

A METHODOLOGY FOR ANALYSIS OF MANUFACTURING OPERATIONS DUE TO COMPLEXITY

Ali K. Kamrani^{1,2}, Ph.D., P.E., Arun Adat² and Maryam Azimi²

¹Visiting Professor, FARMAT, Industrial Engineering, King Saud University, Riyadh, Saudi Arabia

²Design and Free Form Fabrication Laboratory, Industrial Engineering Department, University of Houston
Houston, TX 77204-4008

Corresponding author: Ali K. Kamrani, akamrani@uh.edu; aKamrani.c@KSU.EDU.SA

Variability in products is driven by the customer and pushes the manufacturer to offer product variants by mass customization. Companies that offer product variety while maintaining competitive cost and quality will gain a competitive edge over other companies in today's market. As auto industries adapt to mass customization strategy, they would require the ability to conduct early design, development and manufacturing trade-offs among competing objectives. An analytical approach is then required to manage the complexity and the risk associated with this environment. This article will present a set of simulation-based methodologies for measuring complexity. The developed methodologies will assist designers in analyzing and mitigating the risks associated with product variety and its impact on manufacturing.

Keywords: Product variety, Static complexity, Dynamic Complexity, supply chain management, Inventory Analysis, Simulation analysis.

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1. INTRODUCTION

Product variety in a manufacturing set-up is the different product designs or product types that are produced in a plant. This is further classified into hard and soft variety. Hard product variety occurs when products differ substantially in appearance. In an assembled part hard variety is characterized by a low proportion of common parts. An example for hard variety would be a car and a truck. Soft product variety occurs when there is a high proportion of common parts and there are only small differences between products. An example for soft variety will be the different car models. Product variety can be broadly classified into, external variety and internal variety (Anderson, 1997). External variety is product variety seen by the customer and internal variety is the product variety experienced inside manufacturing and distribution operations. External variety is further classified into useful variety and useless variety. Useful variety is appreciated by the customer and useless variety is transparent, unimportant or confuses the customer. Internal variety usually takes the form of excessive and unnecessary variety of parts, features, tools, fixtures, raw materials and processes.

An alternative classification of product variety is fundamental variety, part variety and peripheral variety (MacDuffie et al., 1996). The difference between models and body styles is defined as the fundamental variety. Parts variety includes the combinations of the sub-systems such as engine/transmission combinations, the number of interior/exterior color combinations etc. The peripheral variety deals with all the different options available per each model. American and Japanese auto manufacturers have different production strategies to tackle product variety. American car manufacturers believed in the philosophy of mass production, producing high volumes and achieving economies of scale. They always chose to offer minimum fundamental variety to keep the production costs low and offered very high peripheral variety (Kamrani et al., 2004). Japanese auto manufacturers offered more distinct models to choose from and less option combinations thus increasing the fundamental variety.

One of the operational reasons for this fundamental difference in product variety was their adversative production strategies. American manufacturers followed the push production system and the Japanese manufacturers followed the pull production or JIT system (Clair et al., 1996). In the push production systems the flow of materials are planned and controlled by a series of production schedules. The ability to handle product variety in push system is governed by the setup time. In most cases due to high setup times the resulting batch sizes are large rendering the push system, the least flexible to handle product variety. In pull production there is emphasis on reducing inventory at every stage of production. The successive station triggers production at the preceding station which ensures production only if there is downstream demand. Pull system is commonly known as just-in-time manufacturing (J.I.T) because the product and the corresponding sub-assemblies are produced as and when required. The JIT philosophy (often coupled with low setup times) facilitates lower work in process and is popularly known as the lean manufacturing methodology. The agile nature of the pull manufacturing systems offers higher flexibility in manufacturing to accommodate higher product variety. Manufacturing complexity is defined as a systematic characteristic which integrates several key dimensions of the manufacturing environment which include size, variety, information, uncertainty, control, cost and value. Manufacturing complexity is

classified into structural (static) complexity, and operational (dynamic) complexity (Frizelle and Woodcock, 1995). Structural or static complexity is defined as the expected amount of information necessary to describe the state of a system (Frizelle, 1996, Calinescu et al., 1997, Calinescu et al., 2002). Production schedule could provide the necessary data to calculate the static complexity of the manufacturing system. Static complexity is typically measured using the entropy equation. Operational or Dynamic Complexity is defined as the expected amount of information necessary to describe the state of the system deviating from schedule due to uncertainty. The calculation involves the measurement of the difference between actual performance of the system and the expected schedule. A fair estimate of the cost of increased product variety is often difficult to estimate because variety incurs many indirect costs which are not clearly understood and are not easy to capture. Costs that are difficult to determine include raw material inventory, work in process inventory, finished goods inventory, post sales service inventory, reduction in capacity due to frequent set-ups and cost of increased logistics due to added variety (Garcia-Sabater, 2001).

In this article, we propose a structured methodology for analyzing manufacturing complexity due to increased product variety. A series of cost models are developed to capture the impact of increase in inventory and storage cost of the sub-assemblies due to an increase in product variants. This is accomplished by generating a mixed model assembly sequence that aims to minimize the variation of subassembly inventories of the production span. The mixed model assembly line is simulated to track the inventory levels of the individual subassemblies. The output of the simulation model is used in the cost model to provide the daily cost of inventory holding and storage of the different subassemblies.

2. IMPACT OF PRODUCT VARIETY ON MANUFACTURING COSTS

Malik and Sullivan used mixed integer programming that utilizes activity based cost (ABC) information to determine optimal product mix and product cost in a multi-product manufacturing environment (Malik and Sullivan, 1995). They showed by an example that with traditional costing approach, it was possible to arrive at a product mix which may not be achievable with a given capacity of indirect resources. Furthermore adopting a product mix strategy suggested by traditional costing methods might also increase the overhead costs which are not anticipated in the early stages of planning and costing. MacDuffie, Sethuraman and Fisher examined the effect of product variety on manufacturing performance (MacDuffie et al., 1996). The performance factors include total labor productivity and consumer-perceived product quality. They define three dimensions of product variety; fundamental, peripheral and intermediate variety. Their study supports the hypothesis that lean production plants are capable of handling higher levels of product variety with less adverse effect on total labor productivity than traditional mass production plants. They study partly explains how the leanest Japanese plants have been able to achieve higher overall performance with much higher levels of parts complexity and option variability. Ishii and Martin introduce the concept of design for variety (DFV) which is a tool that enables product managers to estimate the cost of introducing variety into their product line (Ishii and Martin, 1996). They claimed that cost estimates used to determine the profitability of the companies that offered new product offerings did not account for all the costs associated with providing this additional variety. Their model attempts to capture the indirect cost of variety through the measurement of three indices; commonality, differentiation point and set-up cost. DFV methodology was a basic procedure for helping managers and engineers understand the true costs of introducing variety into their product line.

Benjaafar, Kim and Vishwanadham examined the impact of product variety on inventory costs in a production inventory system with finite capacity assuming make to stock production, set-up times, finite production rate and stochastic production times (Benjaafar et al., 2004). Their results show that inventory costs increase linearly with the number of products. They also show that rate of increase is sensitive to system parameters including demand and process variability, demand and capacity levels, and setup times. Dobson and Yano formulate the problem of product variety and pricing as a non linear program (Dobson and Yano, 2002). They assume a manufacturer who has a single machine or production line which is capable of producing a range of potential products. They effect of inventory costs associated with the products is captured by modeling the time between production runs as a decision variable. Their results show that the optimal product mix depends strongly on the production cycle duration. Ozbayrak, Akgun and Turker estimated the manufacturing costs of an advanced manufacturing system that runs under a material requirement planning (MRP) or Just in time (JIT) system by using activity based costing (Ozbayrak et al., 2004). They use simulation a modeling tool to observe the manufacturing cost behavior under two separate control strategies, the push and pull system. Parts are either pushed or pulled and are sequenced according to the four scheduling rules, which are: shortest processing time, longest processing time, first come first serve and slack. They found that randomness, buffer capacity and lead times are found to be important cost drivers in terms of their effect on work in progress (WIP) and throughput and an increase in variation and buffer capacity can result in a build up of WIP inventory and a slight increase of throughput volumes with the expense of considerable increase in manufacturing costs.

3. AN INDUSTRY CASE STUDY: A SIMULATIO-BASED METHDOLOGY

The research site for the project is the axle assembly operation of a major automobile company that assembles a variety of vehicle models with different combinations of axles and spring coils. Axles and coils are delivered daily based on the scheduled production, and a level of safety stock is always available in the event of any out of sequence production. Rear and front axles are installed onto the vehicle chassis using a moving platform at the first two stations and then moved through the line for other assembly operations such as brake line, spring and coil assembly. The following lists the different subassembly variants of front/rear axles and front/rear springs in the assembly line:

- 9 front axles: 184AP, 184AQ, 187AQ, 187AR, 600AC, 600AD, 601AC, 601A and 601AE
- 4 rear axles: 426AG, 429AG, 430AF and 433AG
- 7 rear spring coils: 344, 345, 400, 404, 500, 550 and 551
- 7 front spring coils: 262, 263, 264, 265, 267, 268 and 269

Theoretically, there are 1,764 product combinations of front/rear axles and front/rear spring coils possible, but in reality there are only 55 vehicle models allowed because of the design and operational qualifiers. For instance, a heavy duty axle cannot match with a low stiffness spring. A pictorial representation of the possible axle and coil combinations is shown in Figure 1. The assembly line has an operation cost (inventory holding and storage) corresponding to the current inventory level. The problem is to determine the variation in inventory level and the corresponding operational costs if an additional model (product variant) is introduced into the manufacturing system. The study only focuses on the possible vehicle variants due to various axle and spring coil combinations. The impact of product variety due to the engines, transmission and transfer case is not considered in this study. Prior to the development of the cost impact due to the addition of a new variety, it is necessary to identify the best possible method of part delivery. Three possible scenarios were considered. These are, push delivery, sequencing delivery and in-house sequencing delivery models. Currently, axles are delivered daily based on the scheduled production. Safety stock is always available in-case of any out of sequence production event. This value is estimated by the axle supplier. Out of sequence events could occur due to wrong part sequence, added schedule and other situations such as breakdown, part damage, etc. Wrong axles are manually transferred and placed in pull-off bins. In this case, bins for safety stock are searched until the right axle is located and assembled on the platform. Excess inventory is stored at various locations in the plant.

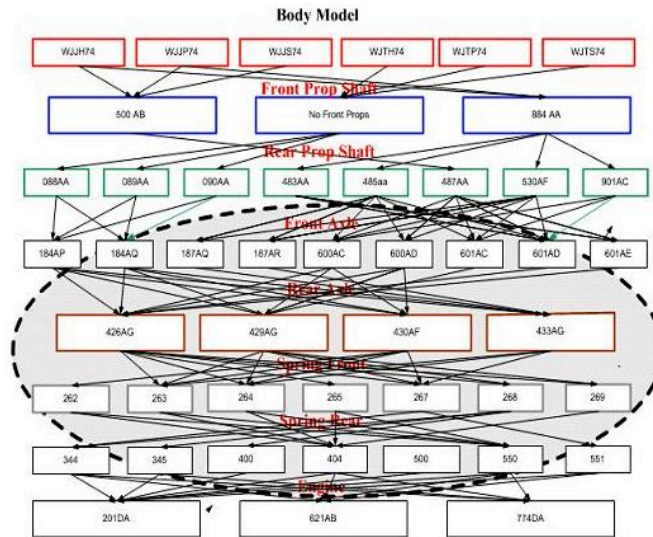


Figure 1. Schematic view of the possible combinations of subassemblies

4. ANALYSIS OF DELIVERY AND STORAGE POLICY

The first part of the project required the identification of best part delivery policy to minimize the required storage area for safety and excess inventories. This area can be used for other value adding operations. Figure 2 illustrates the scope of the proposed simulation-based methodology for the first part of analysis. The implementation steps includes: 1) Data Collection & Verification, 2) Simulation model development and verification, 3) Base model complexity analysis; Part mix complexity analysis (Structural) and Manufacturing mix analysis (Dynamic) and Delivery and Inventory Policy Analysis.

The required data for implementation is collected using the available operational data and series of daily data collection. Table 1 lists the required data for the development of simulation models.

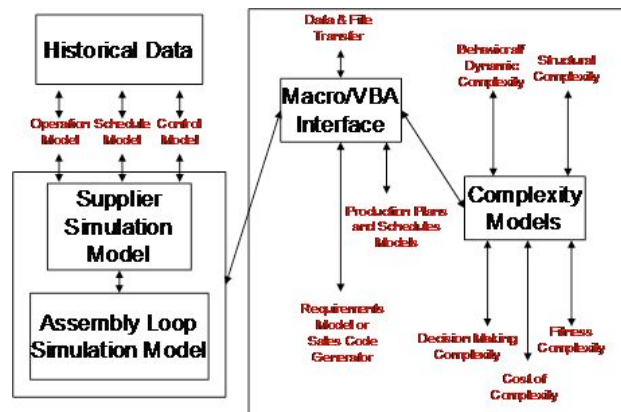


Figure 2. Scope of the proposed system

Three different simulation models are developed based on the three policies. The policies include sequence delivery by vendor, push and in-house sequencing. An example of the simulation model is illustrated in Figure 3. The simulation model is validated and verified using the current mode of operation based using actual production data. For this problem only part-mix complexity (structural) and dynamic complexity (WIP) are measured. For all three models, the value of the part-mix complexity is the same, although the dynamic complexity significantly varies from one model to another. The static complexity is calculated using the following expression (Frizelle, 1996):

$$H_s = - \sum_{i=1}^m \sum_{j=1}^s p_{ij} \log_2 p_{ij} \quad \dots \quad (1)$$

Where H_s is the static measure of complexity (Entropy), m is the number of resources, s is the number of scheduled states and P_{ij} is the probability of resource i being in scheduled state j .

The dynamic complexity is calculated using the following expression (Frizelle, 1996):

$$H_d = - P (\log_2 P) - (1 - P) \log_2 (1 - P) - (1 - P) \sum_{i=1}^m \sum_{j=1}^{ns} p_{ij} \log_2 p_{ij} \quad \dots \quad (2)$$

Where H_d is the dynamic measure of complexity, P is the probability if the system being in control, $(1-P)$ is the probability if the system being out of control, m is the number of resources, ns is the number of non scheduled states, and P_{ij} is the probability of resource i being in non scheduled state j .



Figure 3. Simulation model of axle loop assembly area

The dynamic measure indicates that the operation of the manufacturing system using the sequenced delivery is going through changes. This is due to both schedule and non-schedule disturbances during the assembly. Although, the dynamic measure for push and in-house sequence is significantly lower and it is mainly due to the production stoppages (breakdown, repair, etc.). For this stage, factors considered for calculating the cost at the assembly area include: 1) Cost of axle delivered to the assembly plant, 2) Cost of storage, 3) Cost of Hi-Low operator, 4) Cost of pull-off, 5) Cost of re-sequencing, 6) Cost of operators and Overtime. Even though the generated result indicates that the current system sequenced deliver model is well designed to handle the current combinations of the vehicle assembly, the impact of complexity is evident on the cost of material handling including inventory. From Figure 4, parts delivered and then sequenced in-house would result in a higher cost saving to the operation.

Table 1. Required data for the simulation model

Data Group	Data Type
Production Mix Data	Front and rear RS Spring, Front and rear LS Spring, T-Case, Rear and Front Prop Rear and Front Axle, Engine Type
Pull Off Data	Number of Pull off, Type of axle, Frequency, Reason
Delivery Information	Delivery Schedule, Number of Delivery per day for the axles, Type of axles, Number of Hi-Low travel moving/removing per day, Number of Hi-Low, Number of Delivery per day for springs, Type of springs, Number of spring per batch, Number of Hi-Low travel moving/removing per day
Cycle and Stoppages Data	Cycle time at each station of axle loop, Number of downtime at each station, Mean time to Failure (MTTF), Mean time to Repair (MTR), Reason for Failure, Number of set-up, Set-up time at each station
Repair Data	Number of repairs due to wrong axles install (Done at axle loop), Number of repairs due to wrong axles install (Not done at the axle loop), Repair Time for each case, Delay time before maintenance schedule, Other repairs due to the process done at the axle loop, Repair Time, Number of repairs due to wrong spring install (Done at the axle loop), Number of repairs due to wrong spring install (Not done at the axle loop), Repair Time for each case, Delay time before maintenance schedule
Facility Data	Square footage for the WP inventory for the springs, Square footage for the WP inventory for the axles, Sq/ft Cost

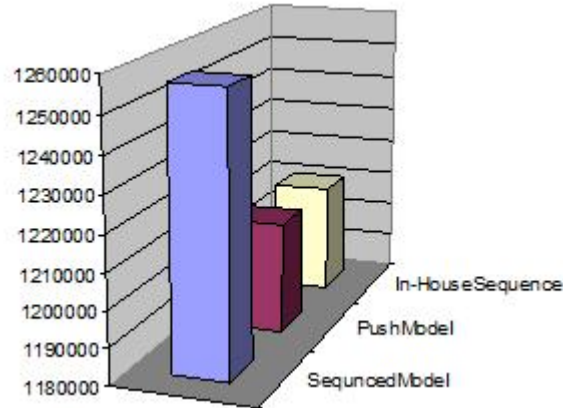


Figure 4. Cost comparisons between different delivery and inventory policies

5. IMPACT OF INCREASED VARIABILITY ANALYSIS

A comprehensive cost analysis is required to study the impact of the added product variety. This is captured by the proposed sequence driven simulation model as shown in Figure 5 (Adat, 2006). The three phases are:

- **Sequence generation:** In the first phase a mixed model assembly sequence is determined by using Toyota’s goal chasing algorithm. The goal chasing algorithm is coded in Visual C++.
- **Assembly line simulation:** In the second phase the assembly line is simulated using Witness ® simulation software. The assembly line is assumed to operate in adherence with the just-in-time methodology wherein subassemblies are delivered to the main assembly line as and when required.
- **Cost estimation:** The results from the simulation model are used in the third phase to compute the cost of increased product variety in the manufacturing system.

Given the monthly production schedule, the daily production is calculated assuming that there are 22 production days in a month. From the daily production requirement, the consumption rates of the sub assemblies are calculated assuming that a production comprises of two shifts of 435 minutes each.

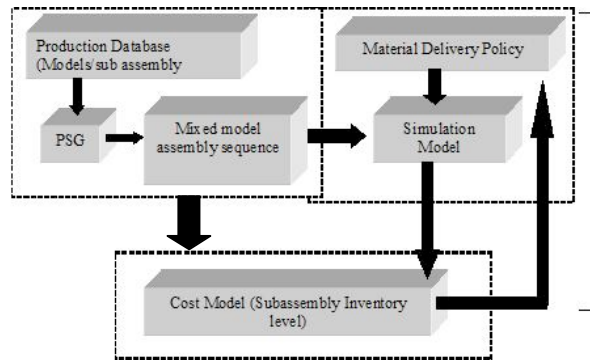


Figure 5. The proposed cost model for added variety analysis

The product structure graph (PSG) is used to identify the monthly production schedule. This information is used as input for sequence identification. The assembly sequence in a mixed model assembly line is generated by using the goal chasing heuristic (Monden, 1998). The primary goal of the heuristic is to minimize the variation of consumption of subassemblies that feed the main assembly line. The VC++ code is developed to model the goal chasing heuristic portion of this method. This project only focused on the assembly stations corresponding to the axles and spring coil assemblies. The assembly stations adhere to JIT philosophy. The experiment file of the Witness® is set up by referencing respective model files (Figure 5). The daily production sequence model was executed for 869 minutes and for 22 replications. The last minute is

ignored to avoid any inventory flushing into the system. The model is allotted an initial warm period of 15 minutes. The replications are executed in consecutive execution mode. Hence the vehicle models that remain at the end of every replication are forwarded and assembled in the next replications. The output of the simulation model is used for further cost analysis. The inventory costs associated with the increased in product variety is comprised of cost of inventory holding and storage. The inventory holding and the storage costs are calculated by monitoring the average daily inventory level of all the subassemblies from the simulation model. The daily total cost of operation is proposed by the equation:

$$C_{day} = \sum_{i=1}^n C_i \cdot h \cdot A_i + \sum_{i=1}^n (S \cdot B_i) \quad \dots \quad (3)$$

Where,

- C_i Cost of the axle (i)
- h Inventory holding cost as a percentage
- A_i Average inventory level of subassembly (i) per day
- B_i Number of storage bins required for subassembly (i)
- S Storage cost per square feet per day
- n Total number of sub assemblies in the system.

The inventory holding cost for a given subassembly is calculated as the product of average inventory holding and the daily average inventory level per subassembly and it was assumed a cost of capital of 10% (h). The axles and spring coils are assumed to be stored in storage bins. Each bin can store 10 axles (Front/rear) or 192 spring coils (front/rear). One bin occupies a storage space of 8.89 square feet and the company incurs a storage cost (loss) of \$70.00 per day. It is assumed that sub assemblies and safety stock are stored in separate bins. In most cases, the cost of inventory holding includes the cost of storage but for the present scenario, holding and storage costs are computed separately due to the increase in storage space and the increase in the number of number of bins. This is used to measure the system's response to handle the additional variant.

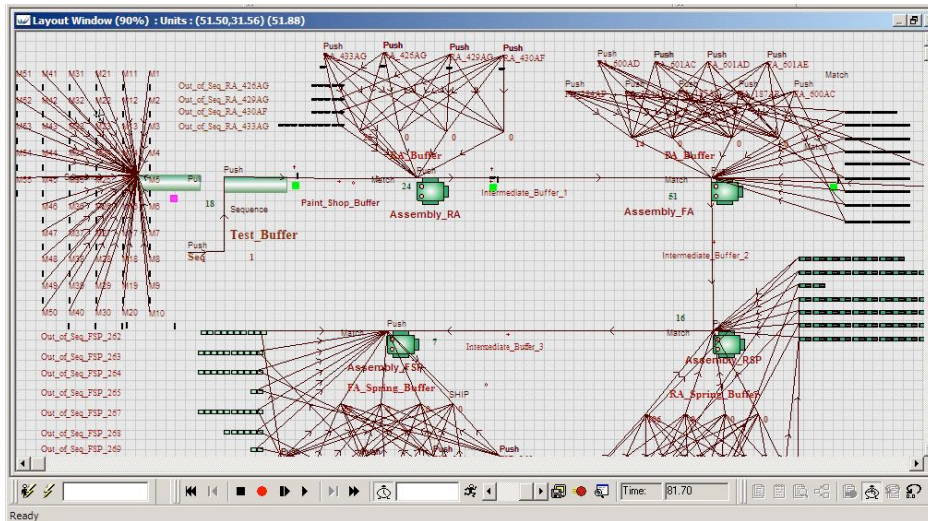


Figure 5. Witness ® screen capture of the multi model assembly line

6. EXPERIMENTATIONS AND RESULTS

The cost impact of increased product variety was studied in two production models: 1) Daily production sequence shift replenishment model and 2) Monthly production sequence hourly replenishment model.

In the daily production sequence model, the production sequence is generated by averaging the monthly demand of the vehicle models and estimating daily demands. The daily sequence generated is repeated every day over the span of 22 consecutive days. The replenishment of all the subassemblies is done at the beginning of every shift. In the monthly production sequence model the monthly demands of the vehicle models are used to determine the production sequence. The resulting sequence is continuous and the replenishment of most of the subassemblies is done on an hourly basis. Those

subassemblies that have a low consumption rate are replenished at the beginning of every shift to reduce the work-in-process inventory, handling costs, and line stoppages.

6.1 Daily production sequence with shift replenishment

The average inventory levels for subassemblies plotted for four different scenarios are illustrated in Figures 6 through 9. The base scenario (0,0) has 55 product variants with a total production of 1,249 vehicles per day. The second scenario (0,1) has a new product variant (56th vehicle), which uses rear axle 429 AG, front axle 184 AQ, rear spring coil 500 and front spring coil 263. The new production requirement is 1,250 vehicles per day. The third scenario (1,0) introduces the 57th product variant but removes the 56th product variant. The 57th variant uses rear axle 429 AG, front axle 184 AP, rear axle 500, and front 265. The production rate still remains at 1,250 per day. The fourth scenario (1,1) includes both the vehicle variants and hence the production rate is 1,251 vehicles per day. The storage cost per day for all the subassemblies is summarized in Figure 10. The graph shows that there is a steady increase in the storage cost of front and rear axles, but there is only a marginal increase in the storage cost of rear spring coils and no increase in the storage cost of front springs.

The primary reason for the storage cost difference is the storage capacity of the bins. A storage bin can store only 10 axles or 192 spring coils. Therefore, when there is an increase in the average inventory level of the subassemblies, the number of bins corresponding to the axles increase drastically, but the number of bins corresponding to the springs increase marginally. This explains the considerable increase in storage cost of the axles compared to the springs.

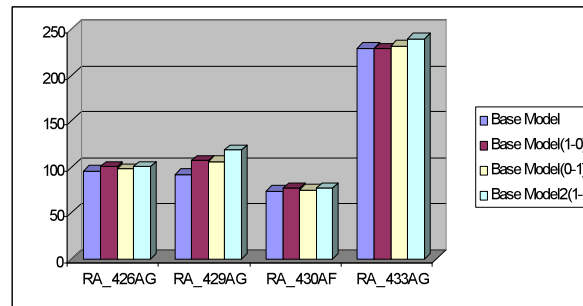


Figure 6. Average daily inventory level of rear axles

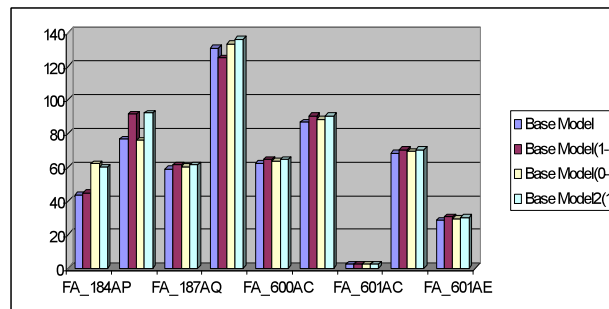


Figure 7. Average daily inventory level of front axles

Furthermore, the consumption of subassemblies does not have a similar pattern. Among the subassemblies, the consumption rate of the individual models also makes a difference in the ability to handle product variety. For instance, among the front spring coils, there are a few spring models that are consumed at a very high rate, but the majority of the models have a low rate of consumption. This enables the front spring coils to absorb the added product variety with a corresponding result of no additional storage cost. A gradual increase in the inventory holding cost of the subassemblies is observed with the inclusion of new product variants. Figure 11 summarizes the results for different scenarios.

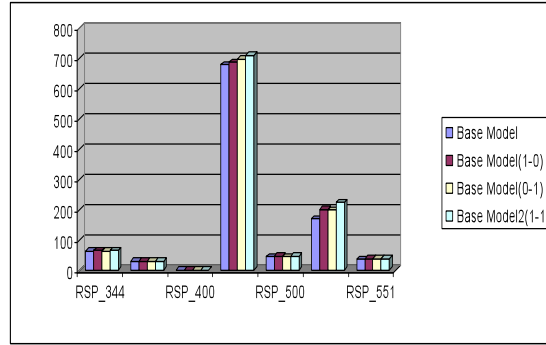


Figure 8. Average daily inventory level of rear spring coils

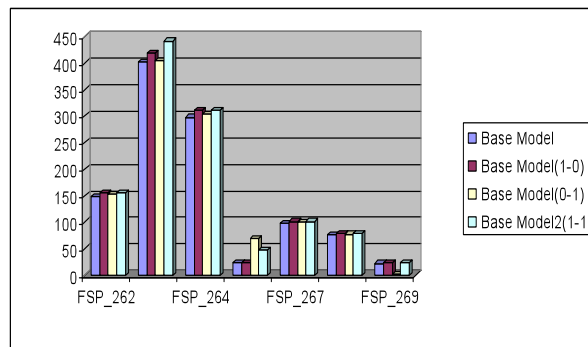


Figure 9. Average daily inventory level of front spring coils

6.2 Monthly production sequence with hourly replenishment

It was observed that with hourly inventory replenishment policy the average inventory level of the high consumption subassemblies was low but that the average inventory level of the low consumption subassemblies was high enough to prevent line stoppages. Thus, a new delivery policy was proposed and modeled. The high consumption subassemblies are replenished on an hourly basis and the low consumption models are delivered at the beginning of every shift. Front Axle 601 AC, rear spring coils 345, 400, 500, 551, and front spring coils 265 and 269 are replenished at the beginning of every shift and the rest of the subassemblies are replenished hourly. The results are plotted in Figure 12 and Figure 13. The results show that average daily inventory holding cost and storage cost for the monthly schedule hourly replenishment model is less than the daily sequence hourly replenishment model. Theoretically, this is accompanied by an increase in material handling cost, but this analysis is not included in the study.

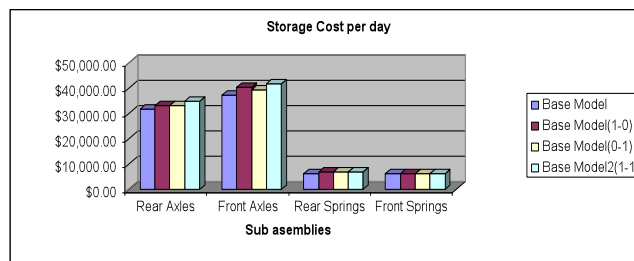


Figure 10. Average daily storage cost for all subassemblies

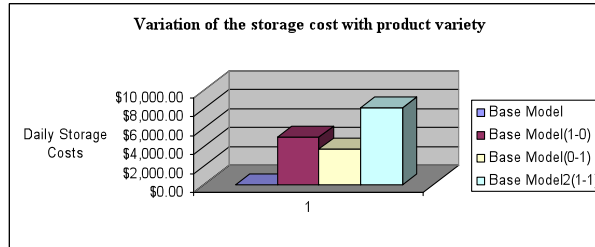


Figure 11. Increase in storage cost with added product variety

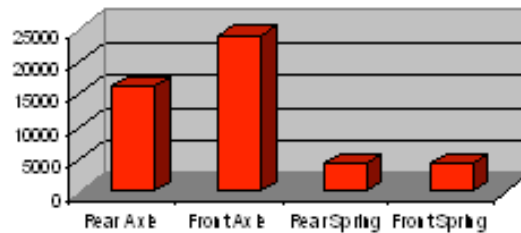


Figure 12. Average daily inventory storage cost for all subassemblies

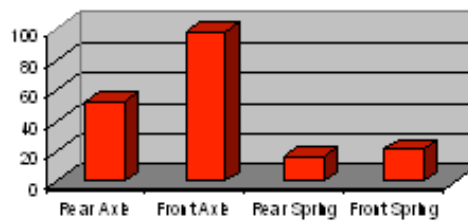


Figure 13. Average daily inventory holding cost for all subassemblies

In summary, the proposed methodology provides insight into the behavior of the manufacturing system by capturing the variation of the inventory holding cost and the storage cost due to added product variety. Although it is expected that the inclusion of a new model will only increase the inventory level (and correspondingly inventory holding and storage costs) of the corresponding subassembly, the results of the analysis show that the inclusion of the new product variant also impacts the inventory level of other subassemblies in the system. Thus, the final inventory level on the assembly line is determined primarily by the sequence of vehicle assembly and the delivery policy. The simulation model successfully captures these parameters. Hence, the model is an analytical tool for production managers to make informed decisions regarding a new product introduction. The model can also be used to study the inventory holding and storage costs for alternative replenishment policies. The result from the developed methodology proposes that product variety in a mixed model assembly line can be handled successfully by altering the assembly sequence and the delivery policy. The cost model is generated by capturing the model mix complexity in a PSG (product structure graph) and generating a schedule to feed the simulation model which runs on the JIT philosophy. The simulation model helps to reveal the impact of added product variety on inventory holding and storage cost. The cost model provides an analytical tool in manufacturing to estimate the projected increase in inventory holding and storage cost and also to study the impact of the manufacturing system on various material handling policies.

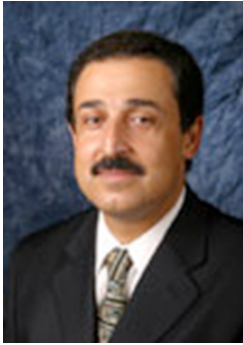
7. CONCLUSION

Auto manufacturers worldwide face the constant challenge of striking a balance between product variety and mass production. While increased product variety enables better market coverage by tailoring a product to niche markets, companies struggle with variety to accomplish productivity and quality attained by mass production. Product variety complicates the part supply process. Inventory policies are crucial and decisive factors in improving a company's manufacturing policies. There are conflicting views on holding inventory to strike a balance between the costs associated with holding inventory and not meeting customer expectations. The reasons for holding inventory include: Rapid response to customer demands (less order lead-time), Ordering costs, Stock-out costs and Start-up quality costs. The reasons for not holding inventory include: Inventory carrying costs, Loss of system sensitivity, Cost of frequent set-up changes, Lower return on investment. The proposed method uses a combination of different policies to simplify and improve manufacturing performance impacted by variety and complexity.

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BIOGRAPHICAL SKETCH



Ali K. Kamrani is an associate professor of industrial engineering and the founding director of the Design and Free Form Fabrication Laboratory at the University of Houston, United States. He is a visiting professor at the Princess Fatimah Alnijris's Research Chair for AMT, Industrial Engineering Department at King Saud University, Riyadh, Saudi Arabia. His research interests include the fundamental application of systems engineering and its application in the design and development of complex systems. He is a professional engineer at the State of Texas



Maryam Azimi is a PhD candidate in the Department of Industrial Engineering at the University of Houston. Azimi received her BS in textile technology engineering (2001) and her MS in textile management (2004) from Tehran Polytechnic (Amirkabir University), Tehran, Iran. Her current research interests include systems engineering, statistics, and application of data mining in health care and CAD/CAM.



Arun Adat is the Supply Chain Strategy and Development Manager at Hewlett Packard. He is responsible for developing world-wide product fulfillment strategies. Arun's expertise includes supply chain network design, Emerging market assessment, New Product Introduction Processes and mathematical modeling of supply chains. Prior to joining Hewlett Packard, Arun was the Logistics Solutions Analyst at Goodman Manufacturing. He designed and prototyped customized algorithms, demonstrated potential cost savings in freight and distribution, collaborated with IT and implemented heuristics on the production system. Arun holds a Bachelor of Science in Mechanical Engineering from Manipal Institute of Technology, India and Master of Science in Industrial Engineering from University of Houston.
