the questions "what are the *hot spots* we need to worry about" and "what is the overall tolerance of the GFFSC" to ruptures in production or consumption of fossil fuels in those places. A related question involves the *degree of disruption* in a given place (if we can define that).

The standard theory of scale-free networks is that they follow a power law distribution. But before we get into that, let's make the basic analogy between the GFFSC and the internet. Our naive model runs as follows.

1. A node in the network is a country.
2. A link (or *connection*) in the network is the exchange of some fossil fuel between two nodes.
3. Nodes have links to themselves. This is simply the case where fossil fuel production is used to meet domestic consumption. On the internet, this is a analogous to internal links within a website.
4. Links come in two flavors, outgoing (exports) and incoming (imports) with respect to some fossil fuel. Links are always reflexive ie. bidirectional (my exports are your imports). On the internet, site X may link-in site Y but not vice-versa. In other words, X exports traffic to Y and Y recieves imported traffic from X. In this sense, the analogy holds and the lack of

across the board cross-linking makes no difference to this analysis.

5. Links are not all created equal. They must be weighted (as is done in neural networks). The *weight* for a given fuel (eg. natural gas) could be simply the amount moved along the link in one direction or another, in this case as measured in billion cubic feet per day. Generalizing, one could use British Thermal Units (btu) to measure the weight, thus covering all fossil fuels. Importantly, weights apply to intrasite (domestic consumption) connections.

And that's it. Pretty simple, hey? Just like the internet except for the *weight* (#5 -- although we could make an analogy there, too). Looked at this way, a number of the stories we write or the comments that are posted are about *changes in the network* including

- new (or recent) connections (Angola/China for oil)
- stronger/weaker connections (US/Qatar for natural gas)
- lost, or *dropped* connections (Indonesian exports for oil)

Finally, I must mention two aspects of the GFFSC not covered here. First, *inventories* are discounted. I consider those to be fossil fuels that have already been delivered (if imported) and as hedges against lost connections. Second, *spot cargoes* are "free floating" links looking for an attachment. They are not directly considered here but do highlight the dynamic nature of the GFFSC.

Now, from Wikipedia (see the scale-free link above):

> A scale-free network is a specific kind of complex network that has attracted attention since many real-world networks fall into this category. In scale-free networks, some nodes act as "highly connected **hubs**" (high degree [of connectivity]), although most nodes are of low degree....
>
> In physics, such right-skewed or heavy-tailed distributions often have the form of a power law, i.e., the probability P(k) that a node in the network connects with k other nodes was roughly proportional to k−γ, and this function gave a roughly good fit to their observed data.

Pursuing our analogy, Russia or the US are both hubs -- they are highly connected. Outer Mongolia and even Chad are not -- they have a low degree of connectivity.

But here we need a **conjecture** and an **assumption**. The conjecture is that if we assessed and counted all the import/export links in every country of the world, we would get a power law distribution. The assumption is that the conjecture is true. In any case that is my intuition about the GFFSC ie. that it is like the internet, it is scale-free to some large extent. But to strengthen our conjecture and assumption, we must add in the *weight* W of the connections to the degree of connectivity. So, I am really assuming that the measure of a country's importance in the network comes from some function *f(D,W)* where D is the degree of connectivity. A hub has a high value for *f*, a singly connected node (eg. the Falkland Islands) has a low value. Once we've made this move, I believe that the conjecture becomes much more plausible. One large difference between the internet and the GFFSC, however, is the overall size.

There are only so many countries in the world but the internet is made of literally billions of nodes. We could consider individual *oil fields or producing basins* as nodes in our GFFSC graph. This would make the network bigger but still considerably smaller than the internet. However, the power law distribution can apply to a smaller network. The standard use of the power law in the analysis of the peak oil situation applies to oil field reserves as Khebab did recently in What can we learn from the oil field size distribution? originally from his Graphoilogy weblog. Highly recommended. His analysis considers the top 2092 world oil fields (excluding the US and Canada) with sizes greater than 50 Mb (million barrels). Specifically, I am making the claim that S(g) is close to 1 as shown below.

> Although the scientific community is still debating the usefulness of the scale-free term in reference to networks, Li et al (2005) recently offered a potentially more precise "scale-free metric". Briefly, let g be a graph with edge-setε, and let the degree (number of edges) at a vertex i be di. Define
>
> $$s(g) = \sum_{(i,j)\in\epsilon} d_i d_j$$
>
> **This is maximised when high-degree nodes are connected to other high-degree nodes**. Now define
>
> $$S(g) = \frac{s(g)}{s_{max}}$$
>
> where smax is the maximum value of s(h) for h in the set of all graphs with an identical degree distribution to g. This gives a metric between 0 and 1, such that graphs with low S(g) are "scale-rich", and graphs with S(g) close to 1 are "scale-free". This definition captures the notion of self-similarity implied in the name "scale-free".

Visually, a power law distribution often looks like this.

Highly connected nodes and a power law (non-gradual) relaxation

Looked at another way, here's Wikipedia's illustration of a scale-free network.

The dark nodes are hubs -- Click to Enlarge

My strong intuition is that the GFFSC is not a random network. And if you think about it, that is just obvious. There are two standard results as regards scale-free networks. The first is that strongly connected nodes (using our function *f* above) garner more connections over time. This is known as the *rich get richer* or *winners take all*. The second result is that a disruption (oil shock) in a highly connected hub can have a cascading effect in the network, thus bringing it down. Let's take our analogy further for both results.

Regarding the rich getting richer, as oil declines continue in various countries (eg. the UK, Indonesia, Mexico), export connections in the network are dropped though they may be replaced by incoming links -- imports. On the other hand, for the rich, like Saudi Arabia or Russia, the number of connections increases. For example, China has recently renewed efforts to establish connections with Saudi Arabia and other Middle East suppliers. This results in a higher degree of weighted connectivity for both countries. The rich get richer. In particular, as Wikipedia notes, "these scale-free networks do not arise from chance alone". What is required to model a network this way is to define a *growth process*. In the usual case, this is referred to as *preferential attachment* (see the scale-free networks link cited above). In the case of the GFFSC network, this can be described by this fairly simple formulation which quotes Billie Holliday:

> Them that's got shall get
> Them that's not shall lose
>
> Those who have the fossil fuels and export capacity and can easily support their own needs **or** can pay for their required imports will thrive -- the value of *f(D,W)* increases. Those who can not do either will suffer -- the value of *f(D,W)* decreases.

For our original topic, oil shocks, the analogy is even stronger. If a strongly connected fossil fuel consuming or producing nation (hub) is "taken out" to a some (undefined for now) extent, the results for the network as a whole could be disastrous. We need to look more closely at this question. Would the effects cascade thoughout the entire network causing damage everywhere? Or is the network resilient enough to absorb the loss of a hub and keep the damage in the immediate network neighborhood?

As described in the first New Scientist article "The Net Reloaded", John Doyle of MIT casts some doubt on the internet as a scale-free network following a power law distribution. Speaking of the internet, we read

> After finding that this power law described the statistics of internet routers, Barabisi and colleagues [who discovered the scale-free network/power law result for the internet] used a theoretical network with the same proportion of highly connected routers to model the net, and from this idea came the idea that eliminating highly connected routers [hubs] could shut the net down. Doyle argues that this approach, which superficially attractive, ignores a simple fact: the highly connected routers are ISPs [internet service providers] on the edges of the network, close to end users.... Take down highly connected routers around the US and you'll knock out ISP's that serve users in certain neighborhoods.... [But] the bulk of internet data ... will flow unimpeded....
>
> The router example reveals the weakness of scale-free models as a predictor of how a system will behave .... A useful model would specify what the nodes do, where they are in the network and how their connections work.

Toward making a more accurate model of how the internet behaves, Doyle and others have developed the *highly optimised tolerance* (HOT) model as briefly described in the link above. "With HOT", Doyle explains, "we're trying to explain [in simple models] that are more faithful to the specifics of the domain, what is general about complex networks". Look here to find out more about HOT modelling of complex networks.

Following Doyle, we must pay attention to the specifics of the network domain which I've defined as the Global Fossil Fuels Supply Chain [GFFSC]. I do not know how HOT would model this domain but in terms of fault tolerance concerning the vulnerability of hubs to disruptions in that domain, we can observe the following:

1. There is no little or no spare capacity in the network. This is a bit like saying that there is an internet routing system without extra bandwidth. If a major hub like Saudi Arabia (eg. Ras Tanura or Abaqaiq) goes down, the withdrawal of oil supplies on the world market guarantees a cascading ripple effect over the entire network due to the supply & demand pricing mechanism. In this sense, the GFFSC network is *more of* a scale-free network than the internet is. Unlike Doyle's formulation, the ISP router hubs do not lie on the periphery of the network. Think of it this way. If the Saudi hub is crippled, does that affect Angolan imports to China? Can China lose its Saudi Arabian exports network connection but strengthen it's Angola import link to compensate? If there were spare capacity (bandwidth) in the system, fungible oil can be re-routed to compensate for disruptions in the system. But that is not the case now and I speculate that it will never be the case.

2. On the other hand, if a general war between Chad and Sudan occurs and the export link from Sudan to China is dropped, describing a case where the degree and strength of connectivity is so much lower, can China establish new import links with other suppliers or strengthen it's import links with it's important current suppliers (Saudi Arabia, Angola and Iran)? Probably. Chad and Sudan lie on the periphery of the network.

So we see that viewing the GFFSC as a scale-free network described by a power law distribution reveals the extent of the security problem. The GFFSC as I have called it is taut as a bowstring. This is why I worry about oil shocks.

A Note on Intrinsic and Extrinsic Affects on the GFFSC

Here we return to the work of Sornette linked in at the top. In his paper *Endogenous versus Exogenous Origins of Crises* summarized at the cited link we find

> Analysis of precursory and aftershock properties of shocks and ruptures in finance, material rupture, earthquakes, amazon.com sales, etc: we find ubiquitous power laws similar to the Omori law in seismology that allow us to distinguish between external shocks and endogenous self-organization.
>
> This question, whether distinguishing properties characterize endogenous versus exogenous shocks, permeates many systems, for instance, biological extinctions such as the Cretaceous/Tertiary KT boundary (meteorite versus extreme volcanic activity versus self-organized critical extinction cascades), commercial successes....
>
> We study the precursory and recovery signatures accompanying shocks in complex networks, that we have tested on a unique database of the Amazon sales ranking of books and on time series of financial volatility. We find clear distinguishing signatures classifying two types of sales peaks. Exogenous peaks occur abruptly and are followed by a power law relaxation, while endogenous sales peaks occur after a progressively accelerating power law growth followed by an approximately symmetrical power law relaxation which is slower than for exogenous peaks....

Please read the whole text. Sornette is talking about being able to distinguish endogenous versus exogenous influences on network behaviour *after the fact*. For peak oil, we are right in the middle of things. But I think it is possible to make a few observations. Among endogenous (intrinsic) causes, we note the following.

1. As more weight is added to intra-node links (domestic consumption), other import/export connections in the network are weakened or lost. This is *not* analogous to the internet but rather is a specific property of the network domain we are describing.

2. As oil field production in a country declines (eg. Mexico, Cantarell), we observe the same effect as in #1 above.

3. Extrapolation of the discoveries curve trend is correct. The big fields are found first and are mostly all accounted for. Any large field discovered now would be a statistical outlier. This in turn suppresses the creation of new, strong connections in the GFFSC. New EOR techniques for increasing URR in oil fields will have a negligible or even damaging effect going forward regarding #2 above.

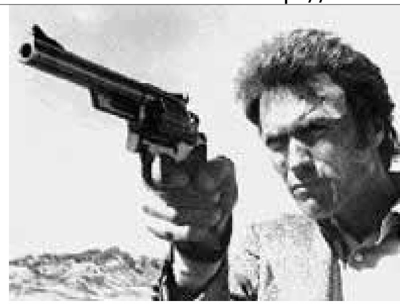
The basic observation is that Sornette's Amazon sales ranking of books is analogous to fossil fuels sales ranking of exports.

As for exogenous (extrinsic) causation (*aka* oil shocks) we note the following types that could affect hub nodes in our scale-free GFFSC network.

- Wars
- Labor Disputes
- Terrorism
- Natural Disasters
- Economic Recessions
- Political Upheavals (Coups)

This brings us to the work of Nassim Nicolas Taleb, an applied statistian who wrote the 2nd article in New Scientist *Life Is Unpredictable*. In particular, he is referring to *Black Swans* in which he distinguishes between what he terms "type one" randomness (eg. throwing a dice) and "type two" randomness (eg. a 10 kilometer bolide hitting the Earth). This latter is a Black Swan. His analysis claims that events of the latter type are effectively unpredictable and simply a matter of luck. Why do *Harry Potter* or *The DaVinci Code* win while many other worthy efforts lose? While I agree that life is unpredictable, particularly for type two randomness, I dispute any claim that the exogenous factors that could cause oil shocks (excepting perhaps Natural Disasters) fall into this category. For example, here is a list of recent conflicts in the Middle East. Not only are there current conflicts, but it would seem that new conflicts, arising from Iran and Israel for example, are fairly predictable in the future.

Still, we must admit that luck regarding exogenous events is unavoidable as it affects the GFFSC in the future. However, in line with our modeling of the supply chains as a scale-free network, I do conjecture that the rich will get richer and the poor will remain that way or become even more impoverished. For example, South American countries like Argentina are already feeling the pinch. I hope this post will stimulate some discussion of the ideas contained herein. Obviously, there is lot of stuff I didn't get to discuss. Personally, I'm not feeling particularly lucky about the future of the GFFSC. In my view it appears to be a real-world scale-free network subject to a power law distribution and the endogenous and exogenous factors affecting it as described above. To finish up on a lighter note and acknowledging the role of luck in our future, we end with a famous quote from the movies.



I know what you're thinking. Did he fire six shots or only five? Well, to tell you the truth, in all this excitement, I've kinda lost track myself. But being as this is a .44 Magnum [peak oil], the most powerful handgun in the world, and would blow your head clean off, you've got to ask yourself one question: Do I feel lucky? Well, do ya punk?

Dirty Harry fired five shots, not six.