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An examination of national supply-chain flow time

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ABSTRACT

The US and other national governments invest in research and development to spur competitiveness in their domestic manufacturing industries. However, there are limited studies on identifying the research efforts that will have the largest possible return on investment, resulting in suboptimal returns. Manufacturers commonly measure production time in order to identify areas for efficiency improvement, but this is typically not applied at the national level where efficiency issues may cross between enterprises and industries. Such methods and results can be used to prioritize efficiency improvement efforts at an industry supply-chain level. This paper utilizes data on manufacturing inventory along with data on inter-industry interactions to develop a method for tracking industry-level flow time and identifying bottlenecks in US manufacturing. As a proof of concept, this method is applied to the production of three commodities: aircraft, automobiles/trucks, and computers. The robustness of bottleneck identification is tested utilizing Monte Carlo techniques.

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Supply chain; flow time; manufacturing; competitiveness

1. Introduction

In 1994, the US had the 9th largest manufacturing value added per capita in the world. By 2004, this ranking dropped to 16th and by 2014 it was ranked 19th (United Nations, 2017). The US remains a major manufacturing nation; however, evidence suggests that it might be losing its market share and may need to take action to remain a competitive location for production. The loss of manufacturing may result in a loss in innovation, as innovation occurs in factories and is often spurred when factories and laboratories are in close proximity (Tassey, 2010; Standard Chartered, 2015).An additional risk is the loss of supply chains to other nations. As national manufacturing supply chains migrate into an integrated global system, there is concern that US manufacturing might be hollowed out where intermediate goods and services for manufacturing are imported rather than produced domestically (Pisano and Shih, 2009; Tassey, 2010; Levinson, 2013).

Gregory Tassey and others identify that the more labor intensive a technology, the more likely it is to be offshored (Tassey, 2010). Efficiency improvements and automation, however, can reduce unit cost and potentially increase quality and flexibility. These increases

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can cause growth in employment and value added as the domestic share of global markets expand (Tassey, 2010). Another benefit of efficiency and productivity improvements in production is long-term economic growth and increases in per capita income (Weil, 2005, p. 181). To improve efficiency, Tassey has concluded that 'system-level productivity must become the focus of economic growth policy, which means the supply chain must become the focus of policy management, in contrast to the traditional emphasis on single technologies/industries.' Companies, however, often work independently from one another, making it challenging to develop an efficient supply chain. Inefficiencies develop such as the bullwhip effect where variations in demand are magnified through a supply chain (Lee et al., 1997; Bray and Mendelson, 2012).Companies will need to look at performance across a range of factor inputs, including transportation, worker skills, materials, components, and energy to remain competitive. In order for domestic manufacturing to remain vibrant, a nation must consider these issues as well, but at a larger scale (McKinsey & Company, 2012). Moreover, challenges to long-term competitiveness are not an individual industry or company problem. Focusing on one industry is not sufficient for maintaining a competitive manufacturing sector.

According to the Bureau of Labor Statistics, labor productivity for assembly-centric products (i.e. transportation equipment, machinery, computers, and electronics) in the US has had an upward trend; however, multifactor productivity has not grown as rapidly for some industries (US Bureau of Labor Statistics, 2017). With the multitude of products, processes, and activities, a holistic supply-chain approach will require a systematic method to examine production. The standard categorization of labor and industry activity combined with data for input–output analysis, which was originally developed by Wassily Leontief (Miller and Blair, 2009, p. 1), provides a foundation for such an approach. Input–output models are typically used to estimate the impact of a shift in demand of a good or service, but it also provides information on inter-industry activity, which equates to supply-chain activity; therefore, this data is an invaluable resource for examining national supply chains.

The US and other national governments invest in research and development to spur competitiveness in their domestic manufacturing industries. For instance, the National Institute of Standards and Technology is a US Federal agency that promotes 'innovation and industrial competitiveness' in manufacturing and other US-based industries (National Institute of Standards and Technology, 2017). However, there are limited studies on identifying the research efforts that will have the largest possible return on investment. The consequence is that research areas in manufacturing are selected based on anecdotal evidence, intuition, and other non-scientific criteria, resulting in suboptimal return on investment. Among the few studies that examine this issue is an article by Thomas and Kandaswamy (2017), which uses input–output analysis to identify high-cost supply-chain points in US manufacturing. This measure, however, is not the sole metric for motivating research investments. Companies and establishments have developed metrics and means for improving efficiency at the establishment and individual supply-chain level by measuring a number of factors, including production and inventory times (Hopp and Spearman, 2008, p. 230). Products often consist of numerous materials and components, each with their own supply-chain path. The longest path, however, is the one that slows the completion of the final product; that is, it is the bottleneck. The longest flow route is analogous to the slowest person in a group of people walking to a destination. The slowest person in the group is the bottleneck, as that person determines when the whole group arrives at its destination. If actions can be taken so that that person can walk faster, then the whole group arrives at the destination sooner. Similarly, all the materials and components of a product are moving toward a destination (i.e. final assembly) and the slowest component is the bottleneck. If that component can be produced faster, then the whole product might be produced in a shorter period of time, reducing the resources needed for production, which is a primary goal of national research in manufacturing.

This paper provides a method to estimate, at the national supply-chain level, the average time (i.e. flow time) required to produce a product from raw material extraction to the assembly of the finished product. Flow time has a significant impact on the efficiency of production, yet few, if any, research articles have focused on this issue at the national scale. The method is applied to the production of three commodities in the US, as a proof of concept: aircraft, automobiles/trucks, and computers. These commodities represent a selection of medium and high-tech products that have a large number of intermediate components. The longest flow routes for these commodities and the longest supply-chain point within these routes (i.e. the bottlenecks) are identified, as reducing these times has a disproportionate reduction on the total time it takes to produce the final product. A sensitivity analysis utilizing Monte Carlo techniques is applied to test the dependency of the results on a subjective parameter, namely the industry reiteration rate.

Section 2 of this paper provides background information regarding inventory and work-in-process times. Section 3 discusses the methods for mapping a supply chain and measuring flow time. It also discusses the use of a sensitivity analysis using Monte Carlo techniques. Section 4 discusses the data used to examine the flow time for a case study of aircraft, automobiles/trucks, and computers with Section 5 presenting the results of the case study. The last section provides a summary and discussion of the methods and the case study.

2. Background

Manufacturers often have a 'push' and/or 'pull' based supply-chain system (Simchi-Levi et al., 2008, pp. 188–191). A 'push' system means manufacturers are producing products and stocking them based on forecasted demand for the product (i.e. make to stock). For instance, auto dealers often stock cars on the lot for consumers to purchase. Companies use a push system and maintain finished goods inventories to avoid costly shortages, which is often encompassed in the axiom, 'buffer or suffer.' When companies experience shortages for their finished goods, it can result in lost sales. Proctor and Gamble, for example, estimates that when they are out of stock, 29% of those potential sales are lost (Harrison et al., 2005). Inventory, however, is costly as it is stored capital that requires warehouse space and it depreciates. It is estimated, for example, that inventory in the personal computer industry depreciates 1% to 4% each week that it is stored (Kuhel, 2001; Park and Burrows, 2001).

A 'pull' system produces a product after it is ordered by a customer. For instance, Subway makes a sandwich after you order it; thus, there is not an inventory of premade sandwiches. A supply-chain system can also utilize a combination of the push and pull systems where some stages in the chain are pushed while others are pulled. For example, Subway may not make the sandwich until it is ordered, but the cheese and bread were premade. The decision whether to push or pull is often based on a combination of demand uncertainty and work-in-process time (i.e. production time or lead time). Pull systems are favored because they reduce inventory costs while push systems are favored to meet customer demand. When demand is uncertain and work-in-process time is short, a producer is, likely, to favor a pull strategy. When work-in-process times are long, however, a producer is, likely, to favor either a push system or a combination of push and pull, resulting in costly inventory. Higher work-in-process times, themselves, also increase costs. Every moment that a material is in work-in-process it is, typically, occupying floor space and machinery while consuming labor resources. It is generally agreed that short work-in-process times or lead times enhance competitiveness, but there is difficulty in quantifying the benefits (Blackburn, 2012).

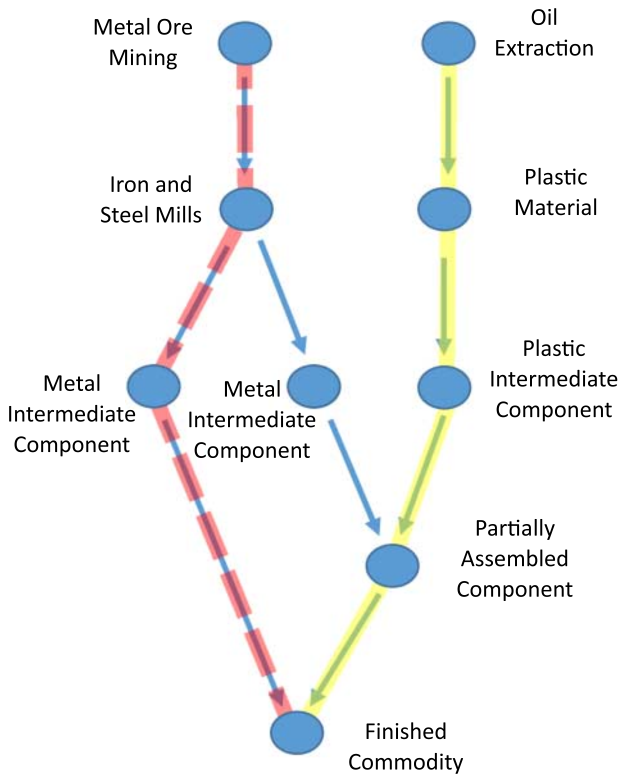
In addition to reduced costs and capital consumption, shorter work-in-process times provide competitive advantages through shorter response time. For instance, a change in a product can be recognized by consumers more rapidly when flow times are shorter, as the time that passes before the new product reaches consumers is reduced. A competitor with a short work-in-process time might change their product multiple times, making it superior and gaining a market advantage.

In addition to work-in-process time and finished goods inventories, companies maintain material goods inventories, which also consume resources. If a company has a shortage of materials, expensive machinery and personnel sit idle until supplies arrive. Inventories are, generally, increased as uncertainty is increased to avoid a shortage. For example, traffic congestion results in uncertainty in deliveries making it necessary to carry larger inventories (Shirley and Winston, 2004). Moreover, there are three primary flow times: material inventory, work-in-process, and finished goods inventory. As the time that a material spends in each of these increases, so does the costs.

Figure 1 provides an illustration of a supply chain for a generic finished commodity. As seen in the figure, there are multiple paths that lead to the finished product or commodity. For this example, let's assume that the dashed path on the left is the longest path while the solid line path on the right is the second longest. Note that a third path exists in the middle, but it is not highlighted. If innovative solutions are identified to reduce the yellow path, any reduction will be partially offset by having to store materials until parts arrive from the red path. The storage of these parts requires capital investment in buildings and real estate to house the parts. Additionally, the stored parts themselves tie up capital that could be used for other purposes. A reduction in the red path, the longest path, is not offset by these costs; therefore, a reduction in the red path is, likely, to result in greater overall savings than a reduction in the yellow path.

This paper examines supply-chain paths at the economy-wide level. Figure A1 in the Online Appendix provides an illustration of a supply chain for a generic product. As seen in the figure, establishments are categorized into industries, which are based on the product and/or processes used at each establishment. Establishments in an industry supply commodities to both establishments in the same industry and establishments in other industries. At the economy-wide level, the individual supply-chain links are, largely, unknown; however, these individual links are still present and the industry categories are such that they correspond to stages in the supply chain. Therefore, the economy-wide level data represents collections of supply chains with various stages of each supply chain being grouped and categorized by industry. This paper identifies those industries with longest average flow time within the longest path in the supply chains for aircraft,

Figure 1. Manufacturing supply-chain illustration.



automobiles/trucks, and computers. This amounts to identifying the supply-chain stage that is, likely, to represent a common bottleneck among the individual supply chains.

3. Methods

This paper focuses on manufacturing activities within the national borders of the US. There are two primary steps in the proposed method and a sensitivity analysis is applied to the case studies. The first step is to measure the flow time for each industry. This involves measuring the flow time for materials inventory, work-in-process, and finished goods inventory. The second step is to map these industries into a supply chain. The two steps and the sensitivity analysis are described below.

3.1. Industry flow time

The calculation for flow time can be thought of as water flowing through a hose into a bucket. The cost of goods sold, *COGS*, is the total amount of water that runs into the bucket over a period of time and the inventory values are the amount of water in the hose at any given time. Since we know the total amount of water that flowed out of the hose (i.e. the amount in the bucket or *COGS*), we can estimate how many times the hose was filled and emptied over that period of time (inventory turns or *TRN* in the equation below) by dividing the amount in the bucket by the volume of the hose. If one takes the number of days in a year and divides it by the number of inventory turns *TRN*, the result is the flow time *FT*, which represents the time it takes to move from the beginning to the end of the hose. This method makes the assumption of first-in first-out (FIFO) where the oldest goods on hand are sold first (Meigs and Meigs, 1993, p. 409). This paper breaks the industry inventory time into four categories (i.e. material goods, work-in-process down time, work-in-process, and finished goods). For this reason, a ratio is included in the calculation to account for each category. An additional issue that must be accounted for is that a material may go through more than one establishment in an industry, as illustrated in Figure A1 of the Online Appendix. As can be seen, establishments may supply other establishments within the same industry before being sent to an establishment in another industry. This is accounted for by multiplying the industry flow time by the multiplier *IRR*, an estimated average of the number of times a material moves through the same industry. The proposed method for estimating the sum of the flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories for a particular industry, represented by NAICS codes, is:

$$FT_{\text{IND,Total}} = \sum_{i=1}^{N} IRR_{\text{IND}} \times \frac{(INV_{\text{IND},i,\text{BOY}} + INV_{\text{IND},i,\text{EOY}})/2}{(INV_{\text{IND,Total,BOY}} + INV_{\text{IND,Total,EOY}})/2} \times \frac{365}{TRN_{\text{IND,Total}}}, \tag{1}$$

where $FT_{\text{IND,Total}}$ is the total estimated flow time for industry IND; i is the inventory item where i is materials and supplies (MS), work-in-process (WIP), or finished goods (FG) inventories; $INV_{\text{IND,Total,BOY}}$ is the total inventory (i.e. materials and supplies, work-in-process, and finished goods inventories) for industry IND at the beginning of the year; $INV_{\text{IND,Total,EOY}}$ is the total inventory (i.e. materials and supplies, work-in-process, and finished goods inventories) for industry IND at the end of the year; $TRN_{\text{IND,Total}}$ is the inventory turns for industry IND (defined below) and IRR_{IND} is the industry reiteration rate for industry IND (defined below).

This equation calculates, for each industry in the supply chain, the flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories and, then sums them together. Calculating each of these stages is useful in identifying the source of the flow time (i.e. inventory time vs. work-in-process time). The industry flow time can be simplified to:

$$FT_{\text{IND,Total}} = IRR_{\text{IND}} \times \frac{365}{TRN_{\text{IND,Total}}}. \tag{2}$$

The days that a dollar spends in each of the inventory categories is being calculated by taking the total number of days in a year and dividing it by the number of inventory turns *TRN*, which is discussed in the Online Appendix. This is then multiplied by average inventory of type *i* divided by the total inventory. The product in the equation is adjusted by an industry reiteration rate *IRR*, which is to be discussed in the Online Appendix. Finally, the summation of all types of inventory is calculated for industry IND.

3.2. Supply-chain map

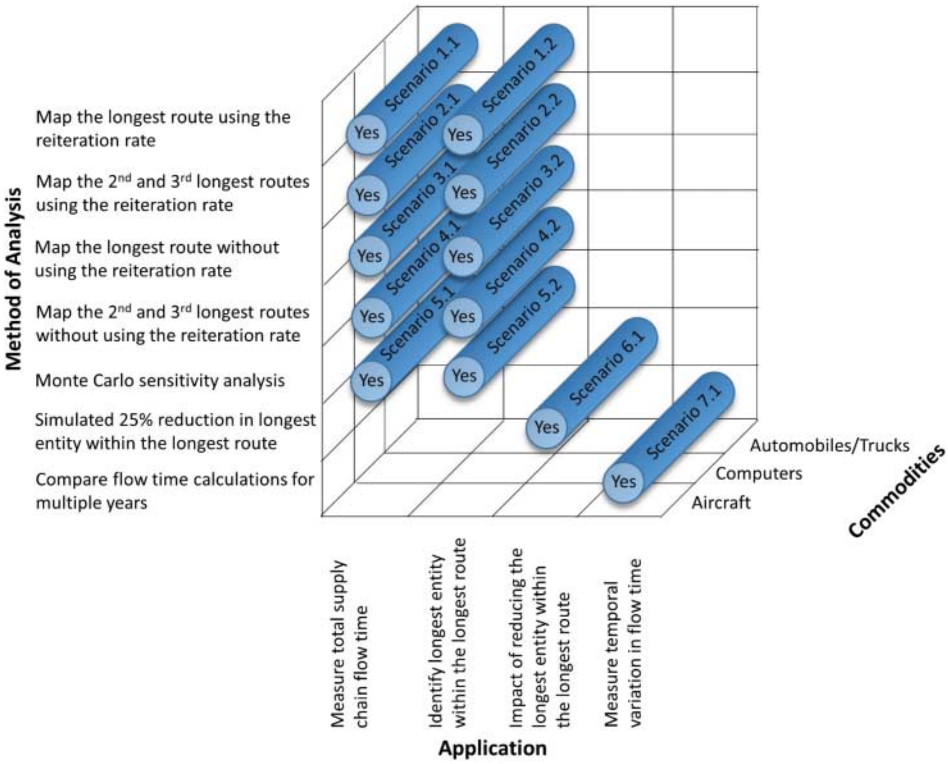
The calculations for tracking flow time, FT, can be made for any individual NAICS code category. Materials flow from establishments in one NAICS code to establishments in another NAICS code. These movements can be traced using Input–Output data from the Bureau of Economic Analysis (BEA). This data includes Make tables, which show the production of commodities (products) by industry, and Use tables, which show the components required for producing the output of each industry. The Use table from the BEA Benchmark Input–Output tables provides the items each industry purchases from other industries, which was used to create a supply-chain map. This data, however, includes not only the materials, but also the energy, machinery, services, and other items that are not a physical part of the final product. To track the flow time and inventory time from NAICS code to NAICS code, it is necessary to identify only those activities that process materials that are physically part of the final product. To identify these activities, the data from the Use table that applies to manufacturing was extracted by examining the NAICS code descriptions and activities. The connections for the earlier part of the supply chain are illustrated in Figure A3 in the Online Appendix, which depicts the complexity of the supply chain even when establishments have been grouped together by the thousands. Dozens more NAICS codes are in the later part of the supply chain, but cannot be shown due to space limitations. Each possible route from left to right through this supply chain is compared to identify the longest route. Then the longest supply-chain entity (NAICS code) of that route is identified. This analysis tracks the supply chain for automobiles/trucks (NAICS 336111 and NAICS 336112), aircraft (NAICS 336411), and electronic computers (NAICS 334111).

3.3. Simulated scenarios

As illustrated in Figure 2, five methods of analysis are used to measure the total supply-chain flow time and identify the longest supply-chain entity within the longest flow route. A sixth approach is used to examine the impact of reducing the longest entity and a seventh approach is used to examine temporal variations in flow time. The first method in Figure 2, seen in the vertical axis labeled 'Method of Analysis,' is to map the longest supply-chain route using the reiteration rate and identify the longest entity within that route. The second method is to map the second and third longest routes using the reiteration rate. This method provides insight into whether the longest entity changes if the longest route identified is inaccurate. The third method maps the longest route and identifies the longest entity within that route without using the reiteration rate (i.e. IRR_{IND} equals 1). A fourth method maps the second and third longest routes without the reiteration rate.

A fifth approach uses Monte Carlo simulation. The methods proposed in Sections 3.1 and 3.2 have two subjective processes involved in examining the flow time for a manufactured good: (1) the selection of a threshold for the industry reiteration rate (discussed above) and (2) the selection of inter-industry connections from the BEA Use tables. Although, the BEA input–output data provides the inter-industry linkages, it does not provide information on how or what is purchased from those industries. This method tracks the flow time for the materials in the finished product and not all goods purchases go directly into the finished product. For example, purchases that a machinery manufacturing

Figure 2. Simulated scenarios.



establishment makes from itself might be parts for its products or it might be machinery that produces the product. The methods in this paper address the former rather than the latter. In order to account for these uncertainties, a probabilistic sensitivity analysis was conducted based on Monte Carlo analysis. This approach is based on works by McKay et al. (1979) and by Harris (1984) that involves a method of model sampling.

A Monte Carlo analysis was applied to the time flow estimates made for aircraft, automobiles/trucks, and computers using the Crystal Ball software product (Crystal Ball, 2013), a software add-on for spreadsheets. Specification involves defining which variables are to be simulated, the distribution of each of these variables, and the number of iterations performed. The software then randomly samples from the probabilities for each input variable of interest.

For this analysis, the industry threshold was varied between 0.01 and 0.15 with a uniform distribution. The higher value was selected so that 90% of the reiteration rates are between 1 and 2. The lower range was selected so that 90% of the reiteration rates are between 1 and 5. A number of inter-industry linkages, as shown in Table A1 in the Online Appendix, were selected with a 0.5 probability of inclusion in the Monte Carlo analysis. When the simulation selects a yes for that linkage, then the total flow time for that NAICS code is included in the calculation for the commodity flow time. If the simulation selects a no, then that NAICS code does not affect the total flow time for the commodity.

The fifth method shown in Figure 2 simulates a reduction in the longest entities in the longest flow routes for each of the commodities examined. This method utilizes the Monte Carlo analysis and the variables previously discussed; however, this method includes a 25% reduction in the longest flow route.

The last method shown in Figure 2 compares flow time calculations for multiple years. Since this work uses past data to influence future investments, it is advantageous to discuss how flow time varies from year to year. The calculated flow times for all US manufacturing industries are compared for 2007 and 2012.

4. Data

There are three datasets that are used to track flow and inventory time in US manufacturing: the Annual Survey of Manufactures (ASM) from the US Census Bureau, the Economic Census from the US Census Bureau (2017a), and the BEA Benchmark Input–Output data. This data is supplemented by another dataset, the Survey of Plant Capacity Utilization from the Census Bureau, which provides the average hours that factories are operating per week.

Every five years the BEA computes benchmark input–output tables, which tends to have over 350 industries (Bureau of Economic Analysis, 2014). The data is provided in the form of make and use tables, with their corresponding matrices replacing the Leontief method (United Nations, 1968, p. 35). There are two types of make and use tables: 'standard' and 'supplementary.' In the US, industries are categorized by NAICS codes. Standard tables closely follow NAICS and are consistent with other economic accounts and industry statistics, which classify data based on the establishment. Note that in this context an 'establishment' is a single physical location where business is conducted. This is in contrast to an 'enterprise' which can be a company, corporation, or institution. Establishments are classified into industries based on the primary activity within the NAICS code definitions; however, establishments often have multiple activities. An establishment is classified based on its primary activity. Data for an industry reflects all the products made by the establishments within that industry; therefore, secondary products are included. Supplementary make-use tables reassign secondary products to the industry in which they are primary products. The data in this report utilizes the original make-use tables.

The ASM is conducted every year except for those years when the Economic Census is conducted (i.e. years ending in 2 or 7). The ASM provides statistics on employment, payroll, supplemental labor costs, cost of materials consumed, operating expenses, value of shipments, value added, fuels and energy used, and inventories. The Economic Census, used for years ending in 2 or 7, is a survey of all employer establishments in the US that has been taken as an integrated program at five-year intervals since 1967. Both the ASM and the Economic Census use NAICS classifications. The inventory data from the Economic Census and ASM is broken into materials inventory, work-in-process inventory, and finished goods inventory. It is important to note that a finished product for an establishment in one industry might be reported as a raw material by an establishment in a different industry. For example, the finished product inventories of a steel mill might be included in the material inventories of a stamping plant. The inventory data does not have a breakout for transport time or down time; therefore, other data must be used for these purposes.

In order to estimate the work-in-process downtime (i.e. the time that materials are in work-in-process, but the plant is closed) one can employ data from the Survey of Plant

Capacity Utilization. This data provides quarterly statistics on the rates of capacity utilization for the US manufacturing industry by NAICS code. In addition to providing capacity utilization, it also provides data on the average plant hours per week in operation for an industry (US Census Bureau, 2017b).

5. Case study results and discussion

Manufacturers commonly measure production time in order to identify areas for efficiency improvement, but this is typically not applied at the national level where efficiency issues may cross between enterprises and industries. Such methods and results can be used to prioritize efficiency improvement efforts at an industry supply-chain level. For this analysis three commodity categories were examined: aircraft, automobiles/trucks, and computers. These three industries were chosen because they produce complex engineered goods whose production employs a large number of people and produces a great deal of economic output. Aircraft is NAICS 336411; automobiles/trucks is the average of the industry flow time for NAICS 336111, 336112, and 336120; and computers is NAICS 334111. The longest flow routes for these commodities and the longest supply-chain point within these routes (i.e. the bottlenecks) are identified, as reducing these times has a disproportionate impact on the reduction of the total time it takes to produce the final product. A sensitivity analysis utilizing Monte Carlo techniques is applied to test the robustness of the method due to uncertainty regarding flow time measurement.

5.1. Results with the reiteration rate

The flow time with an industry reiteration rate of 0.03 (i.e. Scenario 1.1 from Figure 2) was 1024 days, 2029 days, and 963 days for computers, aircraft, and automobiles/trucks, respectively. The second longest route for automobiles is 180.3 days less than the longest route; therefore, the total flow time can only be reduced by reducing the longest route by 180.3 days until one has to consider the second longest route. For aircraft, it can be reduced by 425.3 days and for computers it can be reduced by 310.5 days before the longest route equals the second longest route. Monte Carlo analysis (i.e. Scenario 5.1) was used because some of the links selected for the supply chain were subjectively selected and the reiteration rate selected is also somewhat subjective. Figure 3 shows the frequency of the values for each product and shows the cumulative frequency. As shown in Table 1, the mean flow time from the analysis was 762 days, 1490 days, and 701 days for computers, aircraft, and automobiles/trucks. The minimum for computers was 540 days and the maximum 1317 days. Aircraft had a minimum of 935 days and a maximum of 2617 while automobiles/trucks had a minimum of 456 days and maximum of 1233 days.

The long tails in Figure 3 occur due to the inclusion of the threshold for the reiteration rate in the Monte Carlo analysis where the *log* of the threshold is being calculated. The threshold is varied between 0.01 and 0.15 with a uniform distribution. A larger threshold results in a smaller reiteration rate and a shorter flow time; that is, a larger threshold means the materials are being processed in fewer establishments within an industry. Approximately 73% of the iterations are within one standard deviation of the mean for aircraft manufacturing. For automobiles/trucks it is 71% and for computers it is 73%.

Figure 3. Frequency graphs of the 10,000 trials from the Monte Carlo sensitivity analysis showing all three: (A) aircraft manufacturing – frequency graph, (B) automobile/truck manufacturing frequency graph, (C) computer manufacturing – frequency graph, and (D) cumulative frequency graph.

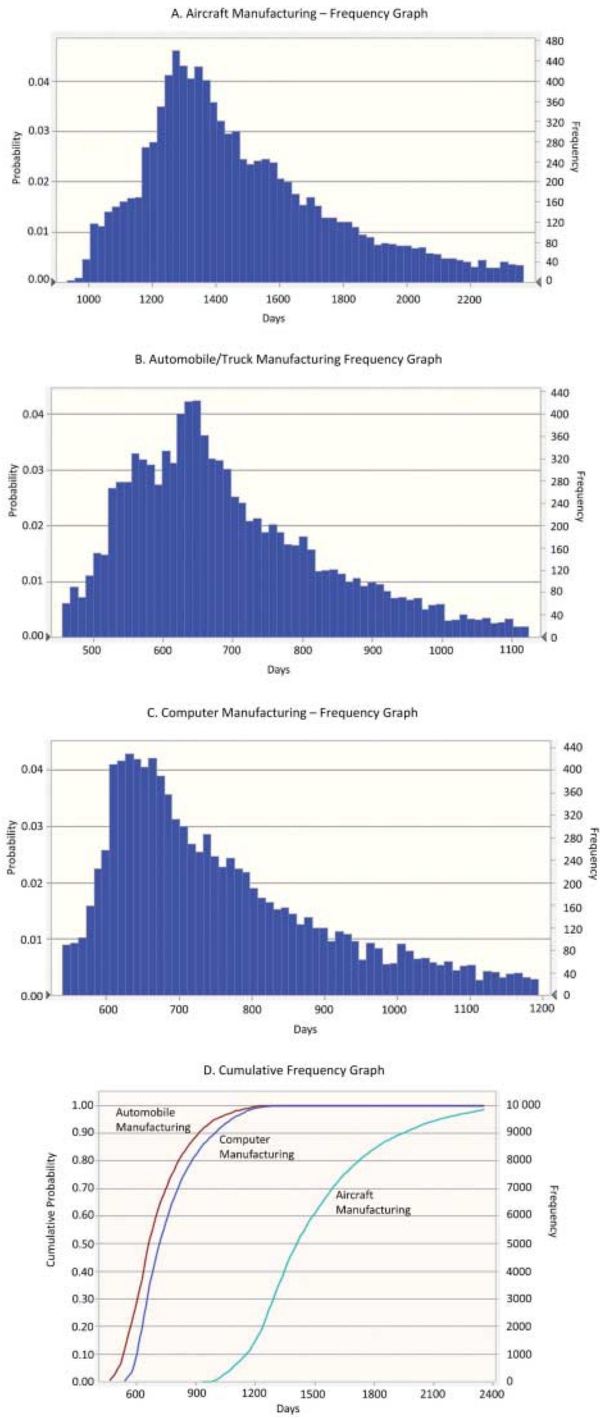


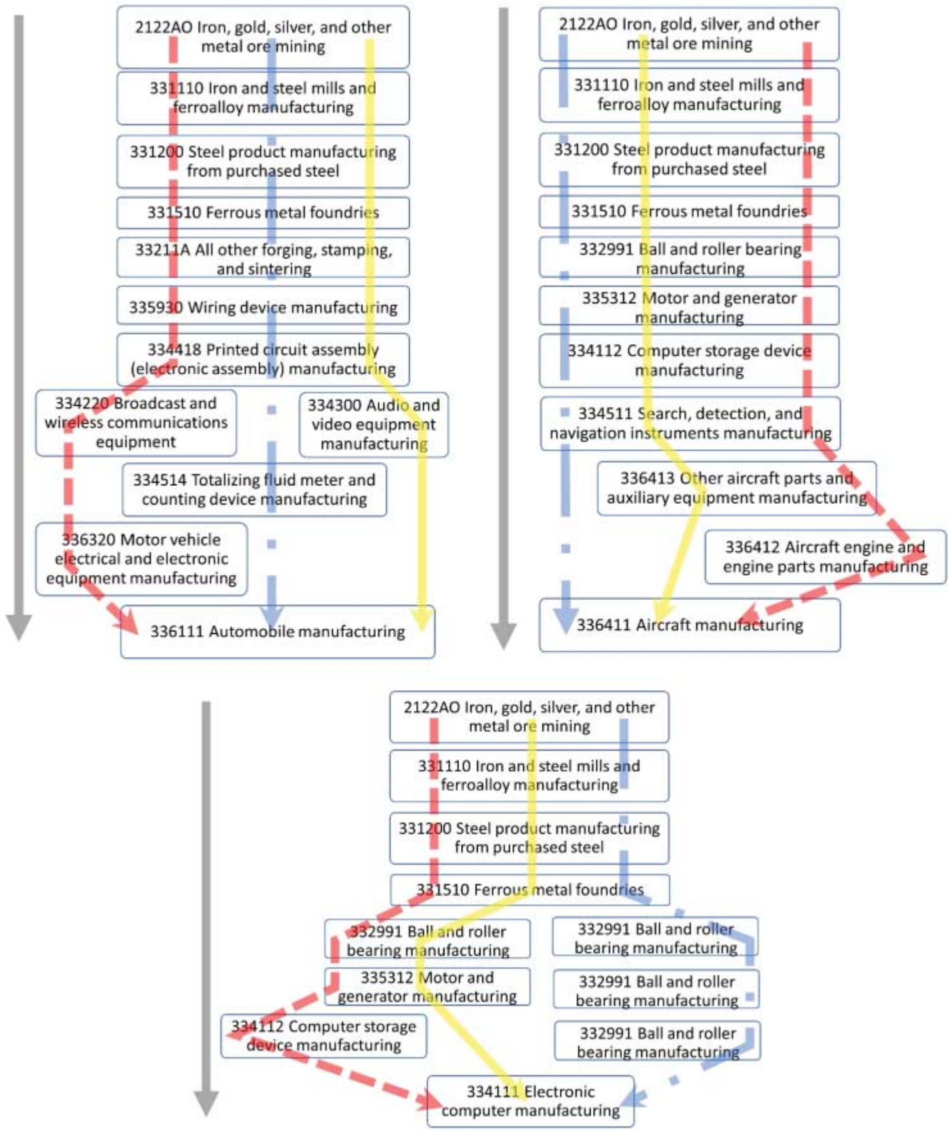
Table 1. Monte Carlo analysis results.

Statistics	Computers	Aircraft	Automobiles/Trucks
Trials	10,000	10,000	10,000
Base case	1024.26	2029.08	963.48
Mean	762.34	1489.97	701.08
Median	720.39	1414.30	666.26
Standard deviation	153.89	311.86	150.74
Coeff. of variation	0.21	0.22	0.21
Minimum	540.30	934.89	456.16
Maximum	1317.39	2617.20	1232.62

The primary purpose of tracking the flow time is to identify bottlenecks, those areas that have the longest flow time. Reducing time spent on the longest route will reduce the time it takes to manufacture the final product. Since there is some uncertainty in linkages, it is beneficial to note the second and third longest routes as well (i.e. Scenario 2.1 and Scenario 2.2). The top three longest routes (i.e. Scenario 1.1, Scenario 1.2, Scenario 2.1, and Scenario 2.2) are mapped for automobile/truck, aircraft, and computer manufacturing in Figure 4 and information on these entities is provided in Table A2 in the Online Appendix. Figure 4 provides a partial mapping of the supply chain for each of the products examined. The map includes the three longest supply-chain routes for each product, which can vary as much as 785 days, to examine other possible routes as being the longest. The top items in the supply chain are the raw materials and the bottom are the finished product (i.e. automobile, aircraft, or electronic computer manufacturing), which is at the bottom of each supply chain map. The longest route is a dashed line with the second longest a solid line and the third longest a dashed/dotted line. For example, the longest route for automobiles/trucks, as seen in the top left, is through motor vehicle electrical and electronic equipment (NAICS 336320) following the dashed line. The next longest supply-chain entity for automobile manufacturing is through audio and video equipment manufacturing (NAICS 334300) and the third longest is through totalizing fluid meter and counting device (NAICS 334514). With there being some subjectivity in the identification of the supply chain, the second and third longest paths provide some insight into other potential routes as being the longest. The three longest routes have overlapping paths, which provides some confidence in identifying the longest supply-chain route. For aircraft manufacturing, aircraft engine and engine parts (NAICS 336412) is the longest route with other aircraft parts being second (NAICS 336413) and search detection instruments (NAICS 334511) being third. For computers, the longest route is through computer storage device manufacturing (NAICS 334112) with the second being motor and generator manufacturing (NAICS 335312) and third being printed circuit assembly (NAICS 334511).

Within the three longest routes for automobile/truck manufacturing, the top three longest flow time entities are broadcast and wireless communications equipment manufacturing (NAICS 334220), audio and video equipment (NAICS 334300), and iron and steel mills and ferroalloy (NAICS 331110), as calculated using the reiteration rate (see Table A2 in the Online Appendix). The implication is that reducing the flow time at these supply-chain points (i.e. the longest flow time entities within the longest supply-chain route) can reduce the total flow time for automobile/truck manufacturing. This could be compared to identifying the slowest person walking in a group toward a destination. If that person's speed can be improved, then the whole group arrives at the destination sooner. The second

Figure 4. Supply-chain map for the longest three routes for automobiles/trucks, aircraft, and computer manufacturing – calculated using the reiteration rate.



Note: Longest route: dashed line, second longest: solid line, third longest: dashed/dotted line.

and third longest supply-chain points are only applicable in the case that the longest point is not truly part of the supply chain or is not actually the longest. Broadcast and wireless communications has the longest individual flow time within the longest route. This item, however, is within the Monte Carlo analysis (i.e. Scenario 5.1 and Scenario 5.2) where its inclusion in the supply chain is varied. Some cars may not have wireless communications equipment and some motor vehicle electronic equipment does not have wireless communications equipment either, which is why it is included in the Monte Carlo analysis. The results for the Monte Carlo analysis had a number of different flow routes as being the longest. Broadcast and wireless communications (NAICS 334220) remained the longest flow entity for 48.8% of the simulations for automobiles/trucks. This is solely the result of whether wireless communications are included in an automobile. The average establishment in broadcast and wireless communications equipment manufacturing (NAICS 334220) has materials and supplies accounting for 22% of the flow time, work-in-process downtime accounting for 45%, work-in-process accounting for 18%, and finished goods inventory accounting for 15%. According to the Quarterly Survey of Plant Capacity Utilization, establishments in this industry were open for between 45 and 51 hours per week or a little over one shift, which is why downtime accounts for 45% of the flow time. Adding shifts (e.g., second or third shift workers) might reduce this time. Additionally, companies have often reduced inventory times through improved demand forecasting and coordination with suppliers.

Within the three longest routes for aircraft manufacturing, the three longest flow time entities are aircraft engine and engine parts (NAICS 336412) followed by other aircraft parts and auxiliary equipment (NAICS 336413) and computer storage device (NAICS 334112), as seen in Table A2 in the Online Appendix. All three entities are within the longest route. Aircraft engine and engine parts manufacturing (NAICS 336412) remained the longest flow entity for all of the Monte Carlo simulations. The average establishment in this industry has 29% of its flow time in materials and supplies, 22% in work-in-process downtime, 24% in work-in-process, and 25% in finished goods inventory.

Within the three longest routes for computer manufacturing, the three longest entities are computer storage device manufacturing (NAICS 334112) followed by ball and roller bearing manufacturing (NAICS 332991) and iron and steel mills and ferroalloy manufacturing (NAICS 331110). The longest flow entity for all of the Monte Carlo simulations was computer storage device manufacturing (NAICS 334112). The average establishment in this industry has 24% of its flow time in materials and supplies inventory, 27% of the time in work-in-process downtime, 16% of the time in work-in-process, and 33% of the time in finished goods inventory.

5.2. Results without the reiteration rate

Since the reiteration rate is a subjective calculation and its accuracy is not proven, it is important to consider the flow time without it (i.e. Scenario 3.1, Scenario 3.2, Scenario 4.1, and Scenario 4.2). There are two primary impacts of examining flow time without the reiteration rate. The first is that it can affect the identification of the longest flow route. Different routes may become the longest if there are multiple establishments from one industry in the supply chain. These estimates represent a lower bound estimate for the flow time in each industry. The longest supply-chain routes for automobile/truck, aircraft, and computer manufacturing are shown in Figure 5 with data on the routes provided in Table A3 in the Online Appendix. These routes are comparable to the longest routes shown in red in Figure 4 with the difference being that those in Figure 5 were identified using flow times that do not use the industry reiteration rate. For automobiles, the longest route is unchanged, but the longest flow time entity within that route changes to steel product manufacturing from purchased steel (NAICS 331200). For aircraft and computers, part of the route changes when excluding the reiteration rate, as can be seen in the figure. The

Figure 5. Supply-chain map for the longest routes for automobiles/trucks, aircraft, and computer manufacturing – calculated without the reiteration rate.

longest entity of the route for aircraft is the final assembly (NAICS 336411). The longest entity for computers remains computer storage device manufacturing (NAICS 334112).

5.3. Identifying bottlenecks

Since there is some uncertainty in analyzing the flow time, which is why a sensitivity analysis was conducted, and we are examining the economy-wide scale, which includes collections of individual supply chains, we can only identify supply-chain entities that are likely to be common bottlenecks (i.e. the supply-chain entity with the longest flow time in the longest supply-chain route) in individual supply chains. This analysis uses average industry flow times; however, each supply chain is unique and may have a set of establishments that vary from the average. At the economy-wide scale, though, an industry with a higher flow time is likely to have a higher flow time for many supply chains. Table 2 identifies the three longest entities within the longest routes for automobiles/trucks, aircraft, and computers for the calculations made both with and without the reiteration rate (i.e. Scenario 1.2, Scenario 2.2, and Scenario 3.2). These entities were each identified in the previous discussions. For example, broadcast and wireless communications equipment was identified as the longest entity within the longest route in Table A2 in the Online Appendix; therefore, it is also listed in Table 2. For automobiles and aircraft, two different supply-chain entities are identified as being the longest, depending on whether the reiteration rate is included or excluded. For computers, the longest entity remains the same regardless of whether the reiteration rate is included or excluded.

The supply-chain entity with the longest flow time in the longest route (i.e. the bottleneck) has, by definition, the largest elasticity for affecting the total flow time for a product. That is, a 1% decrease in the flow time of this supply-chain entity will have the largest reduction in the total flow time of the finished product compared to other supply-chain entities. A reduction in each of these entities for aircraft, computers, and automobiles/trucks can be simulated using Monte Carlo analysis (i.e. Scenario 6.1). Five simulations were performed where each simulation contained a 25% reduction in one of the longest entities within the longest route. The results shown in Table 3 suggest that a reduction in NAICS 336412 (aircraft engine manufacturing) has a larger impact on reducing flow time than reducing NAICS 336411 (aircraft manufacturing) by the same percentage, making it more likely that this supply-chain entity is the true bottleneck. The reduction in the mean days is 5.4% compared to 3.1% for aircraft. The larger 5.4% reduction had a maximum of a 6.0% reduction and a minimum of a 5.0% reduction in the total flow time. These values translate into elasticity values of 0.21 for the mean, 0.24 for the maximum, and 0.20 for the minimum, as illustrated in Figure 6. These are the largest elasticities for reducing the flow time for aircraft manufacturing. The point estimate in the figure represents the average elasticity while the lines extend to the minimum and maximum values. For automobiles, the results suggest that reducing NAICS 334220 (broadcast and wireless communications equipment) has a larger impact than reducing NAICS 331200 (steel product manufacturing from purchased steel), meaning that it is more likely to be the true bottleneck. The former had a 3.6% reduction in the mean flow time while the latter had a 1.4% reduction. The larger 3.6% reduction translates into a 0.14 elasticity. NAICS 334112 had a 7.8% reduction on computer manufacturing flow time, which amounts to an elasticity of 0.31.

5.4. Variation in flow time

Since this work uses past data to influence future investments, it is advantageous to discuss how flow time varies from year to year (i.e. Scenario 7.1). Using data from the Economic Census, the total flow time (i.e. material goods, work-in-process, and finished goods inventories) for each industry was calculated and compared for 2007 and 2012, which are the two years for which all data is available. It is important to note that between these two years, some NAICS codes were altered, which were excluded from this comparison, leaving 276

Table 2. Comparison of the top three supply-chain routes for automobiles/trucks, aircraft, and computer manufacturing – including and excluding the reiteration rate.

		Reiteration rate included			No reiteration rate		
		Within longest route	Within second longest route	Entity ranking within longest route	Within longest route	Entity ranking within longest route	Included in sensitivity
Automobiles/Trucks							
334220	Broadcast and wireless communications equipment	X	–	1st	X	3rd	X
331110	Iron and steel mills and ferroalloy manufacturing	X	X	2nd	X	4th	–
331200	Steel product manufacturing from purchased steel	X	X	5th	X	1st	X
33211A	All other forging, stamping, and sintering	X	X	3rd	X	2nd	–
Aircraft							
336412	Aircraft engine and engine parts manufacturing	X	–	1st	X	8th	–
336413	Other aircraft parts and auxiliary equipment manufacturing	X	X	2nd	X	2nd	–
334112	Computer storage device manufacturing	X	X	3rd	–	–	–
336411	Aircraft manufacturing	X	–	5th	X	1st	–
33451A	Watch, clock, and other measuring and controlling device manufacturing	–	–	–	X	3rd	–
Computers							
334112	Computer storage device manufacturing	X	–	1st	X	1st	–
332991	Ball and roller bearing manufacturing	X	X	2nd	–	–	–
331110	Iron and steel mills and ferroalloy manufacturing	X	X	3rd	X	2nd	–
335312	Motor and generator manufacturing	X	X	4th	X	3rd	X

industries to be compared. The industry flow time between these two years has a correlation coefficient of 0.961, suggesting they have a high correlation. Using 2007 as a predictor of 2012 (i.e. assuming the flow time is the same) results in a mean absolute percent error of 11.2%. Moreover, there is some variation between the two years; however, the 2007 flow time estimates have a high level of accuracy as a predictor for 2012 values.

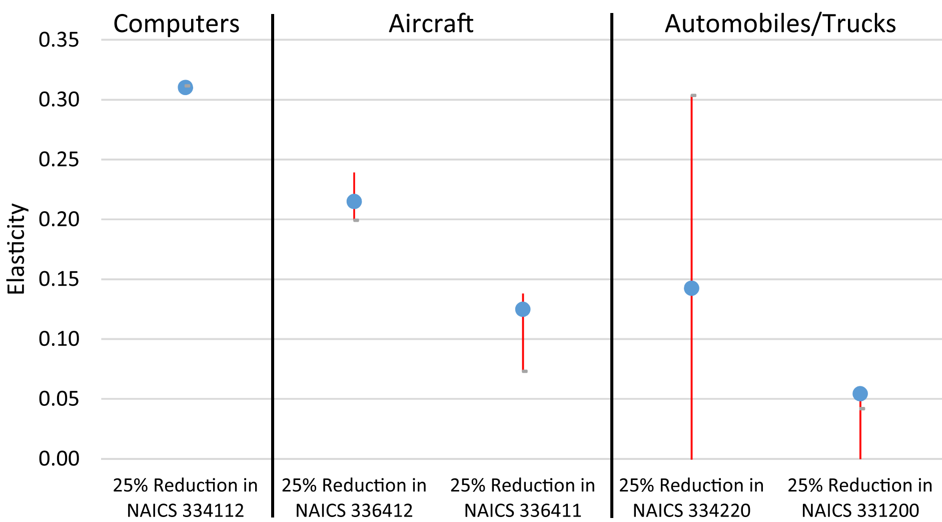
6. Summary and conclusions

National governments invest in research and development to spur competitiveness in their domestic manufacturing industries, but there are limited studies that identify the research

Table 3. Simulating a 25% reduction in the largest entities in the longest routes.

	Computers		Aircraft			Automobiles/Trucks		
	No Change	25% reduction in NAICS 334112	No change	25% reduction in NAICS 336412	25% reduction in NAICS 336411	No change	25% reduction in NAICS 334220	25% reduction in NAICS 331200
Trials	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Base case	1024	947	2029	1923	1980	963	892	947
% Reduction		7.6%		5.2%	2.4%		7.4%	1.7%
Mean	762	703	1490	1410	1443	701	676	692
% Reduction		7.8%		5.4%	3.1%		3.6%	1.4%
Median	720	664	1414	1342	1367	666	644	658
% Reduction		7.9%		5.1%	3.4%		3.4%	1.3%
Minimum	540	498	935	879	903	456	456	456
% Reduction		7.8%		6.0%	3.5%		0.0%	0.0%
Maximum	1317	1215	2617	2487	2569	1233	1139	1220
% Reduction		7.8%		5.0%	1.8%		7.6%	1.0%

Figure 6. Simulation elasticities for a 25% reduction in the largest entities in the longest routes.



Note: The red lines represent the maximum and minimum values from the Monte Carlo analysis.

efforts that can have the largest possible return on investment. Companies have developed metrics and means for improving efficiency at the establishment and individual supply-chain level by measuring a number of factors, including production and inventory times (Hopp and Spearman, 2008, p. 230). However, few efforts have been made to track the average manufacturing flow time through multiple industries for multiple supply chains. This paper utilizes data on manufacturing inventory and flow time along with data on inter-industry interactions to develop a method for tracking industry-level flow time of US-manufactured products. Flow time has a significant impact on the efficiency of production, yet few, if any, research articles have focused on this issue at the national scale. Every moment that a good is in production or inventory it is consuming resources (e.g. factories, warehouses, and machinery). Flow time can be thought of as water flowing through a hose into a bucket. To meet the demand for water, one can either have multiple hoses flowing at a slow rate or one hose that flows at a fast rate. The slow rate (i.e. long flow time) means more resources (i.e. more hoses) are needed than the fast rate (i.e. short flow time). Thus, if the time is reduced, then the resources consumed are reduced. The methodology highlighted in this paper identifies those areas of production and inventory that consume the longest amount of time in the supply chain of a particular product. National governments can use the methods and results in this paper to identify research areas that, potentially, have a larger impact on efficiency than other areas of research.

We used Little's Law to motivate the flow time concept and to show the relationship between inventory and throughput time. This research paper utilizes the metric of inventory turns in manufacturing to develop a method for measuring the flow time. As part of this method, an industry reiteration rate is developed that uses the proportion of materials purchased from an entity in the same industry. This has the benefit of focusing inventory supply-chain tracking on a useful dichotomy between in- and out-industry entities. Three categories of commodities were examined: aircraft, automobiles/trucks, and computers. The longest three flow routes for each commodity was identified. For automobile/truck manufacturing, broadcast and wireless communications (NAICS 334220) was the longest flow. For aircraft, engine and engine parts manufacturing (NAICS 336412) was the longest flow entity and for computers, computer storage device manufacturing (NAICS 334112). A simulated 25% reduction in the longest entities of the longest routes resulted in as much as a 7.9% reduction in total flow time from raw material extraction to finished product.

Since the proposed method has two subjective processes (i.e. the selection of a threshold for the industry reiteration rate and the selection of inter-industry connections from the BEA Use tables), a probabilistic sensitivity analysis was conducted using Monte Carlo techniques to test for the dependency of the results on the subjective parameter. The identification of the longest flow time entities is fairly robust, as they are typically not affected by the Monte Carlo Analysis. Since the reiteration rate is a subjective calculation and its accuracy is not proven, we also considered the flow time without it. When calculated without a reiteration rate, the three longest entities were still on the longest supply-chain route and were among the top 10 longest entities; therefore, reducing the flow time of these entities still reduces the total flow time for the finished product.

The reiteration rate does not significantly change the longest flow route, as all of the entities in the longest route for automobiles/trucks calculated using the reiteration rate were also in the route calculated without it. For aircraft, 7 of the 11 calculated using the reiteration rate were in both routes and for computers 7 of the 10 were in both. Additionally, the three longest routes have overlapping paths, which provides further confidence in identifying the longest supply-chain route. Moreover, a change agent, such as a trade group or public entity, that seeks to reduce the flow time for any three of the commodities examined could focus on either the longest flow time entity identified with the reiteration rate or that entity identified without the reiteration rate and still reduce the total flow time, which is the primary purpose of reducing flow time. The reiteration rate, however, has a larger impact on identifying the longest entity within the longest route. A change agent would have to choose between using the reiteration rate or not using it with the result being that one of the two would have a larger impact, but it is not clear which one.

Reducing the longest flow time route can reduce the required capital invested in buildings to produce the finished commodity and provide a competitive advantage through a shorter time to market. If the reduction in flow time is in the work-in-process stages, it may also result in a reduction in the capital invested in machinery. A large proportion of flow time is material and finished goods inventory, which are maintained to address uncertainty in demand. Reducing demand uncertainty is, likely, to have the largest impact on these flow times. Improved data and modeling of demand might reduce this uncertainty. Improved information flow through the supply chain might also reduce uncertainty for supply-chain entities. Another source of uncertainty is from transportation. Congested roads result in less predictable arrival times and longer transport routes can result in more uncertainty as well, as it is more difficult to predict the arrival time of long trip compared to a short trip. Thus, the geographic planning of supply chains might have some impact on inventory times. Implementing just-in-time manufacturing can also reduce flow time. This approach seeks to deliver intermediate components as they are needed rather than storing large inventories. Change agents can develop improved means for tracking and moving inventory or improving factory design. Improved data analytics can be developed to identify the slow points within a factory or its inventory.

The limited research on national flow time creates some uncertainty with the estimates. However, the methods and results presented in this paper can be used to prioritize efficiency improvement efforts so that change agents might have a higher probability of having the largest impact possible on efficiency per expenditure dollar. Since the methods discussed in this paper use aggregated national data, it identifies supply-chain entities where there are likely to be bottlenecks for multiple supply chains.

Future research might estimate the cost savings associated with reducing flow times. It might also be useful to determine whether establishments that purchase within their industries would have an easier task in reducing flow times. Additionally, this work can be combined with estimates of other costs such as those in Thomas and Kandaswamy (2015) to identify those areas and aspects of US manufacturing that will have the largest impact on efficiency. Further research can also build on this work in developing advances in economy-wide flow time tracking. One limitation of this approach is that it requires that national data be available on inter-industry purchases, manufacturing inventory, and cost of goods sold. Some countries do not collect this data and, therefore, could not apply this approach.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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