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Flow Time Innovations

The Effect on Productivity and Production in US Manufacturing

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Abstract

Between 2005 and 2016, US multifactor productivity declined an average 0.3 % annually. Some debate has ensued about the cause of this decline or whether there even was a decline in productivity. One aspect of productivity that is neglected in the literature is the effect of flow time on production and productivity. This paper examines the impact that innovations in material, finished goods, and work-in-process flow time have on productivity and production, measured using the multifactor productivity index and manufacturing value added. Using data on US manufacturing from 2005 to 2015, 12 regression models are presented and 19 simulations are developed to examine the impact of flow time on productivity and value added. The flow time for work-in-process goods and that for inventories is examined. The results suggest that flow time innovations have a significant impact on multifactor productivity and production. That is, manufacturers can increase productivity through flow time or lose productivity through increases in flow time, as might be expected. The more significant findings are in regards to the magnitude of impact of flow time. A simulated 20 % decrease in work-in-process flow time results in a 1.21 % increase in multifactor productivity and a 2.23 % increase in value added. A simulated 20 % decrease in material and finished goods flow time increases productivity by 0.29 % and increases value added by 2.80 %. These changes may seem small; however, the average industry's work-in-process flow time from 2005 to 2015 increased 98.8 %. During this same period, multifactor productivity declined an average of 2.2 %. If flow time had remained unchanged from 2005, however, multifactor productivity would have increased between 1.73 % and 3.38 % through other factors, according to our model.

Key words

flow time; manufacturing; productivity; production; value added

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1. Introduction

Multifactor productivity, also known as total factor productivity, reflects overall efficiency and measures that part of GDP growth that is not explained by changes in labor and capital. It reflects changes in "management practices, brand names, organizational change, general knowledge, network effects, spillovers from production factors, adjustment costs, economies of scale, the effects of imperfect competition and measurement errors."[1] Between 1992 and 2004, US multifactor productivity increased by an average 2.0 % per year; however, from 2005 through 2016, it declined by an average 0.3 %.[2] Some debate has ensued regarding the cause of this decline or whether it actually declined. [3] From 2005 through 2016, work-in-process flow time decreased 98.8 %. Additionally, total inventory turns, a measure of capital efficiency used to calculate flow time, decreased 48.0 %. This not only suggests that the decline in multifactor productivity is real, but that it can be understood, in part, through the lens of flow time.

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.[4] Unfortunately, there is a limited understanding on flow time and on its effect on productivity at the national or economy wide level. Thomas and Kandaswamy examined supply-chain flow time (i.e., the time it takes for materials to move from extraction/mining to finished product) for a selection of products at the national level and identify those points in the supply chain that account for a larger proportion of the total flow time.[5] Currently, however, there is limited understanding regarding the impact of reducing flow time.

This paper examines the impact that innovations in material, finished goods, and work-in-process flow time have on productivity and production, measured using the multifactor productivity index and manufacturing value added. There are 4 basic models examined in this paper. The first 2 models examine the impact that work-in-process flow time has on productivity (Model 1) and value added (Model 2). Work-in-process flow time is the amount of time that materials spend in production and is directly connected to the productivity of the processes used in manufacturing. However, it does not reflect the efficiency of energy consumption or the consumption of materials used in products. Moreover, one might consider work-in-process flow time as a measure of process productivity. The second two models examine the impact that material and finished goods flow time has on productivity (Model 3) and value added (Model 4). Manufacturers deliberately store goods as a buffer against shortages caused by uncertainty in deliveries and uncertainty in demand for finished goods. Thus, material

[1] OECD. Multifactor Productivity. 2019. https://data.oecd.org/lprdty/multifactor-productivity.htm
[2] Bureau of Labor Statistics. "Multifactor Productivity Slowdown in US Manufacturing." July 2018. https://www.bls.gov/opub/mlr/2018/article/multifactor-productivity-slowdown-in-us-manufacturing.htm
[3] Bureau of Labor Statistics. "Multifactor Productivity Slowdown in US Manufacturing." July 2018. https://www.bls.gov/opub/mlr/2018/article/multifactor-productivity-slowdown-in-us-manufacturing.htm
[4] Hopp, W.J. and M.L. Spearman. Factory Physics. 3rd edition. Long Grove, IL: Waveland Press, 2008. 230.
[5] Thomas, Douglas and Anand Kandaswamy. "An Examination of National Supply-Chain Flow Time." Economic Systems Research. (2016). DOI: https://doi.org/10.1080/09535314.2017.1407296.

and finished goods flow time are not a direct result of the manufacturing process, but rather a necessary cost. Each of the 4 basic models has 3 variants to examine whether different confounders change the impact of flow time in the model, resulting in a total of 12 models. Additionally, 19 simulations are presented to examine the magnitude of flow time's impact.

2. Background

There are a limited number of papers examining flow time innovations; however, there have been numerous studies examining the effect of productivity along with research and development on production. Two approaches are apparent in the literature: the primal approach (production function) and the dual approach (cost function) with the primal approach being far more prevalent.[6] Given its pervasiveness, this paper utilizes the primal approach, which draws on a Cobb-Douglas production function that tends to model real output on research and development capital, capital stock, labor (number of employees or hours worked), and technological progress:

$$Q = Ae^{\lambda}C^{\beta_{x1}}L^{\beta_{x2}}K^{\beta_{x3}}\mathcal{E}^{\beta_{x4}}$$

where

Q = Real output

C = Real capital stock

K = Real research and development capital

L = Labor (number of employees or labor hours worked)

Ae^{λ} = is technological progress with a rate of disembodied technological change λ

β_{xn} = Estimated parameters

This paper uses real value added in place of real output. Output is, typically, the revenue received by an establishment such as a factory while value added is the revenue less purchases from other establishments. Value added is used for this analysis because output has the inherent problem of double counting. Part of the revenue received by one establishment is typically passed on to other establishments to pay for supplies and intermediate goods. Thus, that portion that is passed on is counted when the first establishment receives it and when the second establishment receives it. Moreover, output can increase simply due to having more supply chain points. Because value added excludes the purchases from other establishments, it avoids double counting.

In addition to studies on output, there are also studies and models on multi-factor productivity. These models tend to also use a Cobb-Douglas production function. An OECD paper, for instance, models multi-factor productivity as a function of domestic research and development capital stock, foreign research and development capital stock, public research and development capital stock, and a business cycle variable.[7] There are

[6] Ugur, Mehmet, Eshref Trushin, Edna Solomon, and Francesco Guidi. "R&D and Productivity in OECD Firms and Industries: A Hierarchical Meta-Regression Analysis." Research Policy. 45 (2016): 2069-2086.

[7] Guellec, Dominique and Bruno van Pottelsberghe de la Potterie. "R&D and Productivity Growth: Panel Data Analysis of 16 OECD Countries." OECD Economic Studies No. 33. (2001). https://www.oecd.org/eco/growth/1958639.pdf

numerous papers with varying methodologies for examining productivity growth.[8,9,10] An NBER paper by Bloom et al. modeled economic growth as a function of researchers and research productivity.[11] Some papers estimate the fraction of growth that is attributed to multifactor productivity (also called total factor productivity), which ranges between 0.175 and 0.903.[12] Few papers are available that examine flow time innovations or incorporate flow time into their models, however. Similar to the approach for examining value added, this paper will draw on the models that have examined productivity and use a Cobb Douglas production function.

As previously referenced, Thomas and Kandaswamy developed a method for identifying bottlenecks in national supply chains by mapping material flows and their flow times.[13] This paper developed a method for tracking industry-level flow time of US manufactured products using data on manufacturing inventory and inter-industry interactions. To build on this work, this paper examines the effect of reducing flow time through innovation in an industry. Enterprises and establishments dedicate a substantial amount of resources to improve the efficiency of their operations and supply chains. Managers of supply chains are involved in nearly every facet of a business, including purchasing, production, transportation, and storage. Inventory is maintained by companies to avoid costly shortages, which is often encompassed in the axiom, "buffer or suffer." Shortages of materials and finished products can result in lost sales. Proctor and Gamble, for example, estimates that when they are out of stock, 29 % of their potential sales are lost.[14] That is, 29 % of the customers go elsewhere for their product needs rather than waiting for the out-of-stock product.

In addition to the potential for lost customers, a shortage of materials leaves machinery and personnel sitting idle until resources arrive. To avoid this situation, companies increase their inventories as their uncertainty increases. For instance, traffic congestion results in uncertainty in deliveries making it necessary to carry larger inventories to avoid shortages.[15] Inventory is costly, however, as it is stored capital that requires warehouse space and it depreciates. Inventory in the personal computer industry, for instance, depreciates 1 % to 4 % each week that it is stored.[16, 17] In addition to the costs of inventory, higher production times (i.e., work-in-process time) 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-

[8] Foster, Lucia, John Haltiwanger, and C.J. Krizan. "Aggregate Productivity Growth." Chapter 8 from Hulten, Charles, Edwin R. Dean, and Michael J. Harper. New Developments in Productivity Analysis. University of Chicago Press, 2001. 303-372. http://www.nber.org/books/hult01-1
[9] Jajri, Idris. "Determinants of Total Factor Productivity Growth in Malaysia." Journal of Economic Cooperation. Vol 28 issue 3(2007): 41-58.
[10] Kancs, d'Artis and Boriss Siliverstovs. "R&D and Non-Linear Productivity Growth." Research Policy. Vol 45 (2016): 634-646.
[11] Bloom, Nicholas, Charles I Jones, John Van Reenen, and Michael Webb. "Are Ideas Getting Harder to Find?" NBER Working Paper 23782. 2017. http://www.nber.org/papers/w23782
[12] Baier, Scott L., Gerald P. Dwyer Jr., and Robert Tamura. "How Important are Capital and Total Factor Productivity for Economic Growth." Economic Inquiry. Vol 44 no. 1 (2006): 23-49.
[13] Thomas, Douglas and Anand Kandaswamy. "An Examination of National Supply-Chain Flow Time." Economic Systems Research. (2016). DOI: https://doi.org/10.1080/09535314.2017.1407296.
[14] Harrison, Terry P., Hau L. Lee, and John J. Neale. The Practice of Supply Chain Management: Where Theory and Application Converge. New York, NY: Springer Science&Business Media inc., 2005. 5.
[15] Shirley, Chad and Cliffor Winston. "Firm Inventory Behavior and the Returns from Highway Infrastructure Investments." Journal of Urban Economics. 55 (2004). 398-415.
[16] Kuhel, J.S. Balancing Act. Supply Chain Technology News. June 1, 2001.
[17] Park, A and P Burrows. Dell, The Conqueror. Business Week. September 24, 2001.

process times or lead times enhance competitiveness, but there is difficulty in quantifying the benefits.[18] 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 2016, the US manufacturing industry held an estimated average of $617 billion of inventory for an industry that produces $2.4 trillion in value added.[19] Establishments track and analyze their flow time data to identify high cost areas where efficiency improvements might be made to remain competitive. There is no commonly agreed upon metric for measuring flow time across the variety of manufacturing industries. The metric might be inventory turns, turnover ratio, or flow time among others, but it is standard practice for individual companies to use a selected metric to measure production time in order to improve efficiency.[20] A company that has materials on hand for long periods of time will often have higher costs. Companies will often examine the flow time for different steps in their production to identify bottlenecks. In addition to the efforts of private companies, change agents such as public entities and industry trade groups also strive to improve efficiency in manufacturing. These efforts, however, tend not to focus on the activities of individual factories but on the aggregate performance of factories within a category. Unfortunately, the metrics for an individual factory don't always transfer well to the aggregate due to data availability. For instance, there is limited data on the cycle time for various processes. Even though data is lacking for some metrics, there is still the issue of bottlenecks in the supply chain and how to properly account for them.

The current efficiency metrics and resource tracking at the national level, such as labor productivity, multifactor productivity, and value added, do not by themselves reveal the bottlenecks or potential areas for efficiency improvement in manufacturing supply chains. There are an abundance of books and articles on lean manufacturing, six sigma, and other continuous improvement efforts for manufacturing such as, "The Toyota Way" by Liker[21]; however, these metrics and efforts focus on the efficiency of the individual firm and provide limited insights at the multi-industry supply chain level as the data requirements for these approaches are not feasible at larger scales. Operations management and methods in accounting tend not to focus on examining multiple supply chains for multiple product types. However, inventory turns and flow time are standard measurements for tracking the time it takes to produce a manufactured good and industry level data for these metrics is available from the Economic Census and Annual Survey of Manufactures.

[18] Blackburn, J. Valuing Time in Supply Chains: Establishing Limits of Time-Based Competition. Journal of Operations Management. 30, (2012): 396-405.
[19] US Census Bureau. Annual Survey of Manufactures. 2017. https://www.census.gov/manufacturing/asm/
[20] Hopp, W.J. and M.L. Spearman. Factory Physics. 3rd edition. Long Grove, IL: Waveland Press, 2008. 230.
[21] Liker, Jeffrey K. The Toyota Way. New York, NY: McGraw-Hill, 2004.

3. Data

This paper uses a selection of datasets to examine time flow's impact on productivity and compensation: the Annual Survey of Manufactures from the US Census Bureau, Economic Census from the US Census Bureau, price indices from the Bureau of Labor Statistics, aggregate work hours from the Bureau of Labor Statistics, Occupational Employment Projections from the Bureau of Labor Statistics, research and development data from the National Science Foundation, and research and development data from the Organization for Economic Cooperation and Development (OECD).

US Census Bureau Data: The Annual Survey of Manufactures (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 5-year intervals since 1967. 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. Both the ASM and the Economic Census use NAICS classifications. The inventory data from the Economic Census and Annual Survey of Manufactures 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.

Bureau of Labor Statistics: Three datasets were used from the Bureau of Labor Statistics. The first is the Producer Price Index and the Consumer Price Index. The Producer Price Index "measures the average change over time in the selling prices received by domestic producers for their output."[22] The data is available for over 500 industries and is collected using surveys sent to establishments. The Consumer Price Index is the average change in prices for a selected basket of goods/services paid by consumers.[23] The data is gathered in person from store shelves, calling stores, and from the internet. Both the Producer Price Index and the Consumer Price Index were used in this paper to adjust dollar values to a common year.

The second dataset used from the Bureau of Labor Statistics is aggregate work hours from the Consumer Employment Statistics. This data is collected each month through surveys of establishments.[24] The third dataset from the Bureau of Labor Statistics is the Occupational Employment Projections, which includes education by occupation and

[22] Bureau of Labor Statistics. Producer Price Index. 2017. https://www.bls.gov/ppi/
[23] Bureau of Labor Statistics. Consumer Price Index. 2017. https://www.bls.gov/cpi/questions-and-answers.htm#Question_11
[24] Bureau of Labor Statistics. Current Employment Statistics. https://www.bls.gov/ces/

employment by industry and occupation. This data is developed using the results from various surveys.[25]

National Science Foundation: The National Science Foundation provides data on research and development expenditures by businesses and by the federal government. The business data is collected through the Business Research and Development and Innovation Survey.[26] The survey is conducted by the Census Bureau for the National Science Foundation. Over 40 000 companies are surveyed annually. The federal expenditures on research and development are acquired through the Federally Funded Research and Development Centers R&D Survey and is a census of all known facilities.[27,28]

OECD Statistics: Total gross domestic expenditures on research and development is taken from the OECD Main Science and Technology Indicators. The OECD collects research and development data from various sources. Its methods are outlined in the OECD "Frascati Manual."[29]

[25] Bureau of Labor Statistics. Occupational Employment Projections. https://www.bls.gov/emp/ep_data_occupational_data.htm
[26] National Science Foundation. Business Research and Development and Innovation Survey (BRDIS). https://www.nsf.gov/statistics/srvyindustry/
[27] National Science Foundation. FFRDC Research and Development Survey. https://www.nsf.gov/statistics/srvyffrdc/
[28] National Science Foundation. Science and Engineering Indicators. https://www.nsf.gov/statistics/2018/nsb20181/data/tables
[29] OECD. "Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development." 6th Edition. 2002. http://www.oecd.org/sti/inno/frascatimanualproposedstandardpracticeforsurveysonresearchandexperimentaldevelopment6thedition.htm

4. Methods

The processes used in manufacturing result in some amount of time flow that is then reflected in productivity. When innovations reduce process flow time (i.e., work-in-process flow time), productivity is, typically, increased. It is not clear, however, what the connection is between time flow and productivity. For instance, if flow time is reduced by 10 % through innovation, what is the average impact on productivity. This information provides insight for manufacturers and public researchers on the impact of different types of improvements in production.

When productivity increases, costs go down. The result can be that production goes up due to an increase in consumer demand, given lower prices. Domestic production can also increase due to a shift from offshore production due to more competitive production. It is not clear how much production goes up when processes are altered to reduce flow time.

This paper seeks to test a series of hypotheses regarding flow time:

1. Decreased work-in-process flow time results in increased productivity (Model 1).
2. Decreased work-in-process flow time results in higher production (measured in value added) (Model 2).
3. Decreased finished goods flow time results in increased productivity (Model 3).
4. Decreased finished goods flow time results in increased value added (Model 4).

The paper further seeks to estimate the impact of flow time on productivity and production. To provide evidence for testing the hypotheses, four models were developed with each being in the form of a Cobb-Douglas Production function. Multiple models are used as there are different confounding factors and different dependent variables for examining the different hypotheses. A summary of the data and variables are provided in Table 4-1.

4.1. Model 1

The first model examines the effect that innovations affecting work-in-process time has on productivity. Some portion of productivity is impacted by flow time innovations with the remaining portion being due to non-flow time factors such as the amount of material used in the product and energy consumed for buildings and machinery. The portion of productivity due to flow-time and the portion due to non-flow time factors are affected by a set of potential confounding factors, including investments in physical capital, human capital, technological advancement, and economies of scale. Education levels are used to control for human capital along with research and development capital. The average number of employees per firm is used to control for economies of scale, capital expenditures are used to control for capital investments, and an industry indicator

Table 4-1: Data Summary, Mean of 4-Digit NAICS by Year

Year	Employees (Thousands)	Capital Stock ($million 2015)	Work-In-Process Flow Time (hours)	Material and Finished Goods Flow Time (hours)	Percent with Bachelors or Masters Degree	Employees per Firm	Estimated Research and Development ($2015billion)[a]	Value Added ($million 2015)	Durable Goods ($2015trillions)	Nondurable Goods ($trillions2015)
2005	159	21.99	160	533	26.6	67.6	28.1	31.3	1.35	2.28
2006	159	23.43	161	545	26.6	67.6	29.5	31.1	1.37	2.36
2007	137	26.67	270	936	26.3	71.4	28.3	33.9	1.36	2.44
2008	152	26.55	268	953	26.6	65.1	31.4	28.4	1.35	2.48
2009	135	28.10	300	1 058	26.6	60.5	31.7	25.1	1.21	2.50
2010	126	29.27	291	991	26.6	57.0	31.7	26.5	1.13	2.40
2011	128	30.32	293	991	26.6	57.7	32.1	26.7	1.16	2.49
2012	130	31.51	280	978	26.6	46.8	32.0	26.4	1.19	2.60
2013	131	32.94	281	993	26.6	61.4	33.3	26.7	1.23	2.62
2014	133	34.32	287	1 002	26.6	60.9	34.7	27.0	1.26	2.63
2015	135	35.81	294	1 044	26.6	61.9	36.4	27.6	1.30	2.67
Low	3	21.99	5	70	11.2	1.7	28.1	0.3	1.37	2.66
High	740	35.81	3 342	639	65.4	575.0	36.4	218.0	1.37	2.67

[a] Interaction variable

variable is used to control for the different activities involved in producing different types of products. The education variable is an estimated proportion of the employees in an industry that have a bachelor's degree or higher. It is estimated using data on education attainment by occupation combined with data on industry employment by occupation.

Model 1 has the structural equation for estimating productivity represented as:

Equation 1

$$PD = FT_{wip}^{\beta_{1a}} ED^{\beta_{2a}} RD^{\beta_{3a}} FS^{\beta_{4a}} CAPE^{\beta_{5a}} I^{\beta_{6.1a}} I^{\beta_{6.2a}} \dots I^{\beta_{6.na}} \mathcal{E}^{\beta_{7a}}$$

where

PD = Multifactor productivity from the Bureau of Labor Statistics

FT_{WIP} = Flow time for work in progress by industry by year

$ED =$ Estimated percent of the industry labor force with a bachelors or graduate degree in the previous

year

$CAPE =$ Capital expenditures

$RD =$ National research and development expenditures for the previous year estimated by the OECD

multiplied by the industries share of manufacturing research and development from

NSF data at the 3-digit NAICS code level

$FS =$ Average number of employees per firm by industry by year

$I =$ Indicator variables for each 4-digit NAICS code

$\mathcal{E}$ = Error term

The model is estimated using the log form, resulting in the following:

Equation 2

$$ln(PD) = \beta_{1a} ln(FT_{WIP}) + \beta_{2a} ln(ED) + \beta_{3a} ln(RD) + \beta_{4a} ln(FS) + \beta_{5a} ln(CAPE) + \beta_{6.1a} ln(I) + \beta_{6.2a} ln(I) \ldots + \beta_{6.na} ln(I) + \beta_{7a} ln(\mathcal{E})$$

Two additional versions of this model were also examined. The first, referred to as Model 1.2, adds a trend variable (TRND), capital stock (CAPS), capital stock per employee (CAPS/EMP), and federal research and development (FEDRD). The trend variable is meant to capture technological progress that may be occurring over time. Capital stock captures the total amount of capital that is being used rather than just the expenditures during the year. It is estimated by taking the 2012 estimate of the gross value of depreciable assets from the Economic Census, as this is the only year that it is estimated. Other years are estimated by adding/subtracting expenditures on capital and subtracting/adding an estimate of retirements, which is also estimated using the 2012 Economic Census. The capital stock per employee variable in Model 1.2 controls for the combination of people and machinery. A third version of this model, referred to as Model 1.3, has research and development, education, federal research and development, firm size, work-in-process flow time, and a trend variable. These three variations are examined to further test the impact of flow time.

4.2. Model 2

Model 2 replaces the dependent variable in Model 1, productivity, with value added (VA) in order to examine the impact on production (i.e., Hypothesis 2) and adds employees as a variable representing the amount of labor being utilized. Also, capital stock is used to account for the magnitude of production. An interaction variable between the capital stock and the number of employees is also included, as people and machinery work together to manufacture products. The structural equation for estimating value added is represented as:

Equation 3

$$VA = FT_{wip}^{\beta_{1b}} ED^{\beta_{2b}} RD^{\beta_{3b}} FS^{\beta_{4b}} CAPS^{\beta_{5b}} EMP^{\beta_{6b}} CAPS\_EMP^{\beta_{7b}} I^{\beta_{8.1b}} I^{\beta_{8.2b}} \ldots I^{\beta_{8.nb}} \mathcal{E}^{\beta_{9b}}$$

where

$CAPS =$ Previous year's estimated capital stock, which utilizes the 2012 gross value of depreciable

assets at the beginning of the year. To estimate other year's depreciable assets, the rate of

retirements and the value of capital expenditures is used to adjust the 2012 value.

EMP = The total number of employees

The model is estimated using the log form, resulting in the following:

Equation 4

$$\begin{aligned} ln(VA) = \beta_{1b} ln(FT_{WIP}) + \beta_{2b} ln(ED) + \beta_{3b} ln(RD) + \beta_{4b} ln(FS) + \beta_{5b} ln(CAPS) \\ + \beta_{6b} ln(EMP) + \beta_{7b} ln(CAPS\_EMP) + \beta_{8.1b} ln(I) + \beta_{8.2b} ln(I) \ldots \\ + \beta_{8.nb} ln(I) + \beta_{9b} ln(\mathcal{E}) \end{aligned}$$

Two additional versions of this model were also examined. The first, referred to as Model 2.2, removes the interaction variable, testing whether removing it affects the flow time parameter. The second, referred to as Model 2.3, includes capital expenditures (CAPE), capital stock (CAPS), capital stock per employee (CAPS/EMP), employee compensation (COMP), education (ED), firm size (FS), work-in-process flow time (FT_{WIP}), research and development (RD), and a trend variable (TRND). These different variations reveal whether flow time's effect is changed by the inclusion of other variables due to multicollinearity and if so, how it changes.

4.3. Model 3

The third and fourth models examine material and finished goods flow time. Material goods flow time is the amount of time that a manufacturer holds on to materials before they are used in production. Finished goods flow time is the time that the manufacturer stores a finished product before a customer takes possession of it. The longer these items are stored, the more resources that are consumed. The confounding factors affecting this inventory time are different than those affecting the work-in-process time. Manufacturers deliberately store goods as a buffer against shortages caused by uncertainty in deliveries and uncertainty in demand for finished goods. The primary means for reducing inventory time is to reduce uncertainty through improved forecasting. Improved human capital improves both forecasting and other non-flow time improvements in productivity. In Model 3, education is used to control for these non-flow time improvements. The structural equation is represented as:

Equation 5

$$PD = ED^{\beta_{1c}} FT_{M\&FG}^{\beta_{2c}} I^{\beta_{3.1c}} I^{\beta_{3.2c}} \dots I^{\beta_{3.nc}} \mathcal{E}^{\beta_{4c}}$$

where

$FT_{M\&FG}$ = Sum of the flow time for materials and finished goods

The model is estimated using the log form, resulting in the following:

Equation 6

$$\ln(PD) = \beta_{1c} ln(ED) + \beta_{2c} ln(FT_{M\&FG}) + \beta_{3.1c} ln(I) + \beta_{3.2c} ln(I) \dots + \beta_{3.nc} ln(I) + \beta_{4c} ln(\mathcal{E})$$

This model has two additional variants. The first has research and development (RD) and federal research and development (FEDRD) included as variables to further control for increased forecasting ability. This model is referred to as Model 3.2. The second variation, referred to as Model 3.3, has the same variables as Model 3.2 with the addition of a trend variable (TRND), durable goods (DUR), and nondurable goods (NDUR) to control for changes in demand.

4.4. Model 4

The model for examining the effect of material and finished goods flow time on value added has the variables in Model 3.1 with the addition of two variables, consumer expenditures on durable goods and consumer expenditures on nondurable goods. These two variables account for changes in demand that can affect how much inventory manufacturers are holding and affect production levels. This model also uses education as a proxy for non-flow time improvements in productivity. The structural equation is represented as:

Equation 7

$$VA = FT_{M\&FG}^{\beta_{1d}} DUR^{\beta_{2d}} NDUR^{\beta_{3d}} ED^{\beta_{4d}} I^{\beta_{5.1d}} I^{\beta_{5.2d}} \dots I^{\beta_{5.nd}} \mathcal{E}^{\beta_{6d}}$$

where

$DUR =$ Consumer expenditures on durable goods

$NDUR =$ Consumer expenditures on nondurable goods

The model is estimated using the log form, resulting in the following:

Equation 8

$$ln(VA) = \beta_{1d} ln(FT_{M\&FG}) + \beta_{2d} ln(DUR) + \beta_{3d} ln(NDUR) + \beta_{4d} ln(ED) + \beta_{5.1d} ln(I) + \beta_{5.2d} ln(I) \ldots + \beta_{5.nd} ln(I) + \beta_{6d} ln(\mathcal{E})$$

This model also has two additional variants. For the first variant, consumer expenditures are broken out into eight categories:

VEH: Motor vehicles and parts

FURN: Furnishings and durable household equipment

REC: Recreational goods and vehicles

ODUR: Other durable goods

FOOD: Food and beverages purchased for off-premises consumption

CLOTH: Clothing and footwear

G&E: Gasoline and other energy goods

ONDUR: Other nondurable goods

This model is referred to as Model 4.2. The second variant, Model 4.3, has multifactor productivity (PD) added as a variable to control for increases in the productivity of production.

4.5. Measuring Flow Time

This paper uses the calculation for flow time used in Thomas and Kandaswamy.[30] The method for approximating the sum of the flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories for an industry, categorized by NAICS codes, is:

Equation 9

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

where

$FT_{\mathrm{IND,Total}}$ = Total estimated flow time for industry IND

[30] Thomas, Douglas and Anand Kandaswamy. “An Examination of National Supply-Chain Flow Time.” Economic Systems Research. (2016). DOI: https://doi.org/10.1080/09535314.2017.1407296.

i = Inventory item where i is materials and supplies (MS), work-in-process (WIP), or finished

goods (FG) inventories.

$INV_{\mathrm{IND,Total,BOY}}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished

goods inventories) for industry IND at the beginning of the year

$INV_{\mathrm{IND,Total,EOY}}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished

goods inventories) for industry IND at the end of the year

$TRN_{\mathrm{IND,Total}}$ = Inventory turns for industry IND (defined below)

IRR_{IND} = Industry reiteration rate for industry IND (defined below)

Inventory turns, TRN_{Total}, is the number of times inventory is sold or used in a time period such as a year.[31,32,33] It is calculated as the cost of goods sold (COGS), which is the cost of the inventory that businesses sell to customers, divided by the average inventory:[34]

Equation 10

$$TRN_{\mathrm{Total}} = \frac{COGS}{\left(\frac{INV_{\mathrm{Total,BOY}} + INV_{\mathrm{Total,EOY}}}{2}\right)}$$

where

$$COGS = AP + FB + MAT + DEP + RP + OTH + \left(INV_{\mathrm{Total,BOY}} - INV_{\mathrm{Total,EOY}}\right)$$

AP = Annual payroll

FB = Fringe benefits

MAT = Total cost of materials

[31] Horngren, C.T., W.T. Harrison Jr. and L.S. Bamber. Accounting. 5th edition. Upper Saddle River, NJ, Prentice Hall, 2002. 725, 186.
[32] Stickney, C.P. and P.R. Brown Financial Reporting and Statement Analysis. Mason, OH: Southwestern, 1999. 136–137.
[33] Hopp,W.J. and M.L. Spearman Factory Physics. 3rd edition. Long Grove, IL: Waveland Press, 2008. 230.
[34] Horngren, C.T., W.T. Harrison Jr. and L.S. Bamber Accounting. 5th edition. Upper Saddle River, NJ: Prentice Hall, 2002. 168.

DEP = Depreciation

RP = Rental payments

OTH = Total other expenses

Inventory turns is frequently stated in annual terms and is used to study a number of fields, including distributive trade, particularly with respect to wholesaling.[35] The data for estimating $COGS$ is from the Annual Survey of Manufacturing. Inventories are calculated using the average of the beginning of year inventories and end of year inventories, which is a standard practice.[36]

4.6. Simulation

This paper uses 19 simulations to demonstrate the impact of flow-time on productivity and production. The estimated parameters from models 1.1, 2.1, 3.1, and 4.1 are used to estimate the impact of a 1 %, 5 %, 10 %, and 20 % decrease in work-in-process flow time or material and finished goods flow time, totaling 16 models. Each flow time observation is reduced by 1 %, 5 %, 10 %, and 20 % for the entirety of the study period. Then, the dependent variable is estimated using the estimated parameters. These are then compared to simulations where the flow time was unaltered. The last 3 simulations utilize Model 1.1 through Model 1.3 to estimate multifactor productivity for 2015 using the work-in-process flow times from 2005. This estimate represents the effect of the change in flow time over the study period, all else being unchanged. The growth in multifactor productivity between actual 2005 levels and simulated 2015 levels is then calculated. This is then compared to the actual growth in multifactor productivity.

[35] Hopp,W.J. andM.L. Spearman Factory Physics. 3rd edition. Long Grove, IL: Waveland Press, 2008. 230.
[36] Horngren, C.T., W.T. Harrison Jr. and L.S. Bamber. Accounting. 5th edition. Upper Saddle River, NJ, Prentice Hall, 2002. 725, 186.

5. Results

Table 5-1 presents a guide to the variables in each model and Table 5-2 presents a guide to the results tables. A total of 12 models are examined along with 19 simulations. The effect of work-in-process flow time along with material and finished goods flow time are examined on value added and productivity. These two factors result in four basic models. Each of these models then has three variations. A simulated change in flow time is made to examine the impact on productivity and value added. The results provide evidence that support all four hypotheses:

1. Decreased work-in-process flow time results in increased productivity: Supported by the statistical significance of work-in-process flow time (FT_{WIP}) in Model 1, where the dependent variable is multifactor productivity.
2. Decreased work-in-process flow time results in higher production: Supported by the statistical significance of work-in-process flow time (FT_{WIP}) in Model 2, where the dependent variable is value added.
3. Decreased finished goods flow time results in increased productivity: Supported by the statistical significance of material and finished goods flow time ($FT_{M\&FG}$) in Model 3, where the dependent variable is multifactor productivity.
4. Decreased finished goods flow time results in increased value added: Supported by the statistical significance of material and finished goods flow time ($FT_{M\&FG}$) in Model 4, where the dependent variable is value added.

Table 5-3 and Table 5 present the results of examining work-in-process flow time's impact on multifactor productivity and value added. Work-in-process flow time is significant in all models. The elasticity for its impact on productivity, which is equivalent to the coefficient, is between -0.054 and -0.022; that is, for every 1 % change in work-in-process flow time there is between -0.054 % and -0.022 % change in productivity. It is important to note that the productivity variable is an index that has a base year of 2007 where the index is set at 100 for each industry. Consequently, the index is not comparable across industries; that is, the index for one industry cannot be compared to the index in another industry to determine which industry is more productive. As seen in Figure 5-1, the 95 % confidence interval for work-in-process flow time has some overlap between the three models (i.e., Model 1.1, Model 1.2, and Model 1.3); however, Model 1.1 has only a small overlap with Model 1.3 and no overlap with Model 1.2. These differences suggest that the parameter for flow time changes as Model 1 is modified with other potential confounders.

The elasticity for the impact on value added for each of the models, as seen in Table 5, is between -0.099 and -0.074. As seen in Figure 5-1, there is significant overlap in the 95 % confidence interval for the three variations of work-in-process flow time in Model 2, suggesting that the parameter estimate does not change significantly from model to model. The R^2 value is above 0.98, which is due to the inclusion of the industry indicator

Table 5-1: Guide to Models

		Hypothesis 1			Hypothesis 2			Hypothesis 3			Hypothesis 4		
		Model 1.1	Model 1.2	Model 1.3	Model 2.1	Model 2.2	Model 2.3	Model 3.1	Model 3.2	Model 3.3	Model 4.1	Model 4.2	Model 4.3
Dependent Variable	Productivity	X	X	X				X	X	X			
	Value Added				X	X	X				X	X	X
Independent Variable of Interest	$FT_{M\&FG}$							X	X	X	X	X	X
	FT_{WIP}	X	X	X	X	X	X						
Other Independent Variables	CAPE	X	X				X						
	CAPS		X		X	X	X						
	CAPS/EMP		X				X						
	CAPS_EMP				X								
	CLOTH											X	X
	COMP						X						
	DUR									X	X		
	ED	X	X	X	X	X	X	X	X	X	X	X	X
	EMP				X	X							
	FEDRD		X	X					X	X			
	FOOD											X	X
	FS	X	X	X	X	X	X						
	FURN											X	X
	G&E											X	X
	NDUR									X	X		
	ODUR											X	X
	ONDUR											X	X
	PD												X
	RD	X	X	X	X	X	X		X	X		X	X
	REC											X	X
	TRND		X	X			X			X			
	VEH											X	X

Table 5-2: Guide to Results Tables

	WIP Flow Time	Material and Finished Goods Flow Time
Productivity	Table 4	Table 6
Value Added	Table 5	Table 7
Simulated Change	*Table 8*	*Table 9*

Table 5-3: Results for Models 1.1-1.3 Examining the Effect of Work-in-Process Time on Productivity - Relevant to Hypothesis 1 (Industry Indicator Results not Shown)

	Variable	Coefficient	Std. Error	95 % Confidence Interval		Obs.	R^2	AIC
Model 1.1	CAPE***	0.037	0.008	0.021	0.053	840	0.520	-2229.0
	Constant	3.763	0.754	2.284	5.243			
	ED***	-1.621	0.315	-2.240	-1.002			
	FS	0.008	0.006	-0.004	0.020			
	FT_{WIP}***	-0.054	0.008	-0.069	-0.038			
	RD***	0.328	0.030	0.269	0.387			
Model 1.2	CAPE***	0.060	0.009	0.043	0.077	822	0.568	-2287.1
	CAPS**	-0.065	0.026	-0.115	-0.014			
	CAPS/EMP	0.004	0.014	-0.023	0.030			
	Constant	3.218	1.102	1.055	5.381			
	ED***	-2.601	0.430	-3.444	-1.757			
	FEDRD***	0.144	0.041	0.063	0.225			
	FS	0.000	0.006	-0.012	0.012			
	FT_{WIP}**	-0.022	0.009	-0.039	-0.005			
	RD***	0.432	0.033	0.368	0.496			
	TRND***	-0.004	0.001	-0.006	-0.001			
Model 1.3	Constant	3.230	1.052	1.165	5.295	840	0.538	-2258.7
	ED***	-2.135	0.325	-2.773	-1.497			
	FEDRD**	0.100	0.042	0.017	0.183			
	FS	0.005	0.006	-0.007	0.017			
	FT_{WIP}***	-0.027	0.008	-0.044	-0.011			
	RD***	0.377	0.031	0.316	0.438			
	TRND***	-0.006	0.001	-0.007	-0.004			

* Significant at the 90 % confidence interval
** Significant at the 95 % confidence interval
*** Significant at the 99 % confidence interval

variables -i.e., most of the variation in value added in the dataset comes from across industry variation as opposed to temporal variation. The results from Table 5-3 and Table 5 provide evidence for addressing hypothesis 1 and hypothesis 2, which concern the effect of work-in-process flow time on productivity and production (i.e., value added). The elasticities may appear relatively small; however, it is important to note that a decrease in flow time would, typically, be the result of an initial investment and the increase in productivity and value added would then be realized each year following the

Table 5-4: Results for Models 2.1-2.3 Examining the Effect of Work-in-Process Time on Value Added – Relevant to Hypothesis 2 (Industry Indicator and Trend Variable Results Not Shown)

	Variable	Coefficient	Std. Error	95 % Confidence Interval		Observations	R^2	AIC
Model 2.1	CAPS***	1.459	0.326	0.819	2.099	822	0.981	-885.7
	CAPS_EMP***	-0.139	0.028	-0.193	-0.084			
	Constant***	-24.981	5.779	-36.326	-13.636			
	ED***	3.939	0.938	2.097	5.781			
	EMP***	2.569	0.465	1.656	3.482			
	FS***	0.052	0.014	0.024	0.079			
	FT_{WIP}***	-0.099	0.020	-0.139	-0.059			
	RD**	0.145	0.074	0.000	0.289			
Model 2.2	CAPS***	-0.162	0.034	-0.229	-0.095	822	0.980	-860.4
	Constant	1.675	2.263	-2.769	6.118			
	ED***	4.384	0.949	2.521	6.247			
	EMP***	0.249	0.032	0.187	0.312			
	FS***	0.056	0.014	0.028	0.084			
	FT_{WIP}***	-0.093	0.021	-0.134	-0.053			
	RD	0.083	0.074	-0.061	0.228			
Model 2.3	CAPE***	0.070	0.016	0.039	0.101	822	0.991	-1497.4
	CAPS***	-0.263	0.043	-0.349	-0.178			
	CAPS/EMP	0.083	0.025	0.035	0.131			
	COMP***	0.958	0.040	0.880	1.036			
	Constant***	38.383	2.123	34.216	42.550			
	ED***	-8.633	0.821	-10.244	-7.021			
	FS	0.006	0.010	-0.014	0.025			
	FT_{WIP}***	-0.074	0.014	-0.102	-0.047			
	RD***	0.485	0.053	0.381	0.589			
	TRND	0.002	0.002	-0.002	0.006			

* Significant at the 90 % confidence interval
** Significant at the 95 % confidence interval
*** Significant at the 99 % confidence interval

investment. For instance, an establishment might invest in new machinery, which would be used year after year. Note, however, that the models in this paper do not investigate the impact in subsequent years. It is also important to note that flow time can change significantly, as the average industry's work-in-process flow time from 2005 to 2015 increased 98.8 %.

Capital and Education were significant in both models; however, some of the models had negative elasticities for them. The negative direction of these impacts is not consistent with what might be expected. This might be occurring because flow time is capturing impacts that would otherwise result from education and capital, as education and capital investments are the means for reducing flow time. The variables might then be capturing the cost of capital and education. It is interesting to note that capital stock is negative in Models 2.1 through 2.3[37], however, capital expenditures is positive in Model 2.3. Research and development is significant in Models 1.1 through 2.3.

An observation regarding the models is that investments in larger industries result in larger returns. Utilizing model 2.2, for instance, an increase in research and development for the top quartile industries (i.e., the largest 25 % of industries by value added) has a 4.9 times larger average impact on value added than the same increase on the bottom quartile (results not shown).[38] A decrease in flow time for the top quartile, measured in value added, has an impact 8.5 times greater than that of the lowest quartile.[39] The implication is that research and development expenditures have a larger return on investment for larger industries as does work-in-process flow time. This trend occurs, in part, as a result of the assumptions in the model. A means for testing this relationship is to compare the result to a version of the model with a linear production function. The equations are the same as the previous models excluding the natural logs, making the structural equation strictly linear. The R^2 value for 11 of the 12 linear versions of the production function (results not shown) is less than those for the Cobb-Douglas form (Model 3.1 had a larger R^2 for a linear model); that is, the by this measure 11 of the models outperformed a strictly linear version. The Akaike Information Criterion (AIC), which is used to compare statistical models, indicated that all 12 of the Cobb-Douglas forms of the model outperform the linear versions of the production function (results not shown), suggesting that the relationship holds true. Moreover, the performance of these models suggest that investments in larger industries result in larger returns. A potential reason for this is that industries are categories of production activities. A larger industry suggests that there is more of a particular type of activity occurring; thus, an increase in productivity has a larger impact.

Table 5-5 and Table 5-6 present the results from examining material and finished goods flow time. Recall that these flow times are deliberately set by manufacturers to buffer against shortages in materials and shortages of product for customers as opposed to the work-in-process flow time which is determined by the efficiency and productivity of the manufacturing process. The confounding variables are, then, different for material and finished goods inventory. The examination of its impact on productivity shows that it is

[37] Note that for Model 2.1, capital stock has a negative elasticity after accounting for the interaction variable (results not shown).
[38] The increase was a nominal increase equal to 10 % of the average.
[39] The increase was a nominal increase equal to 10 % of the average.

statistically significant with an elasticity between -0.069 and -0.013, as seen in Table 5-5. Note that there is limited overlap between the 95 % confidence intervals for each of the variations (see Figure 5-1), suggesting that the parameter changes as the model is altered. The examination of its impact on value added is also statistically significant with an elasticity between -0.197 and -0.094, as seen in Table 5-6. These results provide evidence for examining hypothesis 3 and hypothesis 4, which inquire about the effect of material and finished goods flow time on productivity and production.

Table 5-5: Results for Models 3.1-3.3 Examining the Effect of Material and Finished Goods Flow Time on Productivity – Relevant to Hypothesis 4 (Industry Indicator Results Not Shown)

	Variable	Coefficient	Std. Error	95 % Confidence Interval		Observations	R^2	AIC
Model 3.1	Constant***	2.827	0.769	1.317	4.337	853	0.439	-2147.0
	ED**	0.567	0.244	0.089	1.045			
	$FT_{M\&FG}$*	-0.013	0.008	-0.028	0.002			
Model 3.2	Constant**	2.186	1.014	0.196	4.177	840	0.526	-2240.4
	ED***	-1.761	0.304	-2.357	-1.165			
	FEDRD***	0.126	0.042	0.043	0.209			
	$FT_{M\&FG}$***	-0.069	0.009	-0.086	-0.051			
	RD***	0.359	0.032	0.297	0.421			
Model 3.3	Constant***	-13.339	1.866	-17.002	-9.676	840	0.603	-2384.7
	DUR	-0.048	0.042	-0.130	0.033			
	ED***	-2.647	0.298	-3.232	-2.062			
	FEDRD	0.048	0.041	-0.033	0.129			
	$FT_{M\&FG}$***	-0.040	0.011	-0.063	-0.017			
	NDUR***	1.285	0.130	1.030	1.540			
	RD***	0.441	0.031	0.380	0.503			
	TRND***	-0.021	0.002	-0.025	-0.018			

* Significant at the 90 % confidence interval
** Significant at the 95 % confidence interval
*** Significant at the 99 % confidence interval

Table 5-6: Results for Models 4.1-4.3 Examining the Effect of Material and Finished Goods Flow Time on Value Added – Relevant to Hypothesis 5 (Industry Indicator Results Not Shown)

	Variable	Coeficient	Std. Error	95 % Confidence Interval		Observations	R^2	AIC
Model 4.1	Constant***	-10.864	2.627	-16.021	-5.706	849	0.983	-925.983
	DUR***	0.881	0.090	0.704	1.058			
	ED***	7.675	0.519	6.656	8.694			
	$FT_{M\&FG}$***	-0.124	0.024	-0.170	-0.077			
	NDUR***	-0.556	0.145	-0.840	-0.271			
Model 4.2	CLOTH***	-6.027	1.507	-8.986	-3.069	847	0.985	-985.447
	Constant	-9.960	6.408	-22.539	2.620			
	ED***	8.178	0.707	6.791	9.565			
	FOOD*	1.660	1.001	-0.304	3.624			
	$FT_{M\&FG}$***	-0.197	0.035	-0.266	-0.128			
	FURN	1.001	0.709	-0.389	2.392			
	G&E***	0.435	0.167	0.107	0.764			
	ODUR	-0.345	0.748	-1.813	1.123			
	ONDUR	0.779	0.891	-0.969	2.528			
	RD	0.015	0.074	-0.130	0.161			
	REC	0.802	0.783	-0.735	2.339			
	VEH***	1.654	0.397	0.875	2.433			
Model 4.3	CLOTH***	-2.979	1.148	-5.233	-0.726	847	0.991	-1456.085
	Constant***	-24.570	4.890	-34.169	-14.971			
	ED***	12.284	0.562	11.180	13.387			
	FOOD*	1.408	0.758	-0.079	2.895			
	$FT_{M\&FG}$***	-0.094	0.027	-0.147	-0.041			
	FURN	0.865	0.536	-0.188	1.918			
	G&E	-0.007	0.128	-0.259	0.244			
	ODUR	-0.484	0.566	-1.596	0.627			
	ONDUR	0.316	0.675	-1.008	1.640			
	PD***	1.522	0.064	1.396	1.647			
	RD***	-0.712	0.064	-0.838	-0.587			
	REC	0.646	0.593	-0.518	1.809			
	VEH**	0.755	0.303	0.161	1.350			

* Significant at the 90 % confidence interval
** Significant at the 95 % confidence interval
*** Significant at the 99 % confidence interval

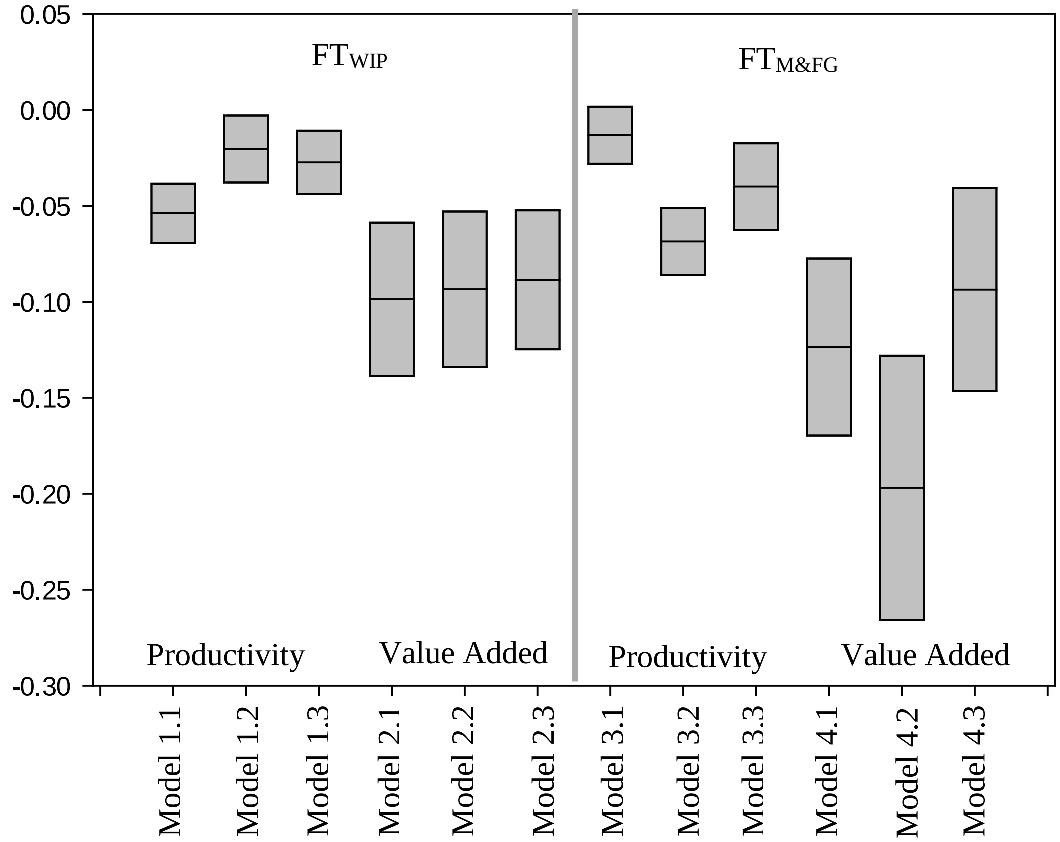

Figure 5-1: 95 % Confidence Interval for Flow Time for All Models

6. Implications

Table 6-1 and Table 6-2 each present the results of two sets of simulations, one for productivity and one for value added. Each simulation is conducted by increasing the parameters by a percentage value (1 %, 5 %, 10 %, and 20 %) and the model is applied to the data to estimate the average change in value added or productivity. The simulations in Table 6-1 uses Model 1 and Model 2 while the results in

Table 6-2 use Model 3 and 4. The results are further evidence for testing the four hypotheses. Table 6-1 shows that a 1 %, 5 %, 10 % and 20 % decrease in work-in-process flow time increases productivity by 0.05 %, 0.28 %, 0.57 %, and 1.21 %, respectively. These changes may seem small; however, the average industry's work-in-process flow time from 2005 to 2015 increased 98.8 %. During this same period, multifactor productivity declined an average of 2.2 %. If flow time had remained unchanged from 2005, multifactor productivity would have increased between 1.73 % and 3.38 % according to our simulation using Model 1, as seen in Table 6-3. That is, multifactor productivity would have grown had it not been for an increase in work-in-process flow time.

Table 6-1: Simulated Change in Work-in-Process Flow Time

Decrease in WIP Flow Time	Average Nominal Decrease (hours)	Increase in Productivity (Model 1.1)	Increase in Value Added (Model 2.1)	Increase in Value Added, $2015 Billion (Model 2.1)
1%	2.6	0.05%	0.10%	25.1
5%	13.1	0.28%	0.51%	128.2
10%	26.2	0.57%	1.05%	264.1
20%	52.4	1.21%	2.23%	562.6

Table 6-2: Simulated Change in Material and Finished Goods Flow Time

Decrease in Material and Finished Goods Flow Time	Average Nominal Decrease (hours)	Increase in Productivity (Model 3.1)	Increase in Value Added (Model 4.1)	Increase in Value Added, $2015 Billion (Model 4.1)
1%	11.7	0.01%	0.12%	31.5
5%	58.7	0.07%	0.64%	161.4
10%	117.3	0.14%	1.31%	332.6
20%	234.6	0.29%	2.80%	709.6

Table 6-3: Simulated Productivity Growth with Constant 2005 Work-in-Process Flow Time

	2005 to 2015 Percent Growth	Compound Annual Growth Rate 2005-2015
Model 1.1	3.38	0.13
Model 1.2	1.43	0.04
Model 1.3	1.73	0.06

Table 6-1 also shows the impact on value added, which increases 2.23 % or by $562.6 billion from a 20 % decrease in work-in-process time. It is important to note that this is not a return on investment, but rather the increase in production.

Table 6-2 shows the results of decreasing material and finished goods flow time. A 1 % decrease results in a 0.01 % increase in productivity and 0.12 % increase in value added. Again, it is important to note that decreasing flow time is, typically, the result of an investment occurring at a single point in time. The increase in value added and productivity would be expected to be realized each year following the investment; although, this paper does not explore this issue.

Previous studies have examined value added and productivity, although they have not included flow time as a variable. One variable of particular interest in these studies has been research and development. Our results for research and development are likely to be different due to the fact that flow time is, in part, a result of these expenditures among other things. Taking the median value from each paper, the elasticities for research and development's impact on value added and output ranges from 0.008 to 0.313.[40] Research and development is not significant in Model 2.2, but in Model 2.1 and Model 2.3 it had an elasticity of 0.145 and 0.485. In Model 2.1 the 95 % confidence interval ranges from 0.000 to 0.289, which incorporates much of the range of other papers. The 95 % confidence interval for Model 2.3 is outside of the range of previous papers. Research and development is not included in Model 4.1, is not significant in Model 4.2, and is negative in Model 4.3. Taking the median value from each paper, the elasticities for research and development's impact on productivity ranges between 0.080 to 0.638.[41] In comparison, the results from Model 1.1 through Model 1.3 are 0.253, 0.145, and 0.317. The 95 % confidence interval for each model overlaps the results from previous papers. Research and development is not included in Model 3.1, but in Model 3.2 and Model 3.3 the elasticity is 0.359 and 0.441. The results in this paper are consistent with the results in previously published papers, suggesting the models used are practical for examining flow

[40] Ugur, Mehmet, Eshref Trushin, Edna Solomon, and Francesco Guidi. "R&D and Productivity in OECD Firms and Industries: A Hierarchical Meta-Regression Analysis." Research Policy. 45 (2016): 2069-2086.
[41] Ugur, Mehmet, Eshref Trushin, Edna Solomon, and Francesco Guidi. "R&D and Productivity in OECD Firms and Industries: A Hierarchical Meta-Regression Analysis." Research Policy. 45 (2016): 2069-2086.

time innovations. Although some values are statistically different, they are not radically dissimilar.

Elasticities from other variables (e.g., education and capital) might be compared to results in previously published literature; however, these variables are not the focus of this paper. Additionally, it might be expected that the elasticities of these other factors vary from the literature, as their impact has some overlap with our primary variable, flow time. Moreover, limited insights are provided from such a comparison.

7. Summary and Discussion

This paper examines the effect of flow time innovations on multifactor productivity and production (i.e., manufacturing value added). It has been proposed in previous literature that flow time can be used to identify bottleneck industries within a supply chain and reducing flow time increases productivity. This paper examines both work-in-process time along with material and finished goods flow time, which equates to 4 basic models. Each of these 4 models has three variants, resulting in 12 total models. The models are used to simulate a change in flow time to further examine the impact on productivity and value added. The results provide evidence that support all four hypotheses made in this paper, as might be expected.

The results suggest that innovations in flow time, both work-in-process along with material and finished goods, does result in changes to productivity and production. These results have some robustness, as flow time is statistically significant in all 12 models. The elasticity for work-in-process flow time, which is equivalent to the coefficient, in each of the models is between -0.054 and -0.022 in regards to its impact on productivity. That is, a 1 % change in work-in-process flow time results in a decrease in productivity that is between 0.054 % and 0.022 %. In regards to value added, the elasticity is between -0.099 and -0.074. A simulated 20 % decrease in work-in-process flow time results in a 1.21 % increase in productivity and 2.23 % increase in value added. The elasticity for material and finished goods flow time is between -0.069 and -0.013 in regard to productivity and between -0.197 and -0.094 in regard to value added. The elasticities have relatively small ranges that give an order of magnitude estimate for flow time's impact on production and productivity.

A simulated 20 % decrease in material and finished goods flow time increases productivity by 0.29 % and increases value added by 2.80 %. These impacts might appear small; however, a decrease in flow time is, generally, the result of an initial investment with the increases in productivity and value added being realized each year following the investment; thus, the benefits would be expected to accumulate over time. The results of this paper, however, do not reveal how the profit of the individual firm is impacted or the compensation of their employees.

The elasticities and simulated impacts may seem small; however, the average industry's work-in-process flow time from 2005 to 2015 increased 98.8 %. During this same period, multifactor productivity declined an average of 2.2 %. If flow time had remained unchanged from 2005, multifactor productivity would have increased between 1.73 % and 3.38 %, according to simulations using Model 1. The statistical significance of flow time in the models, also suggests that it, in part, explains the decline in multifactor productivity.

The implication of the results is that manufacturers, trade organizations, and public research organizations that invest in advancing manufacturing can improve productivity and production through flow time innovations. Investments to do so, would typically seek to have the largest reduction in flow time per dollar of expenditure by focusing on those activities that have a disproportional impact on flow time. It also stands to reason that if an industry's flow time impacts productivity, then a product's total supply chain productivity is also affected by flow time. A supply chain is, in many ways, conducting similar activities as that of an industry, as industries and supply chains are both moving, storing, and altering material goods. Additionally, a supply chain's flow time is made up of individual industry flow times. Moreover, innovations and research efforts that focus on flow time at the supply chain level would be expected to increase productivity and production. Similar to industry level efforts, supply chain level research would typically seek to have the largest reduction in flow time per dollar of expenditure by focusing on those activities that have a disproportional impact on flow time. Thus, those industries within a supply chain that have a disproportionally long flow time are likely to have a greater impact on productivity than those that have shorter flow times.

An increase in research and development for the top quartile industries (i.e., the largest 25 % of industries by value added) has a 4.9 times larger average impact on value added than the same increase on the bottom quartile.[42] A decrease in flow time for the top quartile, measured in value added, has an impact 8.5 times greater than that of the lowest quartile.[43] The implication is that research and development expenditures have a larger return on investment for larger industries as does work-in-process flow time. 11 of the 12 models outperform a linear version (i.e., additive production function) of the model, suggesting that the higher level of impacts for larger industries is accurate.

Future research might seek to use flow time and its components to identify specific industry bottlenecks. These industries represent a target rich environment for improving efficiency and productivity. Trade organizations, public entities, and other change agents might focus on these industries, as they are likely to have a higher probability of having a high return on investment.

[42] The increase was a nominal increase equal to 10 % of the average.
[43] The increase was a nominal increase equal to 10 % of the average.

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