Flexible manufacturing systems performance in U.S. automotive manufacturing plants

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ABSTRACT

Flexible Manufacturing Systems (FMS) philosophy is a key weapon in achieving global manufacturing competitiveness. It encompasses a wide range of dimensions to improve all aspects of operational performance metrics. The aim of the study is to examine the current state of flexibility adoption in U.S. automotive manufacturing facilities and its impact on operational performance metrics. It utilizes survey questionnaire developed based on previous work in US manufacturing industry. The survey was originally distributed to 420 facility managers in the US domestic automotive industry. It was revealed that 70 percent of the respondents have implemented the all fifteen flexibility dimensions listed in the questionnaire. The data analysis conducted shows that implementation of certain flexibility dimensions will lead to significant improvement in specific operational performance metrics. This considerable finding can be used as a guide for manufacturing managers to achieve certain objectives in operational performance improvement in a rapid changing environment.

Keywords: Flexible Manufacturing systems, Manufacturing industry, Automotive assembly, Operational performance metrics

1. Introduction

Globalization in manufacturing industry worked as a critical initiator for the concept of short product lifecycles, increasing products variety and significant changes in the demand which act as new pressures on the companies in today's evolving business market (Schwab, 2017; Wilson 2015;Sangwan and Bahamu, 2013; Gunjan and Rambabu 2012; Chan et. al, 2006; Huerta-

Arribas et.al, 2014). Such reorganization of the market aspects surrounded the firms by uncertainty and pushed them to invest in new practices to thwart against market threats allowing for a more secured business position (Mishra et al., 2014). Though the manufacturing companies are vulnerable to high environmental risk, they were able to build necessary powerful tools to gain competitive advantage. A global CEO's survey conducted by Deloitte Inc. in 2016, identified 12 drivers of global manufacturing competitiveness (Deloitte, 2016). Manufacturing executives identified "Innovation and Talent" as the most important drivers of economy's ability to strive in the global arena (IndustryWeek, 2016). Deloitte (2016) competitiveness report defined innovation as the ability to create and adopt new processes, technologies, philosophies in manufacturing that create solutions which can help organizations meet current and future demands. The report identified flexible manufacturing systems (FMS) philosophy as one of the main driver components of innovation (Deloitte, 2016).

Flexibility is a crucial dimension of a competitive business strategy (Hayes and Wheelright, 1984). The FMS philosophy is defined as the ability of a system to absorb problems such as fluctuation and disruptions of "a system" without impacting the output of the overall process (Slack, 2005; El-khalil, 2009). Authors such as Brown et al. (1984); Gerwin (1987, 1993); Bateman and Stockton (1995); Gupta and Buzacott (1996); and Cordeiro et al. (2000) were some of the first to study FMS definition, classification, categorization, drivers, and enablers. Narian et al. (2000) identified 13 types of flexibility types and classified them into three categories sufficient, competitive, and necessary. Vokurka and O'Leary-Kelly (2000) developed a list of fifteen different dimensions of flexibility which were based on original list developed by others such as Sethi and Sethi (1990), Gupta and Somers (1992), Parthasarthy and Sethi (1993), Slack (1988), and Suarex et al, (1996). Based on the original classification of Narian et al. (2000), Vokurka and O'Leary-Kelly (2000), and El-Khalil (2009) divided the fifteen types of flexibility dimensions into three focus levels operational, tactical and strategical, as illustrated in Table 1. Very few literature discussed the important of flexibility on operational performance metrics (Boyle and Scherre-Rathje, 2009). Authors such as Wei et al. (2017), Oke, (2013) and Inman et al. (2011) studied the impact of few flexibility types such as labor flexibility and mix flexibility on performance metrics such as quality, cost, and lead time. The breadth and depth of previous studies were limited due to issues such as flexibility adoption history (a new topic that very few industries and facilities adopted) and nature of the industry and economy (developed economies in comparison with emerging economies).

[Insert Table 1 here]

This research performs a deep analysis to achieve certain objectives. The specific objectives are of two folds: First, to report the degree of flexibility implementation in U.S.A domestic automotive manufacturing facilities. Based on consensus from eight senior FMS specialist at different manufacturing facilities, a survey that includes fifteen dimensions of flexibilities were adopted. The fifteen flexibility types are based on El-khalil (2009) and Vokurka and O'Leary-Kelly (2000) list, illustrated in Table 1. We studied the degree of flexibility implementation, operational performance metrics improvement achieved by surveyed facilities, and the correlation between FMS dimensions. The second objective was to investigate the impact of flexibility dimensions on performance metrics. Multiple regression analysis was performed to test the impact of fifteen flexibility dimensions on the four most important performance metrics selected by the FMS specialists which are productivity, quality, jobs per hour, and lead time. This study is distinctive since it's the only that embrace a targeted approach to consider all FMS dimensions interactions and impact on each performance metrics. The paper partially covers the theoretical gap addressing the link between flexibility and performance metrics. It is structured as follows: First, we review the literature talking about flexibility and operational performance metrics as a way to reveal the commonly presented thoughts about flexibility tools and the operational performance metrics. We then present the methodology to examine and perform tests on the collected data, along with analyzing the results to reach a critical conclusion. We provide a conclusion by discussing the study contribution, limitation, implication, and future research areas.

[Insert Table 1 here]

2. Literature review

The major transformation determined by innovation and low-cost hit the manufacturing industry, pushing managers to utilize the flexible system as a preparation for the global battle (Bengtsson and Olhager, 2002). With a disturbing pressure of incremental changes, flexibility implementation pace has increased worldwide to improve productivity and respond to the fierce global competition in the uncertain market (Luo et al., 2015; Boyle, 2006; Kitokivi, 2006 and Anand and Ward, 2004). As commonly acknowledged, the term "flexibility" was framed in the context of coping with the changes and uncertainty (Gupta and Buzacott, 1989). Early discussions on flexibility can be traced back to early 1900's. Lavington (1921), was the first to introduce the idea of flexibility and its importance in reducing risk driven by resource immobility in manufacturing. Hart (1940), explained the importance of flexibility in reducing cost and its ability to help manufacturers in "meeting future uncertainty." Aprile et. al. (2005) highlights the importance of flexible supply chain to achieve high levels of satisfaction keeping in mind that it is costly. Marschak and Nelson (1962), discussed the importance of volume flexibility in helping manufacturers reduce and cope with market price and volume fluctuations. Rosenhead et al. (1972) was one of the first authors to provide a definition flexibility as "the alternatives left after one has made an initial decision." Later, authors tried to define and identify flexibility based on different ideas for example, Gerwin (1987) identified flexibility as one of the competitive performance criteria, and Hayes and Wheelwright (1984) advocated that it is one of the primary dimensions of the competitive business strategy. Mishra (2016) shed lights on the different ways of managing change by using flexibility involved in the managerial choices of controlling variations. A study conducted by Zhang et al. (2003) illustrated that flexibility reduces manufacturing time and cost in addition to its ability to allow firms to introduce new products quickly by developing the areas of manufacturing. Luo et al. (2015) dug deeper in this proposed explanation on flexibility and built different elaboration of the two aspects of manufacturing flexibility which is strategic manufacturing flexibility and the operational manufacturing flexibility. Pursuing the perspective of this study, the focus was on operational manufacturing flexibility because in today's rapidly evolving environment (Vokurka and O'Leary-kelly, 2000) operational manufacturing flexibility is referred to as the essential input solution for ambiguity in the manufacturing course of action. According to Oke (2013) and IndustryWeek (2016) the 20th century witnessed a substantial growth in research and implementation on Manufacturing Systems (FMS)and that was mainly driven by issues such as globalization and economic crises of 2007, which forced manufacturers around the world to create/adopt philosophies that can adjust to constant fluctuations and problems in manufacturing.

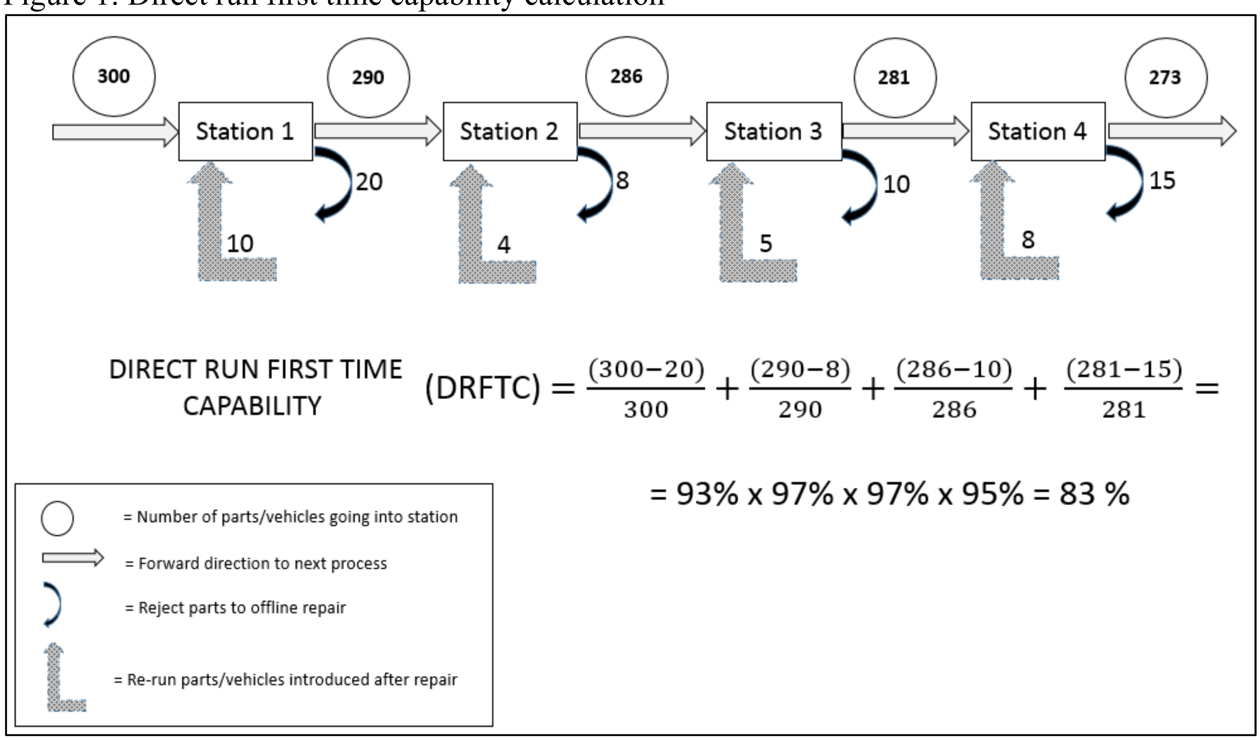
Vokurka and O'Leary-kelly, (2000) divided FMS into 15 dimensions, each dimension designed to support a certain aspect of the manufacturing process. The definition of flexibility dimensions is common among all authors, illustrated in Table 1. For the attainment of flexible system to become more evident and practical, the effect of each flexibility element was screened to design a fit between business model, resource allocation, and business goals. Authors such as Wei et al. (2017); Arif-Uz-Zaman and Ahsan (2014); Oke (2013); Inman et al., (2011); Boyle and Scherrer-Rathje (2009); Cordeiro et al. 2000; Naylor et al. (1999); Hayes and Wheelright (1984), explained the impact of certain flexibility dimension on improving specific operational performance metrics such and quality and cost. Wank and Toktay (2008) stressed on flexible delivery of the orders to customers as a way to increase customer satisfaction. Various research papers were checked to reveal the list of FMS dimension, categories, and operational performance metrics discussed, illustrated in Appendix A. The data revealed provided a comprehensive list of fifteen flexibility dimensions that conclude flexibility. An imperative theoretical framework showing the 15 flexibility tools classified into three different categories based on the outcome of each group of dimensions, illustrated in Table 1. A critical analysis was carried out in this research, based on the 15 flexibility dimensions to trigger the relationship between flexible manufacturing system (FMS) and operational performance metrics.

2.1 FMS tools and Performance metrics

Consistency and steadiness in the manufacturing process are often vulnerable to the risk of shocks and disruptions originated from the unanticipated external or internal variations and instability (Wang et.al 2017). The advanced competitive force opened the way for high rivalry among companies associated with continuous product updates and price war. These alterations can directly lead to amending products' features as a base to gain a competitive advantage in the market. Furthermore, the new technology creation increases the intensity of company's exposure to the fact of demand changing. The new technology e-business facilitates the way for customers to modify their demands (Wang et al., 2017). Such heterogeneous situation influences the crucial role of flexibility in recovering from distraction. Therefore, stable performance under changing conditions is the ability of a firm to quickly adapt to such variations. Simplified transactions, shorter lead time, and lower cost products with higher value enable a company to gain a critical power over other competitors thus resulting in a better performance (Saranga and Sreedevi, 2017). According to Inman et al. (2011), FMS has a direct positive impact on operational performance. Oke (2013), indicates that very few studies have examined the impact of flexibility on performance metrics such as quality, cost, and productivity. Based on his literature review he noticed that several authors discussed the relationship between specific flexibility dimension and certain operational manufacturing metrics. Wei et al. (2017), discussed the positive impact of flexibility on efficiency and productivity and the importance of flexibility on demand fluctuation. Appendix A, present some of the previous literature that focused on performance metrics in manufacturing industry. Mangers interviewed in this research at different visited automotive manufacturing facilities indicated they focus on six main performance metrics and out of which the most crucial metrics were identified as follow:

Quality (DRFTC): measures build in quality of the facility by Direct Run First Time Capability (DRFTC). DRFTC is a standardized method utilized by the domestic automotive industry (Ford, GM, and Chrysler). DRFTC is responsible for evaluating the potential power of the firm to implement practices with build-in quality. To calculate the percentage of quality by using this method, the number of defected products in each stage should be subtracted from the initial number of products that enter that stage and then divide by the initial items amount. Calculation for DRFTC is illustrated in Figure 1 (El-khalil and El-kassar, 2016).

Figure 1: Direct run first time capability calculation



Jobs per Hour (JPH): measures a number of jobs done versus the forecasted number. The calculation formula of this metrics is JPR=Time availability per hour for productivity/Time it takes to produce a vehicle. Accurate calculation of the time availability per hour for productivity requires subtracting time such as downtime, breaks, lunch, and team meeting from total working time. For Time it takes to produce a vehicle, it is determined by dividing available annual working days by the forecasted annual volume of the production, in which the latter formula determines the Takt time.

Productivity: measures the output relative to the input used to produce. It measures the ratio of output to input used in a production process. It is measured by dividing average output per period by the total cost of input during this period (Ghosh, 2016; Gunasekaran et al., 2004).

Lead Time: is the time needed for the manufacturing of an item. It starts at the order time and til the delivery of the product. (Ghosh, 2012)

The above-mentioned criteria along with other dimensions such as safety and employee involvement are considered the foremost goals of business strategy to enhancefirm's business performance (Gunasekaran et al., 2004). In the broad investigation about flexibility prepared by different authors, it was revealed that diverse manufacturing situations lead to different levels of uncertainty and variation in the manufacturing system as well as different performance metrics result (Gerwin, 1993; Pujawan, 2004). Consequently, different manufacturing situations is a key driver for the flexibility type that needs to be implemented (Kara and Kayis, 2004).
Although numerous studies were made on the link between flexibility and business and operational performance, few have agreed on the positive relation between the two constraints. Swamidass and Newell (1987) support the hypothesis which cited the success of a business performance when applying flexibility (mix and volume flexibility). Dreyer and Gronhaug (2004) summarized the relationship between flexibility and performance by showing how survivors are more flexible than failures. Mishra et al. (2014) propose that flexibility is positively connected to business performance (labor and market flexibility). In contrast findings of some papers revealed that higher level of flexibility does not result in higher business performance. None succeed to differentiate between the tools of flexibility and types while examining the relationship, in which their studies do not elaborate on the effect of each tool on each performance metrics. Gerwin (1993) stresses on the need to examine the beneficial effect of

flexibility based on each circumstance of the firm. Each flexibility type is linked to the specific goal of the company, for this firms should understand how to implement the appropriate flexibility that best suits the situation (Correa, 1994). To outperform in a competitive market, there should be a good understanding of the link between flexibility types and tools and the four three performance metrics (Anand and Ward, 2004). Manufacturing flexibility has often been described as situation specific. A company, therefore, should spend considerable effort on identifying what flexibility would be to the benefit of the organization. Limited research was done for forming a scheme that illustrates how each flexibility tool can affect each performance metrics. This paper was employed to fill this gap by suggesting a theoretical framework for the assessment of the effect of each tool.

3.0 *Research Methodology*

The implementation of FMS at the domestic automotive manufacturing facilities is fairly new in North America. According to the facilities surveyed in this research, FMS implementation started during early 21 century. The objective of the survey was to determine the current state of FMS implementation and determine its impact on operational performance metrics at the domestic automotive manufacturing and assembly facilities in North American. The survey was carried out between September 2015 and May 2017. The total sample size used for the survey was 139 originally given to 420 operational managers at 12 different automotive manufacturing companies. The facilities surveyed included domestic Original Equipment Manufacturers (OEM) and suppliers located in the United States of America. The first survey response by email was only 4% (17 responses), all other 122 surveys were conducted through interviews (face to face). Table 2, provide the distribution of the 139 facilities by type of product produced. The individuals surveyed at the manufacturing facilities are distributed as follows: 25 facility/plant managers, 39 production mangers, 29 manufacturing engineering managers, 46 other (quality, material handling, human resource, and engineering mangers)

[Insert table 2 here]

3.1 Survey development and measurement

A self-administrated questionnaire was developed to examine the importance of the tools. The questionnaire item was initially developed from studies conducted previously by Wei et al. (2017); Chauhan and Singh (2016); Inman et al. (2011); Shah and Ward (2007); Slack (2005); Vokurka and O'leary-Kelly (2000) on FMS in US, China, India, and Germany. Fifteen questions pertaining to fifteen distinct dimensions of FMS tools/types. Alternations were made to the survey questionnaire to suit the US automotive manufacturing industry context. The questionnaire items were based on five point Likert scale for each dimension of flexible manufacturing using the following criteria:

1. No implementation = 0 percent;
2. Minimum or little implementation = around 20 percent;
3. Average or some implementation = around 50 percent;
4. High or extensive implementation = around 75;
5. Complete implementation = between 85 to 100%.

Five major questions were asked in the survey and which are related to operational performance (quality, jobs per hour, lead time and productivity), labor efficiency (skilled trade and non-skilled trade), and year of FMS implementation level (Shah and Ward, 2003; Chan et al., 2016). To ensure the accuracy of the survey, it was reviewed and edited based on the feedback received from eight FMS specialist in manufacturing companies (OEM's) and three academicians with extensive experience in manufacturing industry. A section was added to the questionnaire that requires respondents to rank eight operational dimensions motivating FMS implementation (Oke, 2013; Seebacher and Winkler, 2014; Wei et al., 2017) to cover the performance metrics topic. In addition, several other questions were asked to managers in order to reveal the age of the facility; green field (new)/ brown field (old), size of the facility, number of employees, type of products, level of automation, and employee training. All measures utilized in this study were adapted from the literature reviewed, illustrated in Appendix A. This adaptation was needed in order to encompass all variables considered (dependent and independent).

4. *Results*

4.1 Descriptive Statistics

Mean and standard deviation was calculated for all flexibility dimensions and operational metrics, illustrated in Table 3. The descriptive statistics were calculated based on a five-point Likert scale (1 indicates no implementation and 5 indicates full implementation). The total score for each firm was derived from the summation of the individual scores of the fifteen flexibility dimensions. The maximum points achieved for firms which is based on the fifteen flexibility dimension score addition is 75 point (based on the highest score given for each dimension is five). The 75 point was extrapolated out of 100. The highest score was 91.2, the lowest score was 42, and the mean score was 75. The degree of flexibility implementation was calculated for each facility, illustrated in Table 4. The data indicates that over 70 percent of facilities have implemented flexibility to a significant level.

[Insert Table 3 here]

[Insert Table 4 here]

Six different operational metrics were studied to check their improvement. Facilities studied provided information (facility comptroller's office) on improvements observed in six operational metrics, illustrated in Table 5. These surveyed facilities were then asked to rank operational performance metrics that motivated flexibility implementation, illustrated in Table 6. Data indicates that productivity, followed by quality, jobs per hour, and lead time were the biggest motivators for implementing FMS.

[Insert table 5 here]

[Insert Table 6]

4.2 Facility size, age, and number of years of FMS existence

Regarding facility size, 92 percent of respondents were large size facilities (over 2,000 employees and above 300 million dollars investment in plant and machinery). Automotive manufacturing industry in the US is considered old because some facilities were built as early as 1920's. Our survey shows that 52 percent of the facilities surveyed were around 40 years old or above, 28 percent were between 20 and 39 years, and 14 percent of the facilities were between 5 and 19 years. Based on the feedback from facility managers flexibility implementation for the 52 percent presented a major challenge. Since the facilities are old those facilities went through drastic change over in order to allow for FMS implementation. Especially in areas such as Body shop and Chassis departments in assembly facility, which require high level of automation. Concerning years of FMS existence, the survey indicates that the oldest FMS facility adopter started implementation seventeen years back (started implementation in 2000), on the other hand' the latest adopter implemented FMS four years back (2014). Average for FMS implementation was 6.4 years (overall).

4.3 FMS Dimension affecting FMS operational metrics

Correlation analysis was performed to examine the degree of relationship between the FMS dimensions, illustrated in Table 7. The result show, significant correlation between all flexibility dimensions. The main difference in correlation matrix is that some dimension correlation is significant at 0.01 and others at 0.05 level. For example correlation for Machine Flex and Product Flex (0.844), Machine Flex and Labor Flex (0.828), and Machine Flex and Automation (0.910) are all significant at the 0.01 level. Scatter plot was utilized to check for independent variable linearity concerning output variables. In addition, Jarque-Bera test and residuals plot was used to verify normality (p<0.000) and homoscedasticity. The results indicated, linearity, normality, and no obvious pattern.

[Insert Table 7 here]

Multiple Regression analysis was also performed to examine the impact of the fifteen independent variables or FMS dimensions/practices on the four most important dependent variables or performance metrics (productivity, quality, Jobs Per Hours, and lead time). Table 8, illustrates the regression coefficient for each flexibility practice. Productivity model (first model), twelve practices were found as positive predictors. Machine ($p < 0.01$), labor ($p < 0.01$),and routing ($p < 0.01$) were found to be highly significantly positive predictors, material handling ($p < 0.05$), volume ($p < 0.05$), delivery ($p < 0.1$), and production ($p < 0.05$) were found as positive predictors, and product ($p < 0.1$), automation ($p < 0.1$), process ($p < 0.1$), program ($p < 0.1$), new design ($p < 0.1$) and delivery ($p < 0.1$) were found as moderately significant positive predictors. Productivity model explained 60 percent (based on *R^2 value)* variance, associated significance at $p < 0.01$. Quality model (second model), ten practices were found as positive predictors. Labor ($p < 0.01$) and routing ($p < 0.01$) were found to be highly significant positive predictors, process ($p < 0.05$), delivery ($p < 0.05$), and new design ($p < 0.05$) were found as positive predictors, and machine ($p < 0.1$), product ($p < 0.1$), material handling ($p < 0.1$), automation ($p < 0.1$), and program ($p < 0.1$) were found as moderately significant positive predictors. The quality model explained 76 percent (based on *R^2 value)* variance, associated significance at $p < 0.01$. Production flexibility was found to be a negative predictor $p< 0.1$. Production flexibility is defined as the universe of part types that the FMS can produce. This result was shared with managers interviewed and the justification given (for the negative predictor) is linked to the direct relationship between the increase in part type "production" will decrease quality. Since every time we change new part that will require different equipment, training, processes…etc., thus directly causing more quality related issues. Table 3, indicates that average mean score for production flexibility was 2.98 (one of the lowest among flexibility dimensions studied). Jobs Per Hours model (third model), eleven ten practices were found as positive predictors. Machine ($p < 0.01$), labor ($p < 0.01$), and automation flexibility ($p < 0.01$) were found to be highly significant positive predictors, and product ($p < 0.1$), material handling ($p < 0.1$), routing ($p < 0.1$), process ($p < 0.1$), delivery ($p < 0.1$), production ($p < 0.1$), expansion ($p < 0.1$), and new design ($p < 0.1$) were found as moderately significant positive predictors. Jobs Per Hour model explained 51 percent (based on *R^2 value)* variance, associated significance at $p < 0.01$. Lead Time model (four model), ten practices were found as positive predictors. Machine ($p < 0.01$) and labor ($p < 0.01$) were found to be highly significant positive predictors, automation ($p < 0.05$), and delivery ($p < 0.05$) were found as positive predictors, and product ($p < 0.1$), material handling ($p < 0.1$), routing ($p < 0.1$), volume ($p < 0.1$), program ($p < 0.1$), and expansion ($p < 0.1$) were found as moderately significant positive predictors. Lead time model explained 84 percent (based on *R^2 value)* variance, associated significance at $p < 0.01$.

[Insert Table 8 here]

Regression models illustrated in table 8, indicate the impact of different FMS dimensions on operational performance metrics. If manufacturing facility desire high productivity, focusing on machine, labor, routing, material handling volume, production, and stressing on product, automation, process, program, delivery, and new design flexibility might be the best approach. Achieving higher quality, focusing on labor, routing, process, delivery, new design, and stressing on machine, product, material handling, automation, and program flexibility might be the best approach. The coefficient of production flexibility was found to be negative with respect to quality. Higher Jobs Per Hour require focusing on machine, labor, automation and stressing on product, material handling, routing, process, delivery, production, expansion, and new design flexibility is the best approach. While dimensions such as volume program, production expansion, indicated influence only of one or two operational metrics, others such as operations and market indicated no influence on any of the four operational metrics.

5.0 Discussion and conclusion

The 21st century witnessed the dramatic change in the manufacturing industry production system which starts to follow lean management and FMS after being implementing mass production system since early 20th century. The academic community acknowledges FMS philosophy as a platinum standard for operational management. Success stories of FMS implementation at companies such as Toyota and its suppliers drove companies around the world to adopt the FMS philosophy (Aziz, et. Al., 2018). This study makes an attempt to find the degree of FMS implementation in U.S.A. automotive manufacturing facilities and the different flexibility practices/dimensions that have been utilized in the industry. It indicates that many U.S. automotive manufacturing facilities have achieved superior operational performance mainly due to the advanced level of FMS implementation. What makes this study unique is the breadth and depth of FMS dimensions considered. It provides several managerial implications for manufacturing companies to improve operational performance metrics by redesigning the way they implement FMS dimensions. The directed methodology of this study was to indicate the fundamental relationship between flexibility dimensions and operational outcomes. Findings of this research in term of some of the FMS dimensions and operational performance metrics seem to agree with other scholar such as Wei et al., (2017), Oke (2013), Inman et al., (2011), Vokurka et al., (2000). Unlike other research papers, this paper can be separated from previous work by the depth and breadth of dimensions and operational metrics it used. For the sample size of this study, it is not large (139 samples), and focused because it studies only considered automotive manufacturing facilities. Therefore the results need to be analyzed with caution. Future research should focus on investigating impact of FMS dimensions on other industry, along with linking the impact of other manufacturing philosophies on FMS (such as lean manufacturing), in addition to verification and validation of the grouping of FMS dimensions based on surveying how industry currently utilize FMS.

References

1. Anand, G., and Ward, P.T., 2004. Fit, Flexibility and performance in manufacturing: coping with dynamic environments. Productions and Operations Management, 13, 369-385.
2. Aprile, D., Garavelli, A., and Giannoccaro, I. 2005. Operations planning and flexibility in a supply chain. Production Planning & Control, 16 (1), 21-31
3. Arif-Uz-Zaman, K., and Ahsan, N. 2014. Lean supply chain performance measurement. International Journal of Productivity and Performance Management. 63 (5), 588 – 612.
4. Aziz, Z., Koskela, L., and Tezel, A. 2018. Lean thinking in the highways construction sector: motivation, implementation and barriers. Production Planning & Control, 29 (3), 247-269.
5. Bateman, N., and Stockton, D., 1995. Measuring the production range flexibility of a FMS. Integrated Manufacturing Systems, 6 (2) 27-34.
6. Bengtsson, J., and Olhager, J., 2002. Valuation of product-mix flexibility using real options. International Journal of Production Economics, 78, 13-28.
7. Boyle, T.A., and Scherrer-Rathje, M., 2009. An empirical examination of the best practices to ensure manufacturing flexibility Lean alignment. Journal of Manufacturing Management, 20 (3), 348-366.
8. Boyle, T.A., 2006. Towards best measurement practices for implementing manufacturing flexibility. Journal of Manufacturing Technology Management, 28, 195.
9. Brown, J., Dubois, D., Rathmill, K., Sethi, S.P., and Stecke, K.E. 1984. Classification: Flexible Manufacturing Systems. *The FMS Magazine*, 34,114-117.

10. Chan, F.T.S., Wadha, S., and Bhagwat, R., 2006. Increase in flexibility: productive or counterproductive? A study on the physical and operating characteristics of a flexible manufacturing system. International Journal of Production Research, 44 (7), 1431–1445
11. Chan, H. K., Yee, R.W.Y., Dai, J., and Lim, M.K., 2016. The moderating effect of environmental dynamism on green product innovation and performance. International Journal of Production Economics, 38 (1), 56-70.
12. Chauhan, G., and Singh, T.P. 2013. Resource flexibility for lean manufacturing: SAP-LAP analysis of a case study. International Journal of Lean Six Sigma, 4 (4), 370-388.
13. Codeiro, J., Sarkis, J., Yadav, R., and Narain, R., 2000. The strategic implications of flexibility in manufacturing systems. International Journal of Agile Management Systems, 2, 202-213.
14. Correa, H.L., 1994. Linking Flexibility, Uncertainty and Variability in Manufacturing Systems, Aldershot Avebury.
15. Deloitte., 2016. 2016 Global Manufacturing Competitiveness Index. Available online at: https://www2.deloitte.com/global/en/pages/manufacturing/articles/global-manufacturing-competitiveness-index.html.
16. Dreyer, B., and Gronhaug, K., 2004. Uncertainty, flexibility, and sustained competitive advantage. J. Bus. Res. 57 (5), 484-494.
17. El-khalil, R., 2009. Optimization of flexible body shop system, section 2. Doctoral Dissertation, retrieved from ProQuest Dissertations and Theses. Accession Order No. AAT3356289, Lawrence Technological University, Southfield, MI.
18. El-khalil, R., and El-kassar, A., 2016. Managing span of control efficiency and effectiveness: a case study. Benchmarking: an International Journal, 23 (7), 1717-1735.
19. Gerwin, D., 1987. An agenda for research on the flexibility of manufacturing process. International Journal of Operation and Production Management, 7, 65-90.
20. Gerwin, D., 1993. Manufacturing flexibility: a strategic perspective. Manag. Sci., 39 (4), 395-410.
21. Ghosh, M., 2012. Lean manufacturing performance in Indian manufacturing plants. Journal of Manufacturing Technology Management, 24 (1), 113-122.

22. Gupta, D., and Buzacott, J.A., 1996. A goodness test for operational measures of manufacturing flexibility. International Journal of Flexible Manufacturing Systems, 8, 233-245.
23. Gunjan, S., and Rambabu, K., 2012. Evaluating reliability and validity of lean, agile and leagile supply chain constructs in Indian manufacturing industry. *Production Planning & Control,* 23, 864-884.
24. Hart, A.G.,1940. Anticipations, Uncertainty and Dynamic Planning. New York, NY.
25. Hayes, R.H., and wheelwright, S.C ., 1984. Restoring our Competitive Edge: Competing throughmanufacturing, Wiley, NewYork, NY.
26. Hu, Q., Found, P., Mason, R., and Williams, S., 2015. Lean implementation within SMEs: a literature review. Journal of Manufacturing Technology Management, 26 (7), 980 - 1012.
27. Huerta-Arribas, E., García-Olaverri, C., Larraza-Kintana, M., Urtasun-Alonso, A. 2014. Manufacturing flexibility and advanced human resource management practices. Production Planning & Control, 25 (4), 303-317.
28. IndustryWeek, 2016. The Future of manufacturing 2020 and Beyond. Available online at: https://www.nist.gov/sites/default/files/documents/2016/11/16/iw_kronos_research_report_2016.pdf.
29. Inman, R. A., Sale. R. S., Green K.W., and Whitten, D., 2011. Agile manufacturing: Relation to JIT, operational performance and firm performance. Journal of Operations management, 29 (4), 343-355.
30. Ketokivi, M., 2006. Elaborating the contingency theory of organizations: The case of manufacturing flexibility strategies. Production and Operations Management, 15, 215-228.
31. Kara, S., and Kayis, B., 2004. Manufacturing flexibility and variability: an overview. J. Manuf. Technol. Manag, 5 (6), 466-478.
32. Lavington, E., 1921. The English Capital Market, Methuen, London, UK.
33. Luo, B., Cadeaux, J., and Yu, K., 2015. Operational flexibility: Review and meta-analysis. Int. J. Prod. Econ., 169, 190-202.
34. Marschak, T., and Nelson, R., 1962. Flexibility, Uncertainty and Economic Theory. Metroeconomica. 14, 42-58.

35. Mishra, R., Pundir, A., and Ganapathy, L., 2014. Assessment of manufacturing flexibility: A review of research and conceptual framework. Management Research Review, 37, 750-776.
36. Naim, M., Gosling, J., and Purvis, L., 2014. The development of a lean, agile and leagile supply network taxonomy based on differing types of flexibility. International J. Production Economics, 151, 100-11.
37. Naylor, J., Naim, M., and Berry, D., 1999. Leagility: Integrating the lean and agile manufacturing paradigms in total supply chain. International J. Production Economics, 62, 107-118.
38. Oke, A. 2013. Linking manufacturing flexibility to innovation performance in manufacturing plants. International Journal of Production Economics, 143 (10), 242-247.
39. Parthasarthy, R., and Sethi, S.P., 1993. Relating strategy and structure to flexible automation: a test of fit and performance implications, Strategic Management Journal 14 (7) , 529–549.
40. Pujawan, I.N, 2004. Assessing supply chain flexibility: a conceptual framework and case study. International J. Integr. Supply Manag., 1 (1), 79-97.
41. Rosenhead, J., Elton, M., and Gupta, S.K., 1972. Robustness and Optimality as Criteria for Strategic Decisions. Operational Research Quarterly, (23), 413-431.
42. Saranga, H., and Sreedevi, R., 2017. Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. Int. J. Prod. Econ., 193, 332-342.
43. Schwab, K. 2017. The global competitiveness Report. Available online at; http://www3.weforum.org/docs/GCR2017-2018/05FullReport.
44. Seebacher, G., and Winkler, H. 2014. Evaluating flexibility in discrete manufacturing based on performance and efficiency. International Journal of Production Economics, 153 (1), 340-351.
45. Sethi, A.K., and Sethi, S.P., 1990. Flexibility manufacturing: a survey. International Journal of Flexible Manufacturing Systems, 2 (4), 289–328.
46. Shah, R., and Ward, P.T. 2003. Lean manufacturing context, practice bundle, and performance. Journal of operations Management, 21 (2), 129-149.
47. Shah, R., and Ward, P.T., 2007. Defining and developing measures of lean production. Journal of Operations Management, 25, 785-805.

48. Slack, N., 1988. Manufacturing systems flexibility — an assessment procedure. Computer Integrated Manufacturing Systems 1 (1), 25–31.
49. Slack, N., 2005. The flexibility of manufacturing systems. International Journal of Operations & Production Management, 25, 1190-200.
50. Swamidass, P.M., and Newel, W.T., 1987. Manufacturing strategy, environmental uncertainty and performance: a path analytic model. Manag. Sci. 33 (4), 509-524.
51. Vokurka R., and O'leary-Kelly, S., 2000. A review of empirical research on manufacturing flexibility. Journal of Operations Management, 18, 485-501.
52. Wang, D., Song, X., and Wei, Z., 2017. Manufacturing Flexibility, business model design, and firm performance. International Journal of Production Economics, 193, 87-89.
53. Wei, Z., Song, Xi., and Wang, D., 2017. Manufacturing flexibility, business model design, and firm performance. International Journal of Prodcution Economics 19 (3), 87-97.
54. Wilson, L. 2015. *How to implement Lean Manufacturing*. McGraw-Hill, New York, NY. Sangwan, K., Bhamu, J., 2013. Lean manufacturing: literature review and research issues. International Journal of Operations and Production Management, 34, 876-940.
55. Zhang, Q., and Vonderembse, M.A., Lim, J.S., 2003. Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction. Journal of Operations Management. 21, 173-191.

Appendix

Appendix A: Literature review flexibility and performance metrics by author

Construct	Category	Constitute Elements	Source
Operational Flexibility	Necessary	Machine Product Labor Material Handling Routing Volume Automation	Wang et al (2017), Chauhan and Singh (2013), Gunjan and Rambabu (2013), Oke (2013), Gunjan and Rambabu (2012), Youssef et. al (2011), Swafford et al. (2006), El-Khalil, R. (2009), Cordeiro et. al (2000), Bateman and Stockton (1995), Sethi and Sethi (1990), Brown et al (1984), Hayes et al. (1984), Buzacott (1982), Gerwin (1987), Venkatesan (1980), Reix (1979).
Tactical Flexibility	Sufficient Flexibility	Process Operational Program Material/Delivery	Wang et al (2017), Chauhan and Singh (2013), Naim et al. (2014) Youssef et. al (2011), El-Khalil, R. (2009), Cordeiro et. al (2000) Bateman and Stockton, (1995), Brown et al (1984), Sethi and Sethi (1990), Gerwin (1987).
Strategic Flexibility	Competitive	Production Expansion Market New Design	Wang et al (2017), Chauhan and Singh (2013), Naim et al. (2014) El-Khalil, R. (2009), Cordeiro et. al (2000) Sethi and Sethi (1990), Bateman and Stockton, (1995), Brown et al (1984).
Performance Metrics	Operational Performance	Quality Jobs Per Hour Ltime Productivity	Yadav and Desai (2016), Dou et. al (2013), Lai et al. (2012), Ghosh (2012), Youssef et. al (2011), Hakan et.al (2010), Wong et al. (2009), Ebben and Johnson (2005), Sanchez and Perez (2001), Cordeiro et.al (2000)
Efficiency	Lean Management	Labor Efficiency Skilled Labor Efficiency Non-Skilled	Gerstein (2015), Johnson and Marey (2007), Shah an Ward (2003) Ketokivi (2006), Mishra et al. (2014)
No of Employe	ID Variable	# of employees	Oke (2013)
No of Years Implementation	ID Variable	Flexibility years of implementation	
Size of Facility	ID Variable	Size of Mfg facility	