Supply Chain Bottlenecks in a Pandemic

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Introduction: Goods and services reach final consumers via supply chains. These are often complex and disruptions at any stage of a supply chain can prevent the entire supply chain from working. At the same time, to limit the spread of COVID-19, governments around the world have enacted far reaching policies, a bi-product of which has been widespread business disruption (see, for example, (Financial Times, 2020)).[1]

In this environment, how can policymakers keep key supply chains functioning? Which firms are essential for meeting demand in a crisis?[2] And how can data on business-to-business transactions be used to identify these essential firms?

We propose a definition of what makes a firm essential and, based on ongoing work in Carvalho, Elliott and Spray (In Progress), offer tools with which to identifying these key, essential, firms using firm-to-firm transactions data.

We consider a firm to be *essential* if demand for key goods at current prices cannot be met without that firm producing. By carefully mapping this problem into one in which the goods flow through interconnected supply chains, analogously to water flowing through a system of pipes, we show that essential firms are located at bottlenecks in the supply chains. In an nutshell, just as there are essential conduits - pipes which, if blocked, will substantially decrease the total of flow of water - there are also essential firms whose removal will substantially affect economy-wide production and leave final product demand for critical goods and services unmet. We call these firms "bottleneck firms." Framing the problem in this way, gives us access to a large and well developed literature in engineering and computer science studying such "flow" problems.

We show how to design and deploy algorithms to pinpoint bottleneck firms in a system of firm-to-firm transactions. In particular, sourcing tools from machine learning and computer science, we propose scalable network algorithms which take as an input data on business-to-business transactions and output the set of essential (bottleneck) firms.

Once these firms have been identified, the model can perform counterfactual analysis to consider the impact of policies to shore up the performance of key supply-chains such as food or medical supplies.

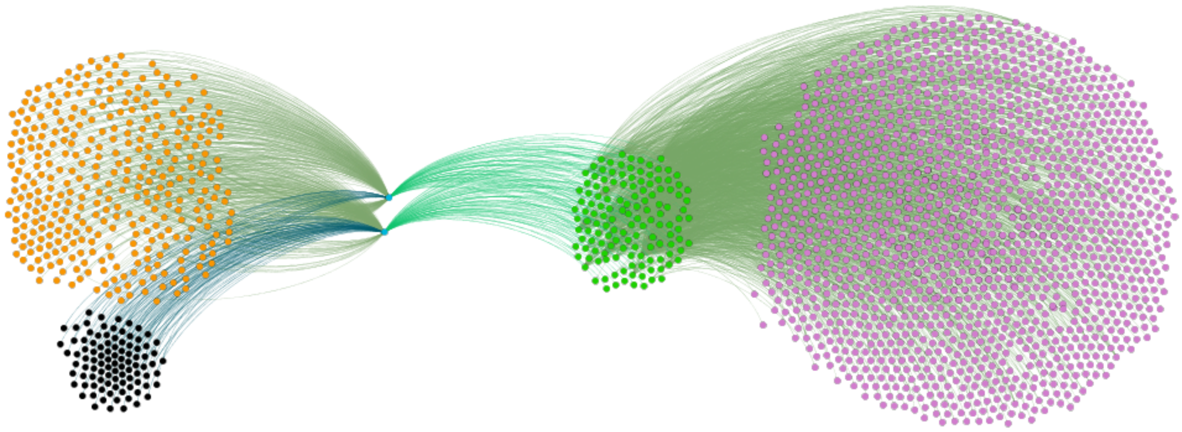
[1]Quote from Financial Times (2020) "two-thirds of businesses do not even know the locations of their second and third-tier suppliers, let alone the factory names and critical details needed to make a solid assessment"

[2]For instance, which firm are needed either directly or indirectly for ventilator demand to be met?

Proof of Concept: As a proof of concept, we now discuss findings in ongoing work Carvalho et al. (In Progress), where we identify bottleneck firms based on large scale business-to-business transaction data from Uganda in 2015.

To make matters concrete, we begin by considering a very simple actual supply-chain operating in Uganda in 2015, producing a particular good.[3] In this supply chain there are two factories, each use two inputs; one sourced locally and one sourced internationally. They then sell to distributors, who then sell onto retailers.

FIGURE 1: Example of supply chain with two bottlenecks



2 factories (blue) buy inputs from 340 suppliers (orange) sell to 135 firms (green) sell to 1548 firms (purple) and import from 96 foreign suppliers (black)
Source: Carvalho, Elliott and Spray (In Progress)

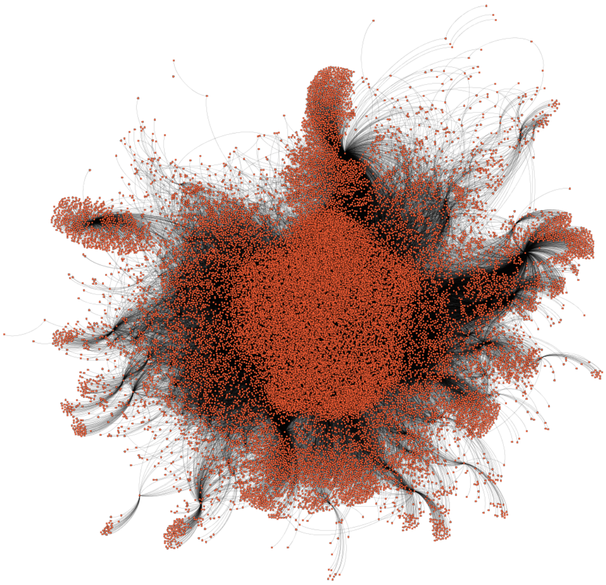
Figure 1 graphs the supply-chain, showing that over 2000 firms depend on 2 essential firms (blue nodes). Goods flow from raw material producers (orange and black), to the manufacturers (blue), to the distributors (green) and finally the retailers (purple), enabling successful production. If either of the manufacturers can't produce, the other manufacturer cannot take up the slack in the short-run; these flows are necessarily diminished and output drops. In this case, the manufacturers (blue nodes) are both bottlenecks.

This is a very simple supply chain, analyzed in isolation. Supply chains are typically much more complex and interact with each other in important ways. Even when firms multisource, overlap in suppliers can mean there is less spare capacity than there might seem. Supply chains also interact with each other—for example a given inputs can feature in the supply chains for several different types of goods. How does all this affect which firms are bottlenecks? How can we estimate the ability of firms to "take up the slack" if a competitor can't produce?

[3]For data confidentiality reasons we cannot reveal the sector of the supply-chain.

The complexity of the problem is highlighted in Figure 2, which shows for Uganda all firms and their connections. Identifying particular bottlenecks in this complex web of 40,000 firms and 90,000 firm-to-firm connections requires a tractable algorithm.

FIGURE 2: All firm-to-firm connections in Uganda



Notes: Each node on the graph represents a firm, while edges represent transactions (between 2010 and 2015). The location of nodes is determined by forceatlas2 which is run on software Gephi.
Source: Carvalho, Elliott and Spray (In Progress)

We overcome several difficulties operationalising these ideas at scale. We make use of hierarchical clustering algorithms to infer production technologies, prune the supply network using algorithms to approximately solve the feedback arc set problem and then deploy the Ford-Fulkerson algorithm to find the maximum flow with and without each firm. By deploying these tools, we start by uncovering the hierarchical nature of supply chain relations shown in Figure 3.

Figure 4, overlays the set of identified bottlenecks on the hierarchical supply chain. In particular, we are able to identify an average of 50 essential bottleneck firms (out of 37K). We observe that a firm's bottleneck status is persistent over time and that bottleneck firms tend to be larger, older, more profitable and operating in sectors with lower entry.

FIGURE 3: All firms

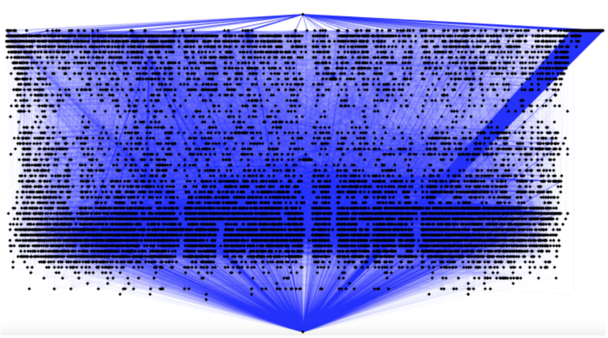
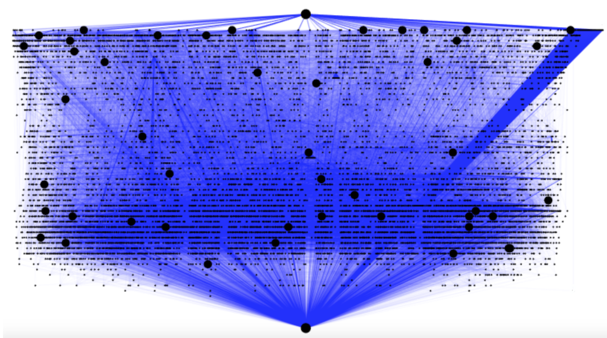


FIGURE 4: Bottlenecks highlighted



Notes: Each node on the graph represents a firm, an edge represents that a trade took place between the two firms at some point between 2010 and 2015 once edges have been trimmed according to the Eades et al. (1993) algorithm. Bottleneck firms are shown as larger circle in panel (b).

COVID-19: In our ongoing work Carvalho, Elliott and Spray (In Progress) we consider a firm to be essential if the total output of the economy drops without it—i.e, there is no way of re-routing demand through the supply network such that other firms can take up the slack. It is relatively straightforward to adapt the objective from meeting overall demand to meeting the demand of goods and services that are deemed crucial in the context of COVID-19. The technology we have developed can then provide policy makers with a fast and scalable tool with which the set of essential (bottleneck) firms for meeting these output goals can be found. Further, this exercise can be done under various scenarios to provide a first cut at forecasting potential problems in supply networks, while counterfactuals for different possible interventions can also be run. To do this we need business-to-business transaction data and a set of "crucial products and services" given current policy priorities.

A set of slides providing further detail are available here.

References

Carvalho, Vasco M., Matthew L. Elliott, and John Spray, "Network Bottlenecks and Market Power," *Mimeo*, In Progress.

Eades, Peter, Xuemin Lin, and William F Smyth, "A fast and effective heuristic for the feedback arc set problem," *Information Processing Letters*, 1993, *47* (6), 319–323.

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