

**An Analysis of Engine Assembly and Component
Production Behavior**

by

Thomas B. Blake

B.S. Mechanical Engineering, United States Military Academy, 1991

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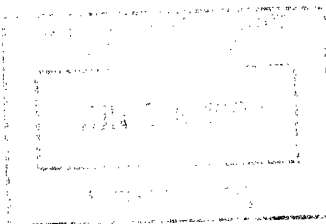
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ABSTRACT

This study analyses the information and material flow through a component manufacturing and turbine engine assembly system. The intent of this work was to understand the inefficiencies associated with the current system, and to propose solutions which would prove valuable to the entire value chain, not only to one manufacturing site. This work was accomplished by identifying a significant problem in the system, developing a model to replicate historical behavior, then developing solutions to improve material and information flow.

The shipment rate of engines from the assembly facility was found to follow a "hockey stick" pattern throughout each production quarter (a three-month cycle), meaning that shipments increased exponentially toward the end of each quarter. Shipments were traced back through the component manufacturing facilities, and the exponential increase of component shipments was shown to follow that of assembly shipments. Interviews were primarily used to establish critical variables in the system, and a system dynamics modeling technique was used to generate a model that mirrored historical shipment data. The model was then manipulated to test the sensitivity of specific production variables, and suggestions were made to improve material and information flow.

Finally, a component kit plan was developed that added value to the assembly facility by delivering gear products by order number rather than as separate components. Also, the component production facilities benefit by shortening the existing information feedback loop between component manufacturing and assembly and allowing more level production with less variability amplification from the bullwhip effect. Demand Flow Technology is introduced as a means to then affect the entire supply chain, including supporting functions not directly related to manufacturing.

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Chapter 1 Introduction

“An information-feedback system exists whenever the environment leads to a decision that results in action which affects the environment and thereby influences future decisions.”

- Jay W. Forrester

1.1 Problem Motivation

This project began as a local optimization of a gear production facility manufacturing process within the framework of a larger engine assembly facility with multiple component production centers and a central assembly center. It was determined that a local optimization would contribute to certain operational improvements within the gear center, and could have some effect on upstream and downstream activities, but the improvements would remain limited in effectiveness due to the gear center's integration with a final engine assembly schedule. Therefore, the scope of the problem was broadened to incorporate the entire supply chain, from procurement of raw materials and externally manufactured components through assembly and delivery to the customer. The specific issues centered on component production and engine assembly rates (contributing directly to delivery performance), and inventory levels throughout the chain. Delays in information and material flow between component centers led to a bullwhip effect, which amplified production schedule disruption and inventory levels, and severely limited the gear facility's ability to smooth production rates and maintain delivery performance without continuous expediting. The problem presented in this work involves a specific manufacturing environment, but has been developed generically to apply to many manufacturing situations which manufacture and procure components, and assemble those components into final products according to a forecasted schedule.

1.2 Introduction

The turbine engine facility represented by this study designs and manufactures auxiliary power units (for commercial and regional airlines, and business/military aircraft) and turbofan, turboshaft and turboprop propulsion engines (for business aviation, regional airlines, military aircraft and marine and industrial markets). Turbofan engines support applications in the 3500-5000 lb. thrust range in business aviation and 7000 lb. thrust range in regional jet applications. Auxiliary power units support applications from corporate jet through the commercial airliner range. Also, the company provides maintenance service and repair parts through a worldwide service and support network.

At the engine facility, a main assembly facility receives both purchased and internally manufactured parts, and maintains sole responsibility for engine assembly and shipment, and kit and spare part order consolidation and shipment. Aside from externally purchased parts, three component manufacturing centers on the campus support the assembly facility with manufactured parts and subassemblies. Manufactured products from these three facilities include gears and shafts, subassembly housings and machined casings, compressor and turbine rotating groups, and a variety of static sheet metal components.

This thesis seeks to understand the information and material flow through a single, on-campus component manufacturing center, the Case & Gear Center of Excellence (COE). This facility was formerly known as the Gear Production Center, a cost center that manufactured only gears and shafts. However, after the adoption of Centers of Excellence (taken from the General Electric business model) and the integration of the Caseline (subassembly housings and machined casings), a new name and organization was adopted as a first step toward providing complete, integrated gear drives, and assuming autonomous profit and loss responsibility.

The critical issues discussed are the detrimental effects of time delays associated with current information and material flow between component production and engine assembly. These delays contribute to production schedule disruption, expediting and delivery performance, and increase in amplitude as the system steps further back in the value chain. This is known as the bullwhip effect. As pointed out by Lee, Padmanaghan and Whang (1997), the term "bullwhip effect" was coined by executives of Proctor and Gamble (P&G). It was noted that although consumer demand for diapers was fairly constant over time, orders from retailers were quite variable. Also, larger variations in order quantities were

observed in the orders P&G received from their wholesalers. This increasing variability was called the bullwhip effect.

Also, component completion and engine shipment rates which exponentially increase during each revenue quarter will be studied. This is the hockey stick effect, where activity increases exponentially to meet a production quota in a prescribed time limit. In this case the limit was one (three month) production quarter. Executives at Compaq Computer Corporation spoke of this topic, noting that most of their quarterly business was shipped in the last month of a production quarter. In that last month, most shipments went out the last week. Finally, in that last week most orders shipped the last day. This exponential increase describes the hockey stick effect.

It is hoped that by developing a mathematically based model that can replicate the current component and assembly behavior, this thesis can quantify the extent to which production schedules are disrupted, orders are expedited, and delivery performance suffers.

Chapter 2 attempts to provide a foundation for building system dynamics models as a way to solve specific management issues related to the bullwhip effect. Jay Forrester's work in Industrial Dynamics serves as a foundation to explain this bullwhip effect and the resulting hockey stick phenomenon that occurs as a target completion time approaches.

Chapter 3 then develops a model of the production and assembly system to explain why inventory, production rates and shipment rates vary during the course of a production quarter. Results are shown which first mirror historical data obtained on site, then the model is used to present options for correcting noted inefficiencies.

Chapter 4 presents one possible solution to minimize the material and information flow delays. A kit plan is developed that de-couples component manufacturing from the assembly production schedule, allowing smoother (more level) component production and more proactive (versus reactive) adjustments to the schedule to project a net reduction in inventory and maintain or improve delivery performance.

Chapter 5 introduces Demand Flow Technology, developed by the John Costanza Institute of Technology (JcIT), which integrates the issues described above into an efficient production system. While names like Just-in-Time, CONWIP, Lean Manufacturing, Kanban and Demand Flow all represent the same type of manufacturing environment, subtle differences will be noted between each. Additionally, their advantages over a traditional MRP-type system are also presented.

Chapter 6 will conclude the work by integrating model building, manufacturing model development (with inherent material and information flow delays), and a kit plan as a first step in controlling the entire gear value chain within the larger engine assembly system.

Chapter 2 Model Building

2.1 Model Introduction

In a simple system involving information and/or material flow, one can easily determine the outcome of a particular action based on common knowledge and basic fundamentals. Even parties unfamiliar with the system can determine likely outcomes in a basic cause and effect relationship. A simple example is the effect of birth and death rates on total population of a given area.

As the birth rate of an area increases, represented as births/time, the total population increases at the birth rate times a given amount of time. The cause and effect are simple – more births equal more population. As population increases, the percentage of people able to have children increases as well, increasing the birth rate. Conversely, as one variable decreases, an accompanying decrease is noted in the other. In this case, since a change in one variable contributes to a similar change in the other, the two are considered positively linked forming a reinforcing causal loop (see Figure 2.1-1). (Note: the “+” symbol denotes a similar relationship – increase to increase, or decrease to decrease.)

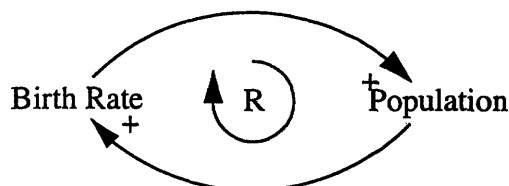


Figure 2.1-1 Birth Rate Loop: A reinforcing causal loop which shows that as either variable increases, a corresponding increase is noted in the other (a + sign signifies a change in the same direction – increase to increase, decrease to decrease).

Population and death rate are also linked, but negatively as shown in Figure 2.1-2. As the death rate increases (more people die in a given amount of time), the population sees a corresponding decrease. Then, as the population decreases, the percentage of people who can die decreases, resulting in a decreased death rate. A change in one variable causes an opposite change in the other. They are negatively linked forming a balancing causal loop,

where a change in one variable produces the opposite change in the other. Here, the “-“ sign denotes an opposite relationship – increase to decrease, or decrease to increase.

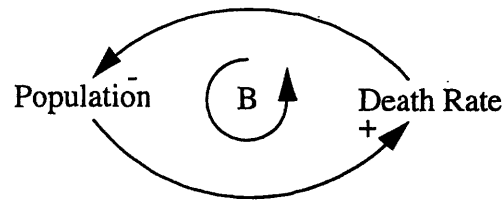


Figure 2.1-2 Death Rate Loop: A balancing causal loop which shows that as population increases the death rate increases, but as the death rate increases, population shows a corresponding decrease (a - sign signifies a change in the opposite direction: increase to decrease, decrease to increase).

When combined (see Figure 2.1-3), the birth rate and death rate both affect population simultaneously. Simple mathematics shows a net increase or decrease in population as birth or death rates outpace one another. Note, however, that the system is dynamic. Fluctuations in birth and death rates simultaneously produce changes in population, and a race between the two loops results in either a population increase or decrease over time.

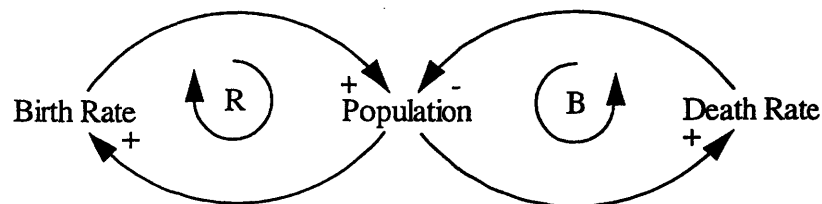


Figure 2.1-3 Combined Birth-Death Loops: The reinforcing and balancing loops have opposite effects on population. Their combined effect is a net increase or decrease in the population, depending on the rate of births or deaths.

Although simplistic, this concept will be examined further as it relates to the introduction of material onto the shop floor and the exit of finished goods from the facility.

The balance between release rates and completion rates is considered work-in-process, or the “population” of material at any one time in the system.

As shown, a simple, first order system is easily determined. However, as additional variables are added to a system the results become much harder, if not impossible, to determine accurately. In the population model above, a myriad of other factors also influence population. Immigration rates, weather, food supply, disease, and medical treatment are only a few factors that are included in a more complete model. As factors are added, the ability to simply balance rates of increase or decrease become increasingly complex, and requires the aid of a model.

2.2 A Manufacturing Model

In a manufacturing environment, the factors affecting the “population,” or inventory of a system are easily identifiable. The introduction of raw material, the completion rate, machine reliability, process time, supplier and process quality, and many other human factors contribute to the level of inventory. However, these factors are constantly changing – even by the minute – making a real time evaluation of inventory almost impossible. Again, a mathematical model can serve to aid in evaluating the performance of a system.

A note about data is required before beginning a discussion of modeling. The use of computers in a manufacturing environment has contributed to incredible advances in process efficiency and information and material flow. Automated production equipment has significantly increased the quality level of many manufactured components by eliminating countless sources of human error. These machines are also able to collect data many times per second, allowing continuous process feedback. Information systems provided up to the minute status of inventory that is readily available to all parties involved. These benefits come at a cost, however.

The sheer amount of data that can be collected has made analysis, in some cases, a nightmare. Although all parties involved in the system have access to the same data, the enormity can be overwhelming and analysis can be incomplete or even wrong. Computer systems that cannot communicate contribute to inaccuracies, and knowledge (or lack thereof) of statistical methods to synthesizing results contribute to flawed conclusions.

The point of noting the above costs and benefits is to further develop the need for a model. By using the collected data, yet making certain simplifying assumptions, one can

replicate the performance of certain system characteristics to determine conclusions. Forrester (1961) notes, “The key to success (in modeling) will lie in clear questions which are broad enough to encompass matters of major consequence but which initially limit a system to proportions that fit the skill, time, and experience of the investigator” (p. 450). Modeling provides a systematic approach to simplifying the problem solving process by collecting only the data needed, and then using that data to come to a concrete conclusion not about the entire system, but about a specific issue or problem.

2.3 Industrial Dynamics

Jay Forrester, currently the Germechausen Professor Emeritus of Management at the Massachusetts Institute of Technology in Cambridge, Massachusetts, first studied these positive and negative effects as they related to industrial management in his work, Industrial Dynamics. The principles contained in this section will form a foundation upon which a model applicable to a specific manufacturing environment will be developed. In general, Professor Forrester provided a framework for studying information and material feedback systems, and the complex interrelationships between variable in such a system. He states (1961):

Information-feedback systems, whether they be mechanical, biological, or social, owe their behavior to three characteristics – structure, delays, and amplification. The structure of a system tells how the parts are related to one another. Delays always exist in the availability of information, in making decisions based on the information, and in taking action on the decisions. Amplification usually exists throughout such systems, especially in the decision policies of our industrial and social systems. Amplification is manifested when an action is more forceful than might at first seem to be implied by the information inputs to the governing decision (p. 15).

What makes this work so applicable to the problem identified in this thesis is that it incorporates many of the same variables one would encounter in a manufacturing system. Information and material flow are traced from an end-consumer back through retail, distribution, wholesale and manufacturing elements. As will be discussed in a later section, the model will not specifically note distribution, wholesale or retail segments. It will, however, use the same concepts to develop production process steps, inventory levels, and delivery to customers.

A schematic of Professor Forrester's system is shown in Figure 2.3-1.

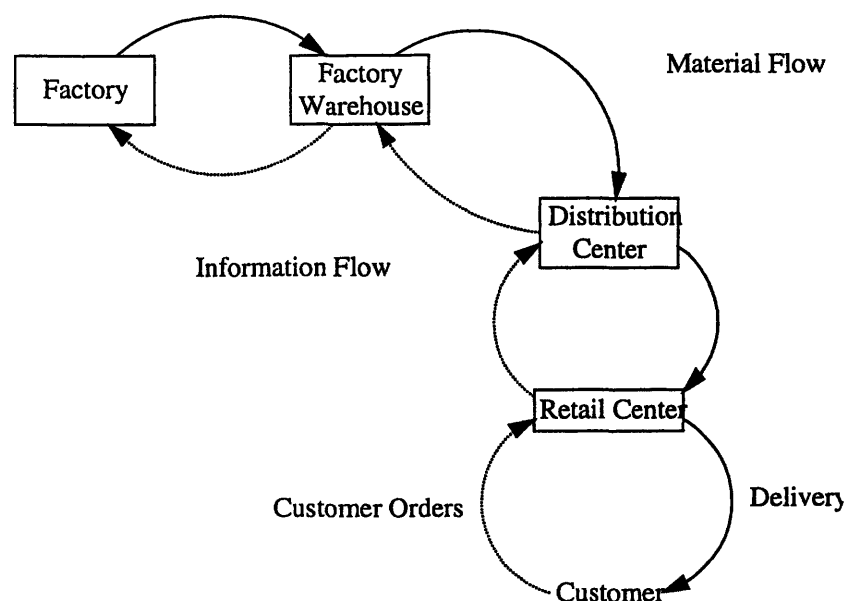


Figure 2.3-1 Distribution Model Structure: This represents a four-stage distribution system where information (dashed lines) is transferred in steps from the end customer back to the factory, and material (solid lines) is then shipped forward to the customer. Delays in information and material flow are inherent in this type of system and contribute to the bullwhip effect. The bullwhip effect results in overordering back to the factory, expediting at the factory to meet customer demand, and then delayed shipment of product at each stage forward.

Solid lines in the above diagram represent the flow of material from the factory through delivery to the customer. Dashed lines represent the flow of information from the customer order back through the system to the factory, where the product is ultimately produced. Delays are inherent in such a system. Rarely does a factory get simultaneous

information of a customer order, and rarely does a customer immediately receive an ordered product. Just as information has to pass through many levels between customer and factory, normally waiting for processing at each step, material follows the same hurry-up-and-wait path. Each level of the above diagram pushes to process orders and ship, but upon arrival at the next step, the material again waits in a queue for processing.

So what issues arise as a result of these information and material delays? Consumer data that is old contributes to a lag in responsiveness to customer needs. If the lag is only a few days, the factory has much more flexibility to adjust production levels to meet demand. As the lag increases, the factory is responding to consumer patterns that occurred sometime in the past. Additionally, if the cycle time of a product is considerable, or if the lead-time from suppliers is long, the factory must hold much more inventory to maintain an adequate level of customer service. If the total lead-time is great enough and customers have to wait, they may simply buy another product instead of waiting, even if it is of lesser quality (although this is not typically the case in the aerospace industry, it should be noted). Finally, if the factory deals in products that are changing rapidly in the face of consumer needs or technological improvements, a long lead-time reduces the manufacturer's ability to get the right product to market to meet customer demand.

More importantly, not having real time information means that each level upstream of the customer must add a safety factor in adjusting to changing consumption patterns. For example, a sudden increase in buying means that a factory must immediately ramp up production. As mentioned earlier, if the delay in learning this information is short, production schedules need only minor adjustment to make up for the increased demand. The time between the actual increase and the arrival of information at the factory means only a small number of backorders. If the time lag is great, much more time has elapsed allowing unfilled orders to increase. Then, when the factory receives the information, production must be dramatically increased. Unfortunately, in a system with both significant information and material delays two main consequences can result. By the time production catches up with demand, the actual demand has either decreased (leaving the factory with excess inventory), or customers have gone elsewhere to place their order (not only leaving the factory with excess inventory, but with lost orders in the future from customers who have lost confidence).

Professor Forrester's model, shown in Appendix B, mathematically models a system with multiple variables and significant delays, and two sets of results are shown. Figure 2.3-2 shows a one-time increase in demand, a "step," which is delayed as it moves back to the factory. Figure 2.3-3 shows cyclical demand, where the oscillation of demand at the consumer level multiplies as it again moves back to the factory.

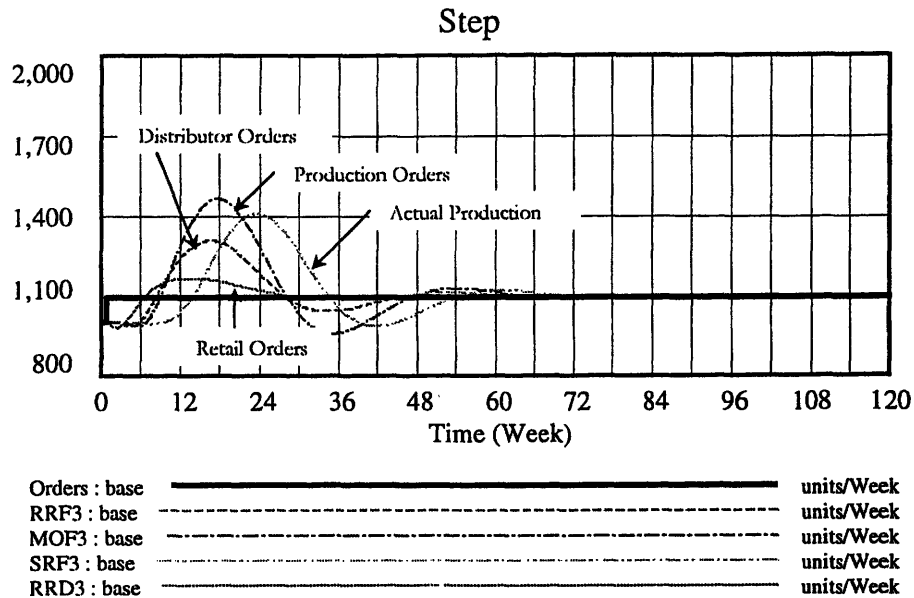


Figure 2.3-2 Step Order Input: A one-time step perturbation is introduced to actual customer demand. The result is delayed orders from retailer to distributor (RRF) and from distributor to factory (RRD). Production orders at the factory (MOF) and then actual production (SRF) are further delayed. At each step, the order increase is exaggerated to meet the rise in demand. Each step must increase further than the previous step in order to meet both the original increase in demand and the buildup of backorders. Actual production peaks last and does not peak as high, since it is able to see that demand is again level after the step input.

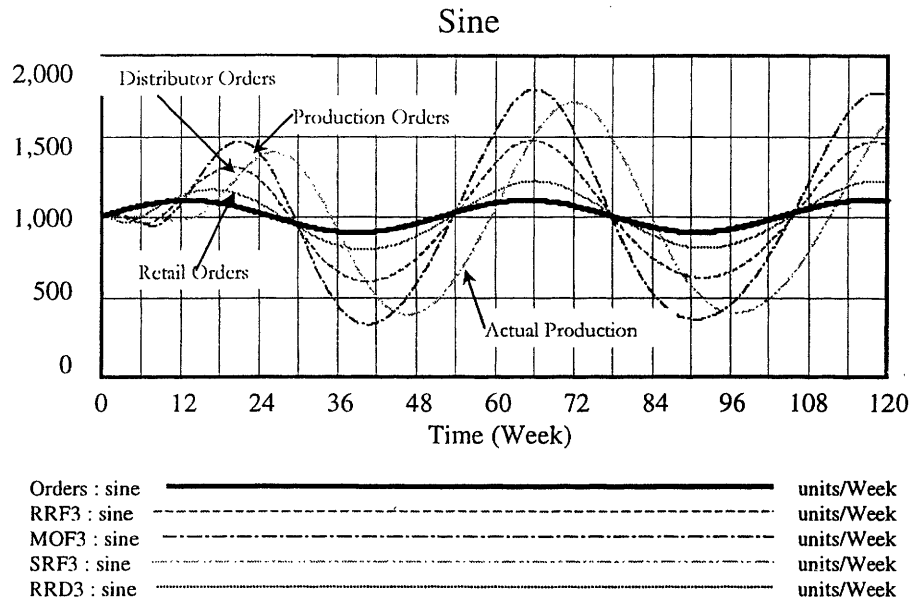


Figure 2.3-3 Sine Order Input: A continuous oscillation is introduced to demand. As in the step input shown above, orders from the customer back to the factory, and then production orders at the factory, are exaggerated in amplitude and peak later than the original order curve. The order curves above appear to be headed out of control. If the oscillations in demand are great enough, this is precisely the result.

Note that each step up from the customer reacts to new information with more pronounced amplitude, and how each reaction peaks later than the previous step. This is known as the bullwhip effect, and it is common in many environments where the distribution channel is extended in multiple steps, and where information is not immediately shared. The graphs above only show information flow from the customer to the factory, and do not show the delays in material flow as product moves from the factory to the customer. Below are the results of that material flow, again both with a one-time step input (Figure 2.3-4) and an oscillation (Figure 2.3-5).

Step (Material Flow)

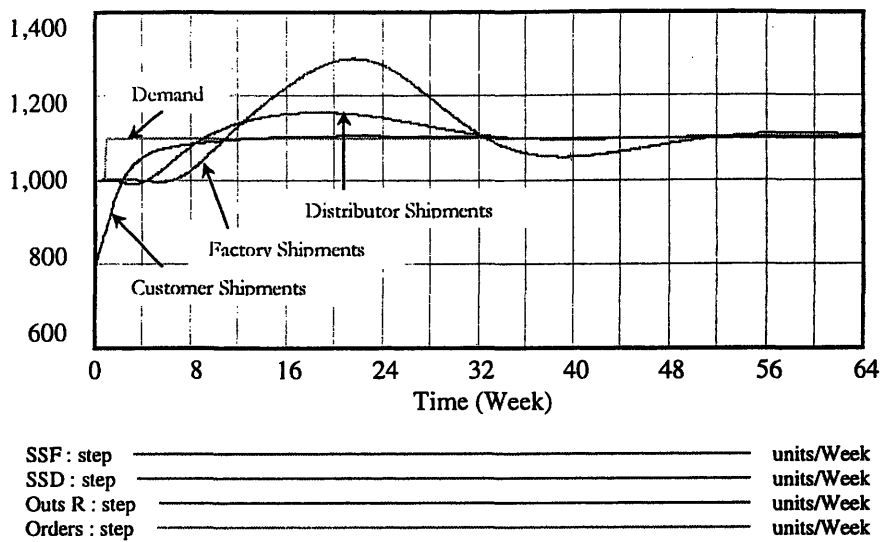


Figure 2.3-4 Step Input (Material Flow): This shows the delays in material flow from a one-time step input. Note that factory shipments peak much later and higher than distributor or customer shipments as they try to catch up with backordered demand. Also, note that as shipments get closer to the customer they more closely resemble actual demand, with customer shipments smoothly rising to meet demand by Week 12.

Sine (Material Flow)

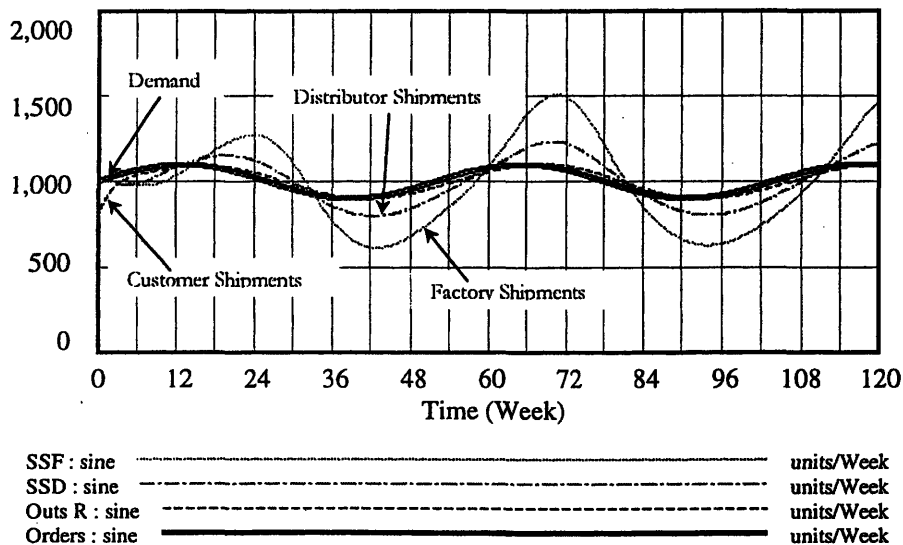


Figure 2.3-5 Sine Input (Material Flow): A constant demand oscillation is shown above. Again, customer shipments closely mirror actual demand, but factory

shipments follow demand trends in exaggerated shipments, peaking much later than the demand curve.

Here, note that again the curves peak higher and later for the distributor and for the factory deliveries, but the reasons are somewhat different from before. Here, it is shown that the retailers are much more responsive to customer changes. Their curve follows very closely with the orders curve and does not peak significantly higher. In the Step figure, the deliveries curve simply rises to meet demand, smoothly meeting it by Week 7. Curves for distributors and the factory, however, again show a delay in moving product to the next stage. Whereas in the first example the information was delayed telling each upstream step to order more goods and their successive orders curves peaked later, here the actual delivery curve peaks later. This is due primarily to the factory's ability to generate enough products to satisfy demand in the distribution chain.

2.4 Component Production and Engine Assembly

Why all the fuss about generic models, and what do retailers and distributors have to do with manufacturing engine components? Actually, everything and nothing. The point of this section was not to develop a model specifically of a distribution network. Instead, the purpose was to introduce a system comprised of many levels in a supply chain from the factory to an end-user, and to demonstrate the inherent material and information flow delays. Distributors and retailers deal in bulk shipments, not make-to-order turbine engines. They exist to make certain supply chains more efficient by providing an effective mechanism for material flow between the factory and customer. Turbine engines are make-to-order, are not shipped in bulk, and do not normally sit in inventory waiting for a prospective buyer. Therefore, there are no distributors or retailers in the industry. A shift will now be made from thinking of distributors and retailers as steps in a value chain to thinking of component production (furthest from the customer) and engine assembly (the last step before the customer). Instead of now thinking of consumer goods moving through a distribution network, now attention turns to an individual engine component moving from a manufacturing facility, through an assembly facility, then on to a customer. Information flow from the customer to assembly, and finally to component production mirror orders for consumer goods. At the same time, the movement of a component from production,

through assembly, and on to the customer represents the same material flow steps developed in the production distribution model of this section.

To further simplify this explanation, Figure 2.4-1 presents a schematic which highlights the similarity of the systems. Note that although fewer steps are shown in the engine model, the same information and material flow delays occur between the existing steps. Subtracting steps means that the furthest step away from the customer will see a smaller amplification of the original input, while adding steps further compounds the amplification. Again, dashed lines represent information flow and solid lines represent material flow.

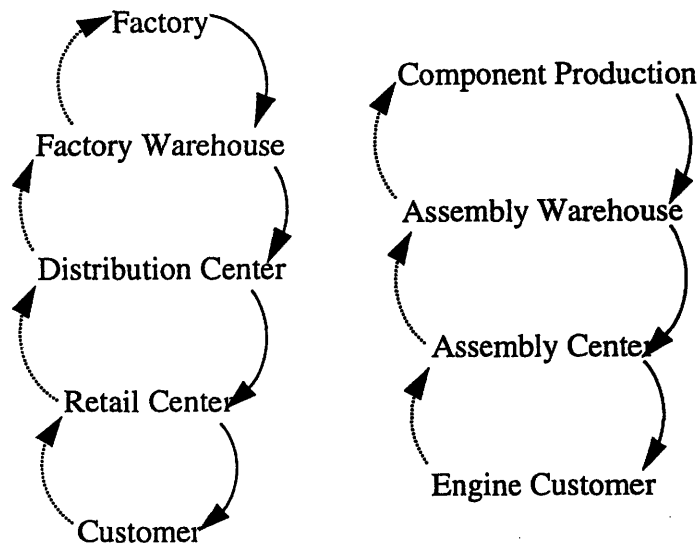


Figure 2.4-1 Structure Similarity: The distribution model that is developed in this chapter is shown on the left. It is a multi-stage system of material and information flow. On the right, the manufacturing system studied in this research is also shown as a similar multi-stage system of flows. The interaction of multiple stages in systems such as these produce similar delays which affect material and information flows.

The next chapter will develop a model similar to Professor Forrester's, and will speak more directly to the information and material flows between steps in a production and assembly value chain.

Chapter 3 Manufacturing Model Development

3.1 Analysis of Interviews and Data

Having motivated information and material flow thus far, and having introduced a technique for analyzing such issues, a procedure to integrate these factors and develop meaningful conclusions must be presented. Original work at the facility was accomplished by interviewing numerous individuals at various levels of the manufacturing organization. The goal was to understand the thought process – to understand the mental models associated with solving similar problems – at all levels. Interestingly, the range of answers to particular questions relating to production schedules, production rates, orders and inventory varied widely from higher level executives to shop floor associates, even though the questions were identical. Their mental models differed based on current information (both externally and internally obtained), historical experience at the facility, and breadth of knowledge of the entire system from raw materials to finished components and engines.

Given the foundation for a production model, attention now turns to its application to the manufacturing environment. As mentioned previously, the assembly facility receives both purchased and internally manufactured parts, then assembles those parts into either rebuild kits or complete engines, or consolidates them for spare parts shipments. This model focuses on the movement of manufactured gears and shafts through the Case & Gear COE and on to the assembly facility.

Originally, linking the Case & Gear COE with the assembly facility in a flow system based on customer demand of engine, kit and spares orders was the goal of the internship. A shift in manufacturing strategy of such magnitude required a high degree of employee involvement and management support. Also, it required absolute commitment to the principles of flow manufacturing as well as a commitment from suppliers for both delivery performance and quality. This system was not ready for such a dramatic change, so the goal was modified to present a feasible way to develop flow manufacturing within the framework of the current MRP system. Namely, to allow the Case & Gear COE to adopt a flow system independent of suppliers deeply rooted in MRP delivery and an assembly facility firmly committed to a production schedule.

Before suggesting improvements over the existing material and information flow structure, one must first understand the key drivers and metrics affecting performance of gear and shaft manufacturing and order assembly and delivery. This model was developed using Jay Forrester's model as a baseline, then adding key variables to first mirror historical data, then suggest why performance is affected. The process first identifies the key variables affecting the system and establishes a causal connection between these variables. Then a model is constructed that can be mathematically manipulated to explain the drivers and metrics. This final step, manipulation of the model, is where we are able to surface unanticipated side effects of management policies, then suggest ways to either rework or eliminate altogether these policies to drive intended behavior. A key deliverable of this process, given the management structure and existing production system, was to write a story that could be quickly synthesized and would naturally lead to possible solutions. The thesis, and indeed the entire internship serve to build system understanding of key drivers and dynamics for decision-makers so that system change can be enabled.

Numerous interviews were conducted at various levels of management, across functions, and finally with shop floor employees. The method chosen was to start from the top levels, then work down through the layers to where production and assembly was actually being accomplished. By using this interviewing approach, each story was either immediately reinforced or refuted, and key variables could be traced down through the system to learn policy impacts of behavior.

Once these variables were determined, they were separated into stocks and flows. These stocks and flows are simply defined as amounts that can be measured exactly at a given point in time (stocks), and rates that change over time (flows). Examples of stocks include work in process, unfilled orders, and finished goods inventory. At any given point in time, the exact number of items in these stocks can be determined. Mathematically, stocks are simply the sum of flows entering and exiting, like water flowing into and out of a tub of water. If inflows are greater than outflows, the tub fills, and vice versa. Examples of flows are order introduction, delivery rates, component completion rate and assembly rate. Although at any given point in time an exact number of items cannot be determined, the rate at which items are moving through the system can be. Mathematically, determining the rate involves taking the derivative of the completion curve, with the result (slope of the line) representing the exact rate.

The basic stocks in the system were easy to uncover. Completed engines, completed components, and work-in-process (WIP) levels for both formed the basis of most interviews. Managers monitored inventory levels through reports for both work in process and finished goods, and shop floor associates were keenly aware of the work waiting both ahead and after their manufacturing cells. Also, the Case & Gear COE tracked raw materials, adding them as the third component of inventory. The stock of unfilled orders, or the number of gear and shaft orders placed yet still to be introduced onto the production floor, was noted and is important in a later discussion. Ironically, however, attempts were never made to mentally link completed orders and WIP with outstanding orders during the personal interviews, and an almost adversarial relationship existed between the enterprise, responsible for customer contact and maintaining order delivery, and production, responsible for manufacturing the order components.

Flows in the system were also obvious, both for material and information. Goods moved from raw material into production, from production to the assembly warehouse, from the warehouse into assembly or kit/spares orders, then finally on to the customer. Although material flow through component manufacturing as well as flow through the assembly process will be linked and are included in the model, during this phase of development each process was assumed independent to avoid confusion and facilitate a complete understanding of each facility. Further analysis of each system showed that neither was truly optimized. Therefore, each system was identified separately as either Gear Production or Engine Assembly, and independent average cycle times were used to compute material flow.

Information flow occurred through both formal and informal channels. Standard production and inventory information was readily available on an internal computer network. Although read-write access to this network was extremely limited, anyone could easily review the data on a read-only basis. In parallel to this official documentation of production and inventory transactions, an elaborate informal network between marketing and sales, engine coordinators and production managers served to keep the system in balance on a more real-time basis. Although this informal channel created natural efficiencies, it is almost impossible to model due to its complexity and continual change. Therefore, the model deals only with the formal information channels to determine appropriate production rates.

3.2 Causal Loop Development

The basic causal loops started with component production and assembly. They highlight the difference between the number of components or engines to be completed in a time period and the actual number of pieces complete. This difference, or gap, forms the basis of an MRP system analysis, and provides a foundation for this model (Hopp & Spearman, 1996). Original interviews uncovered a gap similar to this, occurring at the engine assembly facility, as progress was measured by comparing the number of orders complete in a week to the number of orders scheduled for completion.

Business cycles were measured in calendar quarters. Each quarter had production quotas for engines to be assembled and shipped, and kits and spare parts orders to be shipped. At the beginning of each quarter, employees noted that the shipment rate was slow and gained speed as the end of the revenue quarter approached. Data supported these assertions, and the shipment rates by quarter are shown in figure 3.2-1.

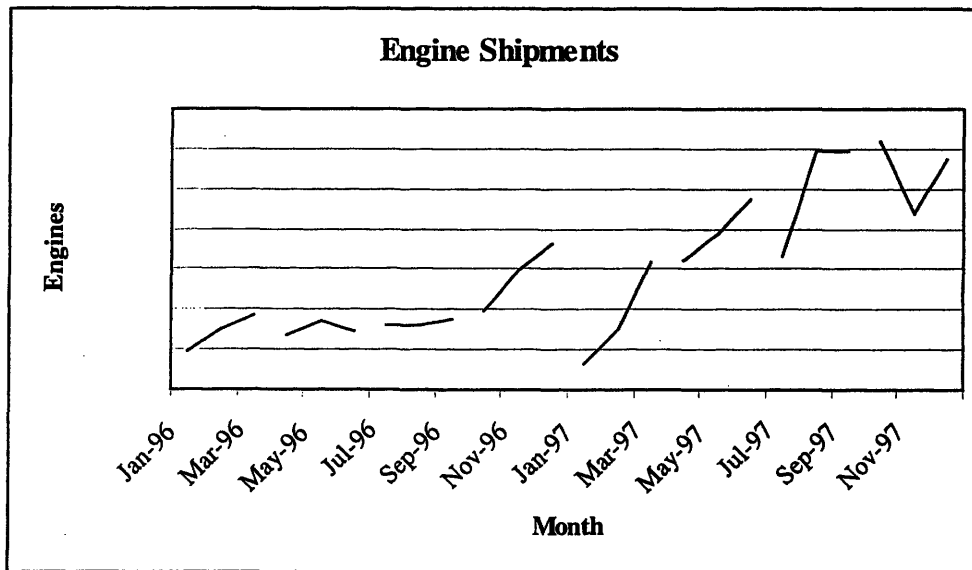


Figure 3.2-1 Quarterly Engine Shipments: Each short line shows the connection of shipment data from each three-month production quarter. For example, the first connection of data points represent of January, February and March engine shipment data. A deliberate break is made between the final month of a production quarter and the first month of the next to highlight the trend in rising shipments within each quarter.

The scale has been deliberately omitted, but the rising trend is clear by quarter. With the exception of the second quarter of 1996, the only outliers are in December 1997 and 1998. Holiday vacations severely decreased production time, and consequently less engines and kits were shipped.

The next logical question was whether the Gear Production Center, linked to the assembly facility by its own production schedule for engine components, followed the same pattern. During almost every interview, the answer was a definitive “No, we produce gears and shafts at a constant rate.” At first this seemed logical since the two facilities were physically separated, produced completely different products with different processes, and were under different management. Also, the volume of spare parts made the production rate seem more level. Data, however, refuted these claims and shows the same rising pattern through the quarter as the assembly facility (see Figure 3.2-2).

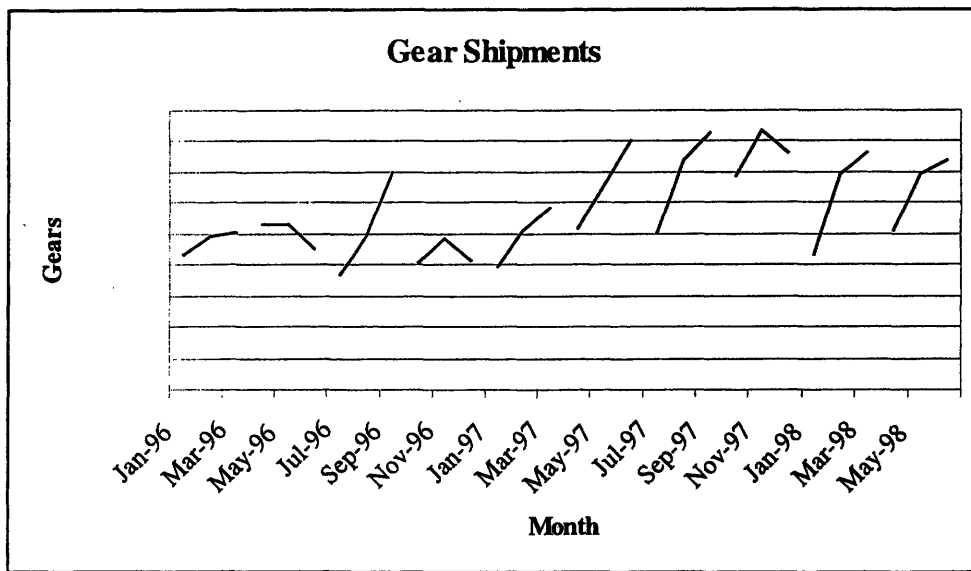


Figure 3.2-2 Quarterly Gear Shipments to Stores: As with engine shipment data, only shipments within each production quarter are connected to show the rising trend. Note the shipment decrease for December 1996, and December 1997. The drop in shipment levels reflects curtailed production due to holiday vacation.

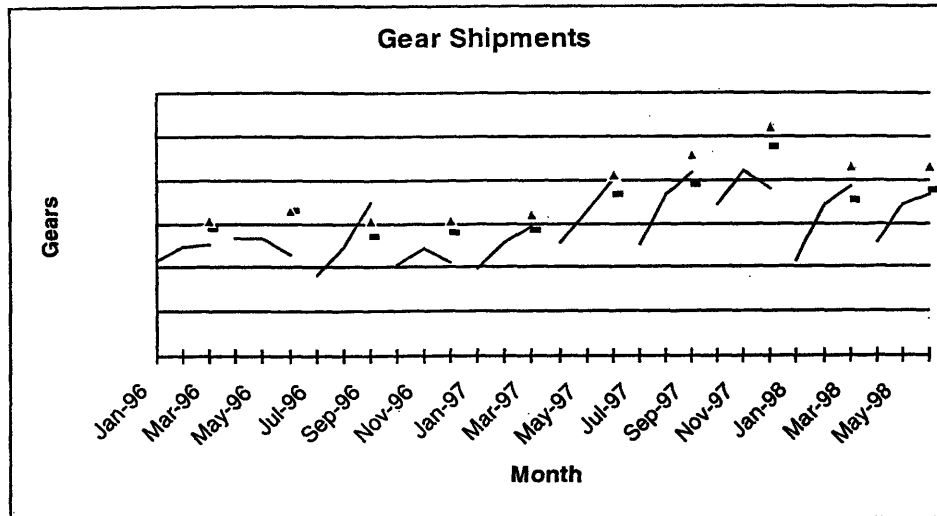


Figure 3.2-3 Normalized Quarterly Gear Shipments: The solid lines are identical to the previous Gear Shipment figure. Here, however, additional data points have been added to answer the argument that the final month of a quarter contains five weeks instead of four. This is included to defend the rising trend.

Again, the scale has been omitted but the rising trend by quarter follows. As expected, this was a startling find for the Gear Production Center management, and many explanations for the behavior soon surfaced. First, it was argued that the first two months in each quarter contain only four weeks and that the third month contained five. Certainly this would explain the rise in the final month. Shown in Figure 3.2-3 are triangles and dashes at each third month of the quarter. They are not data points, but instead represent a normalization of data to account for the difference in weeks. The triangles show the expected production rate in the third month if the second month shipments are increased by 25% (to represent an increase from 4 weeks to 5). The dashes, to further show the failure of the argument, are the average of the first two months in the quarter, again increased by 25%. Next, it was argued that monthly totals did not accurately reflect a true production rate, and that possibly a weekly average would better show a flat production rate. Although this procedure does show a decrease in output/week (shown in Figure 3.2-4) during the last month of the quarter, the output/week statistic is meaningless. A per week statistic simply waters down the meaning of the initial data, measured on a per month basis, by dividing a rising total by a number 25% higher than that of month one or two, in cases where the total

shipments did not increase by that amount. Our interest lies in the per month numbers, not necessarily in the average rate of each week.

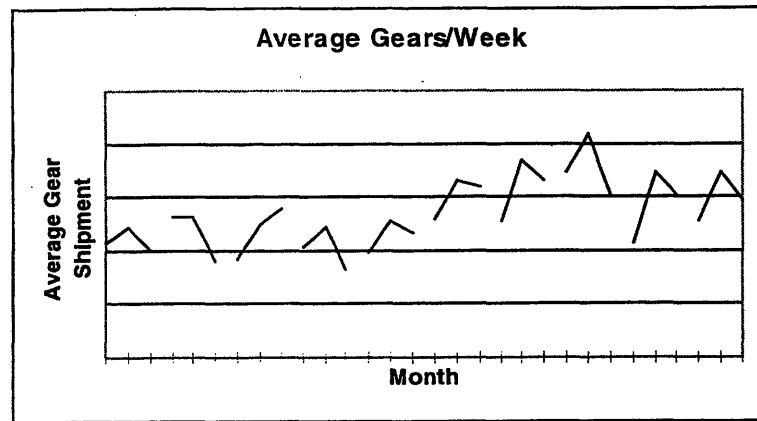


Figure 3.2-4 Average Gears/Week: This figure represents the average number of gears produced each week during a production month. Since the last month of each quarter contains five weeks instead of four, the average is shown to decrease. However, this statistic is misleading in that total shipments for the final month still show a rising trend.

Attention now turns to establishing a causal relationship between the variables already mentioned, to gain an understanding of the system. First, the production and assembly gap will be developed in more detail, and then other variables deemed significant from interviews will be added. At each step, the causal loop diagram was presented to many of the people with whom interviews were conducted to maintain integrity of the story. The relationships that follow are the final loops developed during this phase in the model building process. For simplicity, only the assembly causal relationships will be developed. The production relationships are exactly the same, and will be further investigated when the two systems are linked.

As the assembly gap increases (again, the gap is defined as the difference between the actual number of products complete and the desired number to be completed), pressure to decrease that gap increases resulting in increased assembly. This loop is a balancing loop, where an increase in any variable contributes to a decrease in the production gap. The system tends toward zero to eliminate the gap. Two methods to relieve this production or assembly pressure were through normal assembly and overtime assembly (see Figure 3.2-5). Interviews with many shop floor associates supported this development. It was noted

without exception that the pace of shop floor activity increased dramatically as each month came to an end, with an even more significantly increased noted at the end of each production quarter.

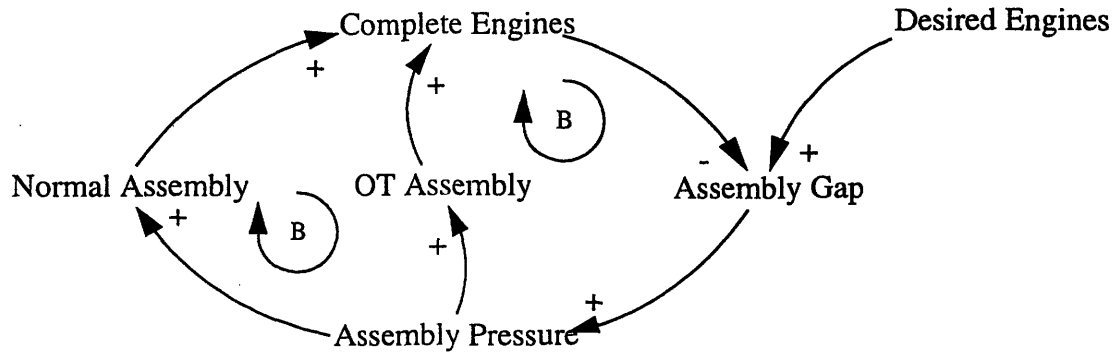


Figure 3.2-5 Production/Assembly Balancing Loops: These simple causal loops show the goal-seeking behavior of this production system. As the gap between desired engines and complete engines increases, normal and overtime (OT) assembly increase to drive this gap to zero. The (-) sign in the link between Complete Engines and Assembly Gap produce an opposite effect (increase to decrease, decrease to increase).

By substituting gears or components for engines, an identical causal loop is constructed for component production. In both cases, a gap exists at the beginning of a production period between orders and complete product, resulting in pressure to fill orders. The stock of completed engines or components rise, the level of unfilled orders falls, the gap approaches an equilibrium level of zero. The most plausible reference mode for this system is a linear increase in engines complete, stopping at the level of desired engines as shown in Figure 3.2-6.

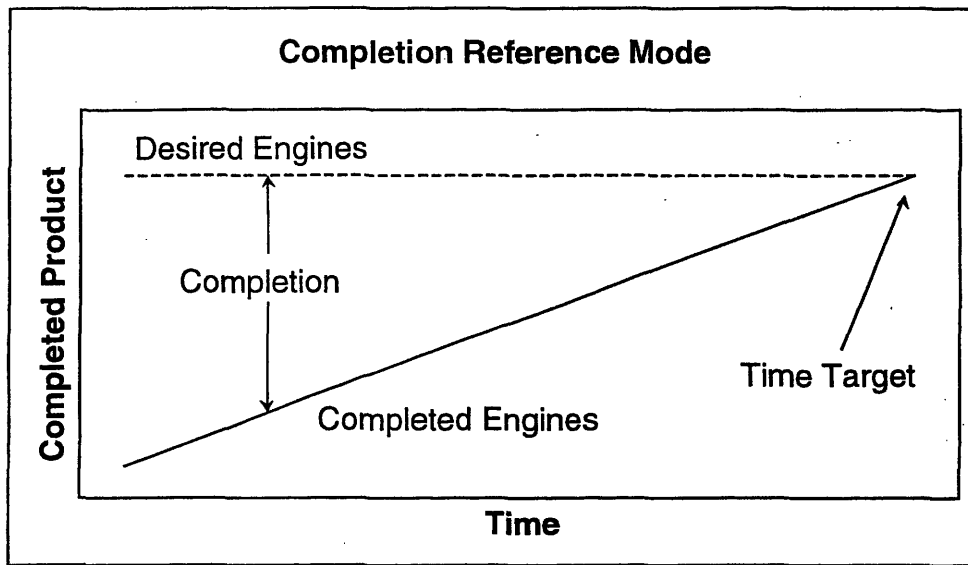


Figure 3.2-6 Original Completion Reference Mode: The level of desired engines remains the same over the complete time interval. Completion of engines, theoretically, rises linearly to meet this desired level at the target time.

As discussed earlier, this was not the case in reality for the assembly facility. The curve began much flatter and rose aggressively as the end of the quarter approached and as pressure to complete engine orders increased (Figure 3.2-7).

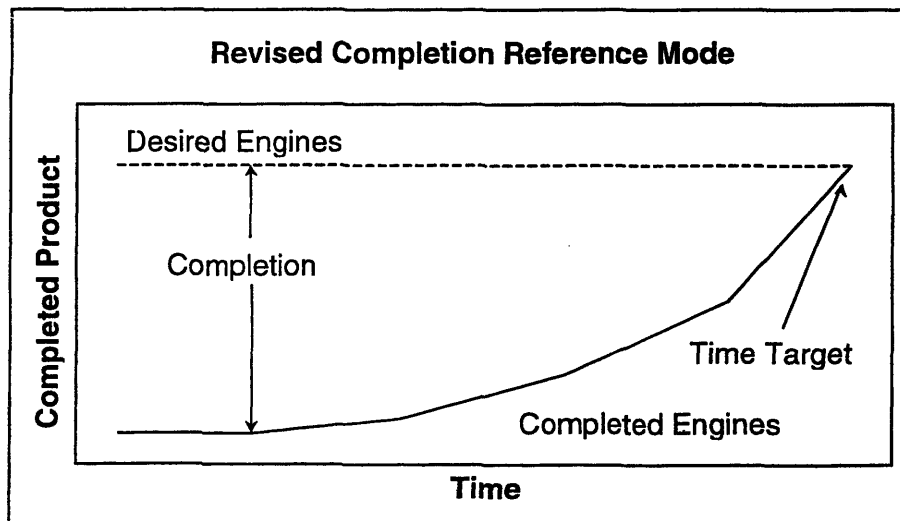


Figure 3.2-7 Revised Completion Reference Mode: In reality, the number of completed engines rises exponentially to meet the desired number. Completion rates at the beginning of the time interval are very low, but increase dramatically toward the end.

Other variables were then added to the basic causal loops in order to determine the management policies which were really affecting assembly rates. The first and most important policy was expediting engine orders as the quarter drew to a close. As can be imagined, as engines are expedited the problem works its way back up stream through the component production centers and finally to suppliers, who must continue to supply raw materials and purchased parts, but to a schedule which shows tremendous fluctuations. This, again, is the bullwhip effect.

How does expediting begin? What drives the decision to deliberately split a production batch in order to speed it through the system? The answer to this question was not at all obvious but could be explained fairly easily after key interviews with engine assembly coordinators. The reason is that engines are started, or released to the assembly floor, even though not all parts necessary for completion are present at release. Associates at the assembly facility were very familiar with this behavior, as they saw engine and subassembly carts wheeled to their stations every day without all necessary components. To the assemblers, the problem was that the carts were taking up space. To engine coordinators, who's responsibility was to integrate both externally purchased and internally manufactured parts before release onto the floor, releasing without parts was the best way to get attention and action on the missing parts. Another reason given for starting engines without all parts was simply that the production schedule specified a certain release date, and that date would not be missed. Whatever the reason, as the quarter began more and more engines, kits and subassemblies found their way onto the assembly floor incomplete.

At some point during the quarter, the actual level of work in process became greater than the desired level for efficient assembly. This difference could certainly not be determined exactly, but at a given time managers realized that shipments were behind, and the level of inventory on the floor was greater than necessary. What was the fix? Managers identified engines that could be completed within the quarter, then identified the parts necessary for completion, and finally either called external suppliers to add pressure to the order, or (as analyzed in this work) forced the component production centers to expedite critical components.

Does this sound inefficient? Certainly, but not because the managers aren't making sound business decisions. In fact, they are making absolutely correct decisions, but only as

they relate to their own piece of the system. Nahmias states, "If a sudden unusual event occurs, such as a much-higher-than-anticipated demand or a sudden decline in productive capacity...it is likely that many managers would tend to overreact" (p. 154). Unfortunately, an expediting decision of this type made very late in the manufacturing process (at assembly) has a great impact on all upstream steps and, as shown in the previous chapter, this effect is magnified at each level. The idea, then, is to understand both the cause and effect of such a decision at each level in the process in order to optimize the behavior of the entire system, not just the behavior at one facility.

Finally, it was proposed that the primary objective of the system was to assemble and deliver as many engines and kits as possible during each revenue quarter, many times at the expense of other orders. Early in the internship this proposition was refuted, but soon the truth surfaced. On quotation in particular, received in an e-mail at the middle of one quarter, supported the original argument and led many managers to finally give up flawed mental models of system behavior. Quoted on October 15 as the Engines facility was making a final push toward end of year production quotas and revenue, "Also, please keep your focus on two things, the first being the close of the month for October is the 24th. Second, we must ship as many engines as possible by the 14th of November in order to have a positive impact on cash flow in the fourth quarter. Please target your delivery dates for the first week in November for all shipments, including both spares and engines that are committed for the month of November." The original production schedule was being abandoned, and any and all engines which could feasibly be completed in time to contribute to cash flow were identified and expedited.

How did this decision affect the component production facilities? Two weeks after receipt of the message above, another message was sent, but only to the component facilities. "Please note that all serial numbers that are highlighted blue is what we must get out the door by Nov 14th for cash flow. Please focus on bringing in the controlling hardware that falls within the blue highlighted engines. We need hardware no later than Nov 10th." Not only were engine orders expedited to meet delivery by mid November, component facilities lost four additional days of production, and were still expected to produce all necessary parts.

Let's again look at the bullwhip effect. After increasing the production rate at assembly, a message is then sent to all component suppliers (both internal and external) to target parts delivery for November 10th.

Compared to the increasing slope of the assembly curve, to meet the same demand four days earlier required the component curve to rise even more aggressively, and due to the delay in information flow from assembly to components, it started to rise later.

The time is right to introduce the causal relationship of other variables noted in order to establish the cause and effect system leading to management decisions. As discussed earlier, the basic causal relationships are between the desired level of engines to be completed and the actual amount completed, and the desired/actual number of components. Shown in Figure 3.2-8 are the causal loops for engine assembly. The loops for component production are identical, but they refer to components instead of engines. Later, they will be discussed together as the two systems are linked.

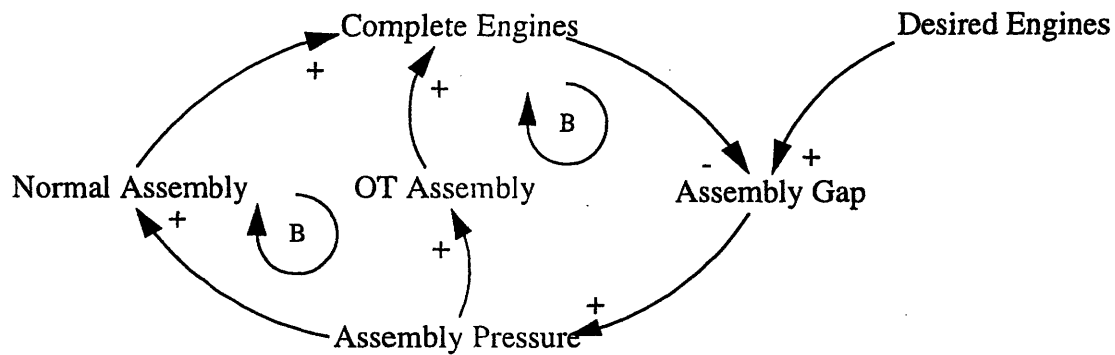


Figure 3.2-8 Balancing Assembly Loop: These balancing loops drive the assembly gap to zero as the number of complete engines approaches the desire number.

As stated earlier these loops are balancing, forcing the engine gap to zero. Assembly pressure increases normal and overtime assembly, increasing the completion rate of engines, closing the gap between desired and actual number of engines for a given quarter.

Next, starting engines without all necessary components is included. In Figure 3.2-9, this variable is referred to as “Starts without Parts,” which increases work in process in the engine facility and decreasing the rate at which engines are complete.

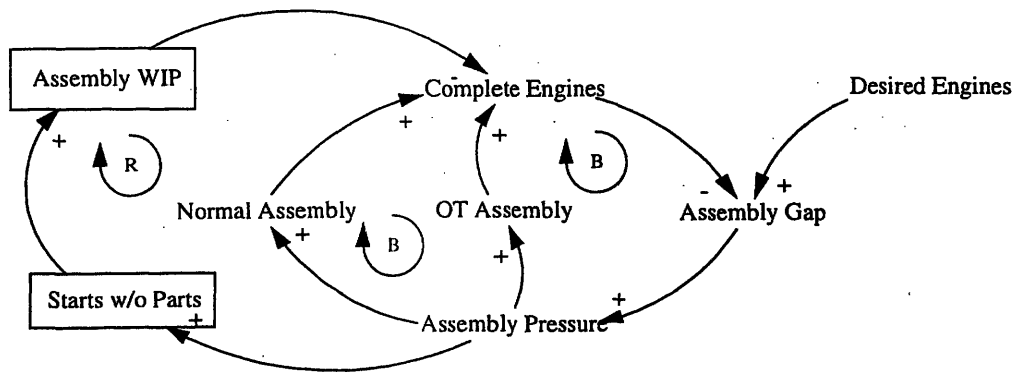


Figure 3.2-9 Assembly WIP Reinforcing Loop: Assembly pressure forces engine coordinators to release engines onto the production floor without all necessary components. This increases WIP on the shop floor and decreases the rate at which engines are completed.

This new loop is a reinforcing loop, which increases the engine gap. As engines are started and WIP levels increase, the number of engines complete actually decreases.

Another reason stated for starting engines without all necessary parts was to gain attention for missing components. Engine coordinators, through past experience, realized that by simply starting an engine missing parts, just to get it into view on the assembly floor, would add priority to those parts, requiring them to be expedited, forcing more parts to assembly stores, and adding to the stock of complete engines. This new, balancing loop is shown in Figure 3.2-10.

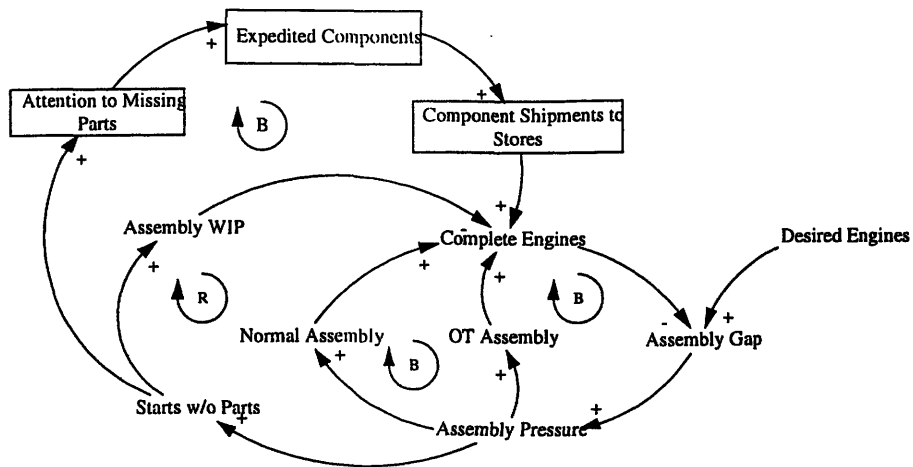


Figure 3.2-10 Component Expediting Balancing Loop: The main reason given for starting engines without all components was to force attention to those missing parts. When attention on those missing parts increases enough, necessary components are expedited through the production system and more parts are shipped to assembly stores.

Finally, as managers note the increase in work in process levels, they are forced to identify engines which can feasibly be completed by the end of a quarter, and expedite them through the system.

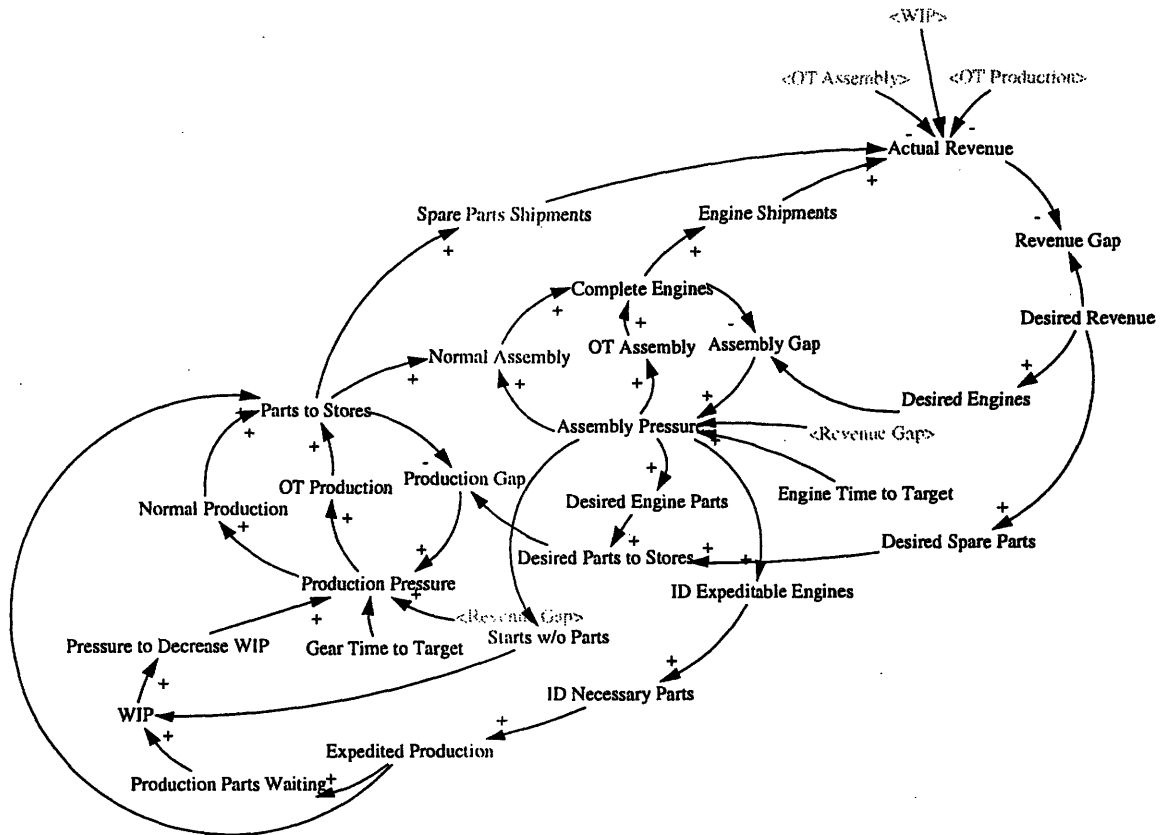


Figure 3.2-12 Complete Causal Loop Structure: Above is the combination of all variables in their appropriate causal loops. Engine assembly, component production and expediting are all included to portray all the dynamics of this system.

First, the revenue gap determines the desired number of engines and desired components (desired components being the sum of rebuild kit orders and spare part orders). The number of engine components is added to the Desired Parts to Stores through the variable Desired Engine Parts. The two systems are then linked through the variable Desired Parts to Stores. This is the number of internally manufactured components that the assembly facility needs to complete engines and fill kit and spare part orders. As the relationship continues, components are manufactured and Parts to Stores feeds back into Normal Assembly and Spare Parts Shipments, completing the cycle.

Next, attention turns to the other key variables noted, namely Starts without Parts and Expediting. Assembly pressure drives both of these variables, resulting in increased WIP and increased pressure to decrease WIP. Again, the loops continue in both cases through parts to stores. But where does this pressure come from?

Pressure in both assembly and production comes from the variables Engine Time to Target and Gear Time to Target. Mathematically, as the time to target decreases, a corresponding increase in pressure is seen.

Although as time decreases pressure should increase linearly, in reality the time decrease is linear and the pressure increase is exponential.

Though the quotations noted above were obtained well after this system-wide study was begun, all preparation led to a problem statement. This statement had to be broad enough to include all variables noted during interviews, yet specific enough to provide solid direction for the model. Our interest is not necessarily to model the entire system, but to model the relevant factors affecting a problem in order to understand the time varying relationships between parts of a system which directly impact the specific problem.

The problem statement evolved as follows. Expediting engines through assembly and test negatively impacts all component production by increasing schedule disruption, where ultimately the benefit of shipping incremental engines is outweighed by the cost remaining work-in-process. The quotations noted above, when they were made, only added support to the problem statement, and provided the impetus for further study.

3.3 Model Development

Once the causal relationships were agreed on, and the problem statement was approved, attention turned to developing a mathematical representation. In the loops above, revenue drives initial engine and parts schedule demand. While in reality this was true, it was not necessary to include this variable in a model that represented only one quarter. It seemed more straightforward to assume a certain number of engines for a quarter, based on historical data, then develop the model to mirror historical behavior in relation to the specified production and assembly quotas. Additionally, this model was not meant to show system reaction to a variety of engine order inputs, but rather to show system reaction to a chosen input, based on a variety of combinations of internal variables.

For simplicity, models for component production and engine assembly will be developed individually. Then, once the similarities and differences between each independent system are understood, they will be linked to show the complete flow of components through production and assembly, then on to the customer.

The stock of unfilled orders (UO Gears) begins the gear production model (see Figure 3.3-1). This represents the stock of outstanding orders awaiting some element of administrative processing, and which have not yet been introduced into production. This stock is increased by incoming orders for gears and shafts (Gear Inc), both from OEM

orders and external spare parts. Through interviews, it was determined that between one and two months of incoming orders rested as unfilled. In the model, one month of orders equals 7800 gears, so the initial condition for unfilled orders was set at 10,000. This stock is decreased by the rate of component completion (Gear Dec) which is the final completion rate after the included production lead-time delays.

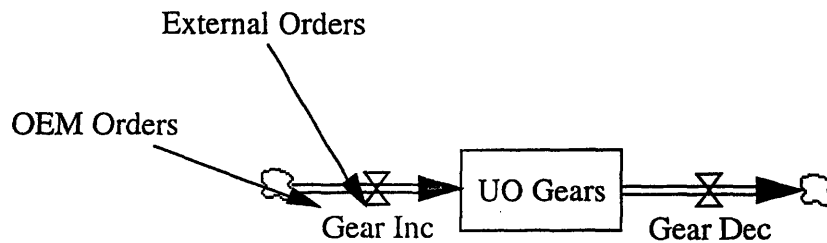


Figure 3.3-1 Unfilled Gear Orders: OEM and spare parts orders combine to form the rate at which unfilled orders increase at gear production. That stock of unfilled orders decreased as gears are shipped from the facility.

The next stock, from Figure 3.3-2, is gear work in process (Gear WIP) which is the sum of the three stocks represented in the third order delay (Gears 1, Gears 2 and Gears 3).

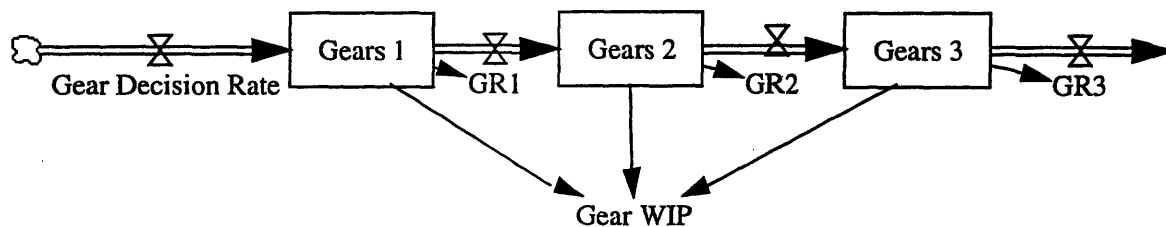


Figure 3.3-2 Gear WIP: This is a three-stage gear production delay. At each stage, a stock of gears represents gear WIP, and the combination of individual WIP stocks equals the total gear WIP in the system.

The flow into these series of stocks is the rate at which gear products are introduced onto the production floor (Gear Decision Rate), and the flow out is (GR3), the rate at which products are completed and shipped from the facility. GR1 and GR2 represent intermediate flows in the production delay. Although the idea of a higher order delay may be difficult to conceptualize, it may aid understanding by simply looking at intermediate flows as individual

processing and transportation steps, and intermediate stocks as process buffers.

Mathematically, this third order delay represents the entire gear production system in time and volume for an average product. The initial condition for gear WIP was 6,000 at each WIP stage, which represented the somewhat reduced level of WIP which the production system would see at the start of a production quarter after expedited depletion at the end of the previous quarter.

A key component here is the Gear Decision Rate. This decision rate must take into account real time knowledge of both outstanding orders and WIP levels in order to release the required amount of material to meet demand, yet not flood the production system. Therefore, the decision rate is simply the sum of the difference between actual and normal unfilled orders and the difference between actual and normal WIP. These actual stocks are dynamic through a production quarter and serve to increase and decrease the rate at which material is released. Normal order and WIP levels, however, remain much more constant. They are based on material handling and out of stock delays, which are inherent in the system, and are neither dynamic enough to change within the time scope of the model, or they are beyond the control of those involved with the production process.

Normal lead times for gear products ranged between 45 and 65 days. Additionally, parts met an additional delay in the stores warehouse of up to 6 weeks. Therefore, a total production delay of three months was used, split into one-month subsections throughout the two individual production delays and one warehouse delay. This delay, however, was only seen at the beginning of a quarter when work rates were most normal. Somehow, the increased pace of production had to be represented, and this was done by decreasing the Gear Assembly Delay (and in effect decreasing the time necessary to produce a product). At the beginning of a quarter, the entire three month delay was used to moderate the third order production system. As the quarter wore on, however, production rates increased with added pressure to produce parts and meet production quotas. An original formulation for this increase (and resulting decreased time necessary to produce parts) simply used the difference between the actual time and the production time as the delay. As can be predicted, however, as the target time is approached the production delay becomes infinitely small, meaning gear products are produced almost instantaneously. Therefore, the assembly delay was decreased linearly from three months to one month, at which point it leveled off. What this accomplished was allowing the system to gain production speed throughout the

quarter, replicating actual events, yet top out at a theoretical maximum completion rate. Shown in Figures 3.3-3 and 3.3-4 are the two different formulations.

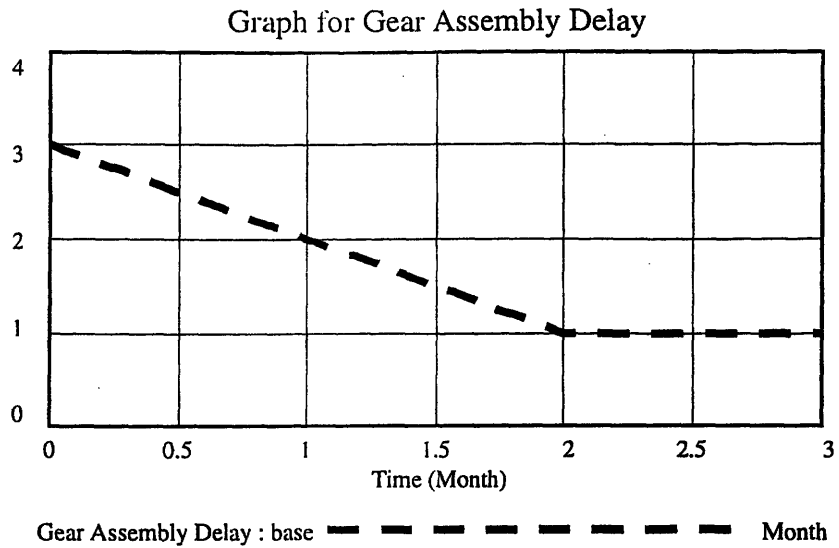


Figure 3.3-3 Model Production/Assembly Delay: Through a three month production quarter, the delay in completing gears steadily decreases as a result of production pressure to a minimum level, or a theoretical maximum rate at which gears can be made.

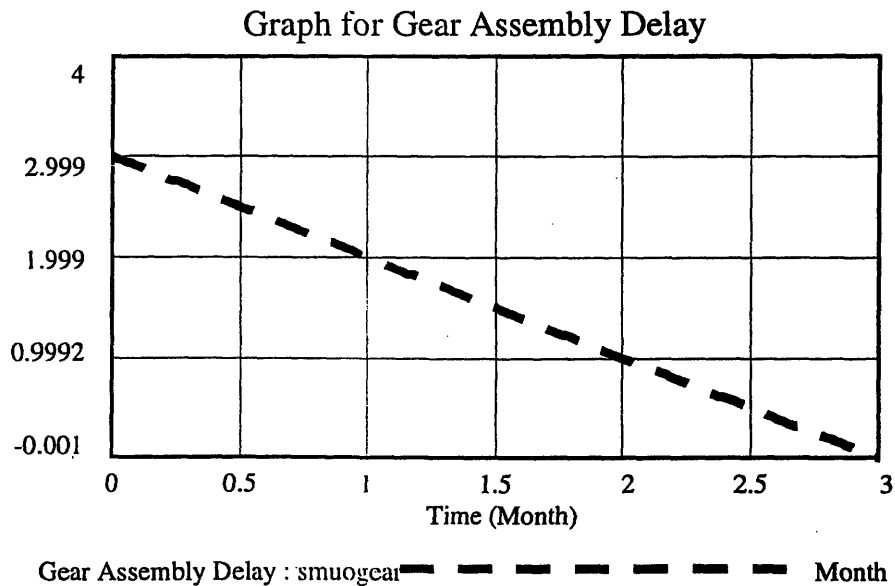


Figure 3.3-4 Theoretical Production/Assembly Delay: Originally, the production delay was modeled as a linear decrease to zero. However, this means in reality that gears are instantly made, which is not possible.

The assembly warehouse (Stores Inventory) represents the last stock in the gear production system. This stock is fed by gears completed (GR3) and depleted by shipments to both assembly and spare parts. The initial condition for Stores Inventory was set to 6000. As mentioned earlier, one month represented 7800 gear products released into the system. And, even though a delay of up to six weeks could be seen at the assembly warehouse, normally the delay was less than one month. It should also be noted that a minimum bound was set on Shipments Sent from Stores, to protect the system from shipping gears even though no gears existed to be shipped. Without this minimum bound, the model would continue to ship gears in amounts far beyond the completion rate, and mathematically the system spun out of control.

Finally, gear expediting had to be included. First, it was necessary to understand the true effect of expediting a part. Upon identification for expediting, a part or group of parts were split from their original production batch, marked for priority processing, then moved through the production system ahead of other orders. This meant that although the expedited order was processed quicker, other orders waiting in queues had to wait even longer for these smaller, priority orders. From the point of regular orders waiting in queues, the effect of expediting was to simply add additional orders into the production system. Therefore, an additional expediting rate (Gear Exp Rate) fed the first production stock, Gears 1.

But how, exactly, is one able to determine the number of orders which will be expedited into the system? As discussed in the development of the causal loops, expediting was a result of WIP buildup in the production process. As the actual WIP exceeded what was considered normal, pressure increased to decrease the WIP and ship the correct orders on time to assembly and to spares. Using the difference between actual WIP and normal WIP levels, the model generates a multiplier based on this difference to artificially infuse extra orders into the system to represent expediting.

Expediting: If (Actual WIP – Normal WIP) < 0, No expediting
 If (A WIP – N WIP) > 0, Expediting Multiple * (A WIP – N WIP)

If the actual WIP is less than a level considered normal, no expediting occurs. However, as the actual WIP level exceeds the normal level, orders are expedited according to amount of difference. The greater the difference, the higher the rate of expediting, and vice versa.

The development of the assembly system is the same, except that the additional stock of a warehouse inventory is not included. For the purposes of this model, as engines are completed they are assumed to be immediately shipped. Therefore, most of the explanation for this half of the model will center on initial conditions.

The stock of unfilled engine orders was set to 600. Although engine orders were introduced at a rate of 200 engines per month, the lead-time between placing an engine order and actually shipping the engine was closer to three months. As in the production model, the stock of unfilled orders was fed by order introduction (OU Inc), and decreased by the engine completion rate (AR3).

Engine WIP, just as with gear production, was the sum of individual WIP levels throughout the three-step delay. Each individual stock (Engines 1, Engines 2 and Engines 3) were initially set at 250. Though the production WIP levels were set slightly lower than the introduction of orders into the system, engine WIP levels were set somewhat higher to capture both the number of engines already released onto the production floor but not yet complete, and the engines which were cleared for production (still staged in the warehouse) but not yet released to the production floor.

Engine expediting was developed the same way as production, where the difference between actual and normal WIP levels produced pressure to identify engines that could be expedited. As the actual WIP level became larger than the level considered normal, the model developed a multiplier of that difference to artificially introduce extra engines into the system, increasing WIP and lead-time.

For both models, a WIP adjustment factor was included to moderate the speed at which pipeline inventory could be identified and then adjusted. For production, the adjustment factor was two months. This allowed time within the production quarter to identify increasing WIP and then target it to more a more appropriate level by the end of the quarter. Also, since spare part orders made up more than half of the orders introduced into production, the volume of pieces alone forced this delay in pipeline inventory adjustment. For engine assembly, however, inventory could be adjusted somewhat more quickly, so the

adjustment delay was 1.5 months. Overtime labor and the strategic release of subassembly work prior to engine release allowed the system to more quickly regulate itself.

To combine the models, then, the Decision Rate of engine assembly fed back into OEM Orders and unfilled orders increased. This allowed the model to replicate the bill of materials explosion that would result upon freezing the engine assembly schedule. Then, by using an average of 9 gear products per engine, the number of engines introduced into the assembly system was simultaneously converted into gear products introduced into the production system. This type of “backward” conversion follows the policy of determining engine and spare part orders from set quarterly production quotas, then determining the number of components necessary to complete the orders.

3.4 Results

The first variable studied was the WIP adjustment rate for both components and assembly. Data suggested that time necessary to adjust pipeline inventory be 1.5 months for the assembly facility and 2 months for components. Although difficult to obtain accurate historical data showing WIP levels at each facility, visual inspection of the facilities at different times during a quarter provided enough proof that the inventory level could be manipulated at this rate. Results of assembly and component production rates and WIP levels are shown in Figure 3.4-1.

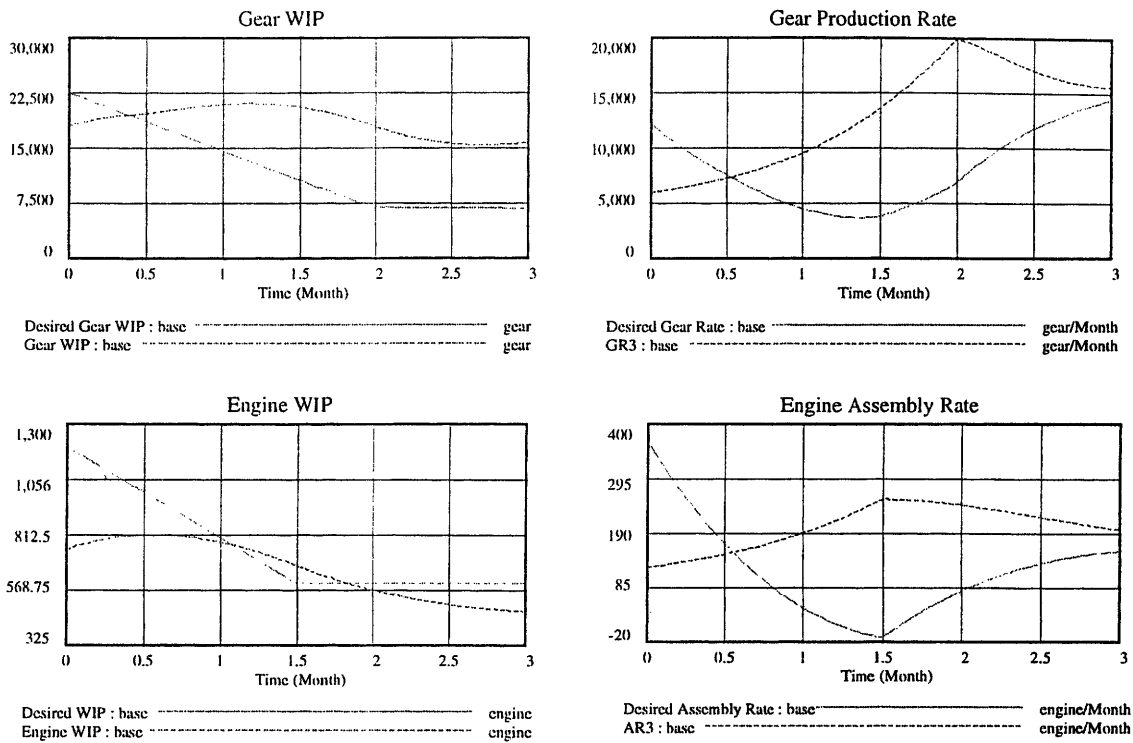


Figure 3.4-1 WIP Base Case Model Results: Both gear and engine actual WIP show an initial increase then a decrease until the end of the production quarter. The desired WIP, however, steadily decreases through the production quarter to a theoretical minimum. The actual gear production and engine assembly rates increase through the quarter to a maximum, then decrease somewhat toward the end of the quarter. The desired production and assembly rates, however, decrease to a minimum then increase toward the end. These results show what this type of system “should” do and how they “really” behave.

First, note both the starting and ending desired WIP levels in assembly and gears. These represents the actions of engine coordinators and raw material procurement to stock material prior to the beginning of a production quarter. They expect the level to gradually decrease to an optimum level throughout the quarter. At the same time, actual WIP levels in the plant start somewhat below that desired, rise immediately to compensate, then collapse as the quarter wears on and orders are expedited through the system to make cash flow. By the end of the quarter, WIP levels are significantly lower than the level desired at the start of the next quarter, as everything available is shipped to increase revenue. One executive noted, “At the end of a quarter, everything that is not tied down and that we can sell goes

out the door.” Unfortunately, this happens without regard to the beginning of the next quarter, when WIP levels start well below the optimum level for efficient assembly, and well above the optimum level for efficient production. Assembly begins the next quarter short critical components, further reinforcing their low initial shipment rate, and components begins with too much material in the pipeline, further increasing WIP carrying costs and system congestion.

Before looking to assembly rates, a discussion of the rate curves is in order. Imaging being given two different directives: 1) “In three months, build as many engines as you can,” and 2) “You have three months, build me (x) engines.” The difference between these two directives is critical to the argument about production and assembly rates. With the first directive, one would begin at a pace considered manageable, possibly even challenging. Then, as the target time approached rates would speed in order to capture every remaining production minute (albeit to a certain threshold). By the end of the quarter, every available resource would be utilized for the purpose of completing engines or components. This directive represents the *actual* production curves above. With the second directive, one would figure out the best way to make a certain number of goods, do that in the shortest amount of time and with a specified amount of resources, and try to finish early. A gradual rise in production rate may result after the initial decline if the time and resources were not accurately determined, but the overall effect would be a smoother, more predictable production rate. This directive represents the *desired* production curves shown above.

To provide some additional direction to the argument before further muddying the water, the initial goal was to implement flow manufacturing for the gear production center in an existing MRP type system. The results above show the system as it operates currently, with all variables set to appropriate initial conditions. Now, these variables can be manipulated individually to find the key variables affecting the system, and their effect.

The first variable chosen is Gear WIP Adjustment Time. This is the time necessary for the gear facility to adjust pipeline inventory with respect to new information of increased or decreased orders. For example, if the desired number of gears immediately steps up (or down) by a certain percentage, an MRP type system will show an increase (or decrease) in pipeline inventory to support an increased level of desired delivery performance. This increased inventory can result from many factors – by adding additional capacity, increasing batch size, or increasing raw material and finished goods inventories. A certain time lag

exists between the time the actual order step happens and that time that information is known, and a second time lag exists as the inventory is increased to meet demand. The sum of these two lags represents the WIP adjustment time.

Initially, the adjustment time is set at two months. Although conservative, the production cycle lasted only three months and the system was responsive enough to make this adjustment during the cycle. Next, the adjustment time was changed to one month, representing an even quicker response time. Finally, the time was set to three months, representing the longest time available during one production cycle to adjust inventory. Shown in Figure 3.4-2 are the WIP levels and production rates throughout the quarter, at varying WIP adjustment times.

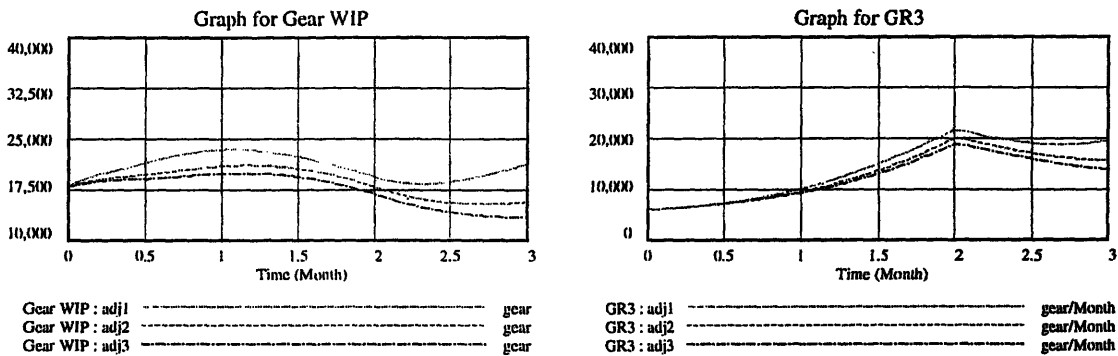


Figure 3.4-2 WIP Adjustment Results: WIP Adjustment Time represents the time necessary to adjust pipeline inventory after a change in demand. As the adjustment time decreases, the ability to proactively react to demand shifts increases. However, if the adjustment time is long, the ability to react to demand shifts is severely limited. Gear completion rates are also affected. As the adjustment time increases, the ability to ramp up production is hindered, whereas a short adjustment time allows production to ebb and flow to more closely match demand.

Remember that the desired WIP level and the desired production rate should remain level throughout the quarter. For WIP levels, an adjustment time of one month allowed for the smoothest curve, with beginning and ending WIP levels being almost equal. As the adjustment time grew, however, the ability to react to increased orders diminished. Ending WIP levels ended significantly below starting levels, leaving the facility with less than efficient inventory levels to begin the next quarter. For production rates, the effect is just the opposite. A shorter adjustment time results in higher fluctuations in completion rate. With

increased responsiveness comes increased desire to continually “fix” the inventory and try to match the variability of demand. As adjustment time increased, though, the inability to change WIP to an efficient level caused that production rate to increase much slower.

The next variable chosen was the delay resulting from stockout of raw material (the results of which are shown in Figure 3.4-3). Two variables are included in the model, Gear Out of Stock and Gear Handling, and both represent a delay associated with introducing material onto the shop floor. They are included for completeness, and their individual delays are added to show a total delay in material introduction rates. Therefore, only one variable need be adjusted to show the effect on the system.

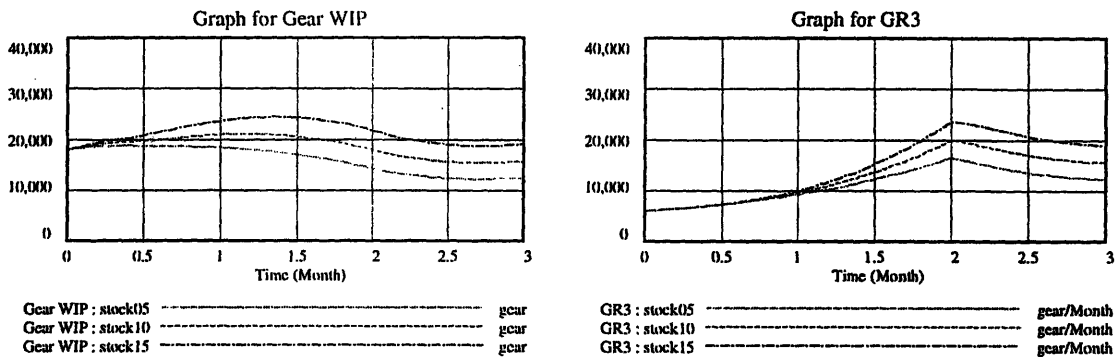


Figure 3.4-3 Stockout Delay Results: Stockout delay represents the time necessary to recover from a stockout of raw material. A longer response time means production must ramp faster to satisfy backorders, and WIP increases more dramatically. A shorter stockout time means that the system is not as drastically perturbed from equilibrium, and the system can easily recover.

The stockout delay was initially set to 1 month. Interviews revealed this as the average time to get material from a supplier due to a complete, unforecasted stockout. The variable was then adjusted down to two weeks, then up to six weeks to show sensitivity.

In Gear WIP, a faster response time from suppliers results in less overall WIP, as material is quickly ordered and received, released into the system, and processed. Given the confidence in the supplier’s ability to deliver means order can be smaller, since the delay in receiving the order is short. Slower response time, as expected, means higher orders must be placed to overcome the initial delay, and those higher WIP level remains through the rest of the production cycle. The problems associated with this type of delay follow into

production rates. As mentioned, shorter supplier reaction time means less of a time lag between order and receipt. Production, therefore, need not increase so drastically upon receipt in order to make up for the delay time lost. A longer delay, however, means that the production facility, upon receipt of the order, must ramp up production much more aggressively to meet demand. And, due to the bullwhip effect mentioned earlier which multiplies the effect of delays, the peak production rate achieved is greater than with a shorter delay.

Finally, attention turns to expediting orders through the system. If WIP adjustment is slow, and out of stock and handling delays produce the undesirable results shown above, then expediting should solve the problem. In reality, however, expediting only adds fuel to the fire.

All of the results shown above were generated without expediting any orders to the system. Now, however, additional orders will be artificially introduced into the system to simulate the effect of expediting. Also, it should be noted that artificially introducing orders into the system replicates another common problem, and that is rework. Both expediting and rework have a similar effect on the production system. With expediting, orders get either simple line cutting privileges or line privileges and tear down of the batch now in process. The net effect is that other orders must wait in queue for these smaller, more important orders. With rework, deficiencies are noted in an individual piece or batch and that batch must be reintroduced into the system to fix discrepancies. The adage, "If you can't find the time to do it right the first time, when will you find time to do it again," justly applies. If an operation is performed incorrectly, a piece or batch must loop back through necessary processing steps, forcing other orders to wait. The conclusion is that expediting and rework have the same effect, and artificially introducing additional orders into the system replicates the effect.

Infusion of gear orders is generated within the production facility, at least for the purposes of the model. This value is generated at the assembly level, through orders identified to expedite through the system to affect cash flow. Therefore, the number of additional gear orders introduced into the system is simply the multiple of engines to be expedited and gears per engine. If there are no orders expedited from assembly (because WIP levels are correct) an additional calculation is added to introduce additional gears based only on the difference between desired and actual WIP levels. This adds reality into the

model by simulating the gear manager's ability to recognize and "fix" an inventory problem based only on an internally generated inventory discrepancy. Figure 3.4-4 presents gear WIP levels and production rates resulting from expediting engines.

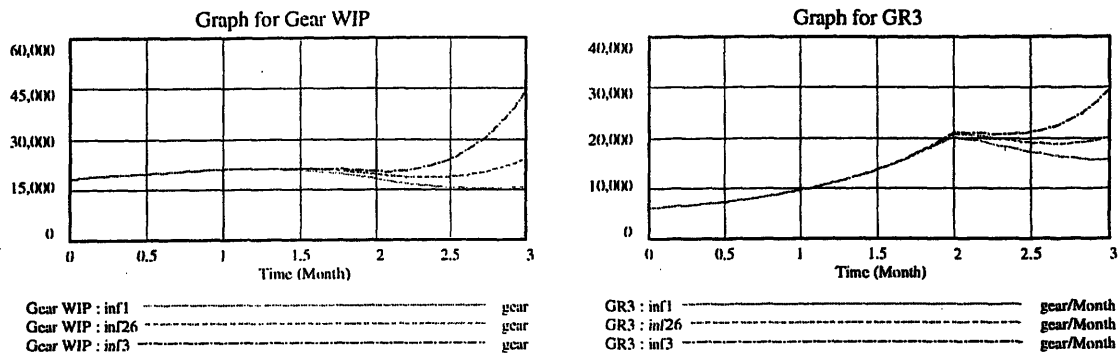


Figure 3.4-4 Gear Expediting Results: As orders are expedited through gear production, both WIP and production rates are driven out of control. Obviously this would not happen in a real factory, but the dynamic of overstressing a production system by continuous expediting are obvious.

As the rate of engines expedited through the system rises, both the gear WIP levels and production rates explode out of control. Mathematically, the introduction multiplier of engines is not important. The trend, however, is vitally important to this study. Expediting engines without regard for component production (and, as one can imagine, for suppliers) has drastic effects brought on by the bullwhip effect. Component manufacturers are left scrambling to make up the difference on key components for expedited engines. Additionally, it must be noted that internally introduced component orders or rework does not produce the increases shown above. Even though the calculation was included to allow for internally generated orders, the pressure seen from expedited engines far outweighs any internal pressure. Imagine what happens, then, when component manufacturing experiences a quality problem and has significant rework. This would magnify an already out of control system.

3.5 Recommendation

So where do we stand? Expediting and rework internally generated at the component level has significant effects on WIP levels and production rates, but a manager

has the ability to fix these problems through quality improvements, efficient inventory management and proactive manipulation of the production schedule. However, this pressure pales in comparison to that generated from expedited engines, and the component manager's hands are tied to fix these external issues. Adding to the confusion is the drive to ship as many engines and kits as possible to meet revenue numbers. What can one manager do?

The answer lies in the linkage between production and assembly, and a manufacturing system designed to meet actual customer demand, not simply a production schedule. As shown, component production is absolutely linked to the assembly schedule, and must follow the same production patterns. Even though original mental models thought the two systems were separate, historical data and the bullwhip effect show their intimate relationship. To see any significant improvement, which is certainly possible at the component level, the systems must be de-coupled (production must follow an independent production schedule based on the actual demand from assembly and from spare parts customer). Component production must focus on making individual gears (in optimum batch size) for specific orders.

Fortunately, this is possible in this environment through the introduction of demand flow technology. Additionally, value can be added one step sooner in the process by shipping gear orders to assembly as complete kits, rather than separate components. This further increases the visibility of gear inventory levels and allows much more proactive manipulation of the production schedule to meet the required level of customer service while maintaining the lowest levels of inventory.

Chapter 4 Kit Plan

4.1 Kit Plan Introduction

The plan to kit gears and shafts, by order, in appropriate quantities served as the first step to building complete gear modules prior to shipment to the assembly facility. Engineers and managers felt that a complete gear module could and should be designed, manufactured and assembled at the Gear Production Center (GPC). The organizational shift to the Center of Excellence (COE) model furthered this idea by co-locating all functions necessary for independent profit and loss operation. Also, to continue studying the material and information delay issues developed in the model, the kit plan served to co-locate production and inventory of all gear products in one location. By kitting, information flows between the COE and the assembly warehouse for individual gear components would be eliminated. Gears would be shipped as complete engine order kits the same day the engine was released to the shop floor, and the only required exchange of information would be the engine release date. Responsibility for production of all gears in a kit would again rest with the COE, and the information transfer would involve gear kits and subassemblies, rather than individual components. Likewise, material flow of bulk gear shipments would now consist of complete kits, allowing the COE to ship the right gear, in the right amount, and to more proactively adjust their gear production schedule to match true OEM and spare parts demand on a pull schedule.

Originally, the GPC manufactured individual gear and shaft products, grouped in batches, then delivered them to the assembly facility in bulk. Although the information system was set up to allow full visibility of finished goods inventory at all points in the manufacturing chain, delays in material and information flow severely decreased confidence in real time information through these channels and caused continual confusion about component order status. Meetings between component directors and assembly occurred three times weekly with the goal of sharing order status to make more informed and proactive adjustments to the assembly production schedule. However, meetings were long and complex, and the continuous stream of order numbers and status allowed for side conversations, last minute deals, and phone calls for up-to-the-minute reports. Much of the coordination value was lost, leaving many directors to simply wait for the word to expedite

critical orders. The information system was poor, communication between directors was mediocre, and the inventory and order status remained a mystery.

By building complete gear modules, the Gear Production Center would take a big step toward de-coupling from the current information and material flow system by completing all value added steps necessary in a module or kit prior to shipment to a customer (either internal or external). The COE, with the added functionality, could actually operate as an independent business.

4.2 Kitting Development

As mentioned earlier, though, an organizational shift of this magnitude was not possible at this point. Instead, a first step was proposed to kit all gears and shafts prior to shipment. Components would still be produced in existing batches, but the finished goods inventory would be delivered to a COE warehouse (not the central assembly warehouse). Components would then be grouped by order number, arranged in trays and carts, and delivered as complete kits. At the assembly facility, these trays could then be pulled by order number and arranged in build sequence on an engine cart, saving warehouse personnel valuable shopping time and giving the Gear COE complete control over finished goods inventory levels and order status. To provide some perspective, it is necessary to present the original assembly warehouse procedures. By doing this, both information and material flows will be shown, and the effects of their delays can be immediately identified.

As components were completed at the Gear COE, they were packaged, loaded onto carts and transported to the assembly warehouse. Upon arrival, each part was immediately scanned, or "bought into" the warehouse by an electronic inventory management system (WMS, or Warehouse Management System) and taken to the appropriate location. Inventory was arranged by engine family, and components from different facilities were loaded onto color coded carts. In theory, this procedure allowed the warehouse personnel to quickly locate the engine family and proper component. Additionally, a hand held WMS transmitter listed the entire order bill of materials and the correct location of the desired component. As each part was "picked," or taken from the warehouse shelf and staged on an assembly cart, it was entered into WMS and the serial number of each part was noted on the bill of materials to track each part during its life with the engine. An average engine used three carts for staging and parts were arranged on each shelf in order, allowing the assembler

easy access with minimal searching. Finally, after the engine was staged then cleared for release, some carts were moved to assembly stations while others went to a subassembly section where intermediate assemblies were completed prior to general assembly. As subassemblies were completed, they were immediately moved to the corresponding engine station to wait for assembly. Graphically, the process flow is shown in Figure 4.2-1.

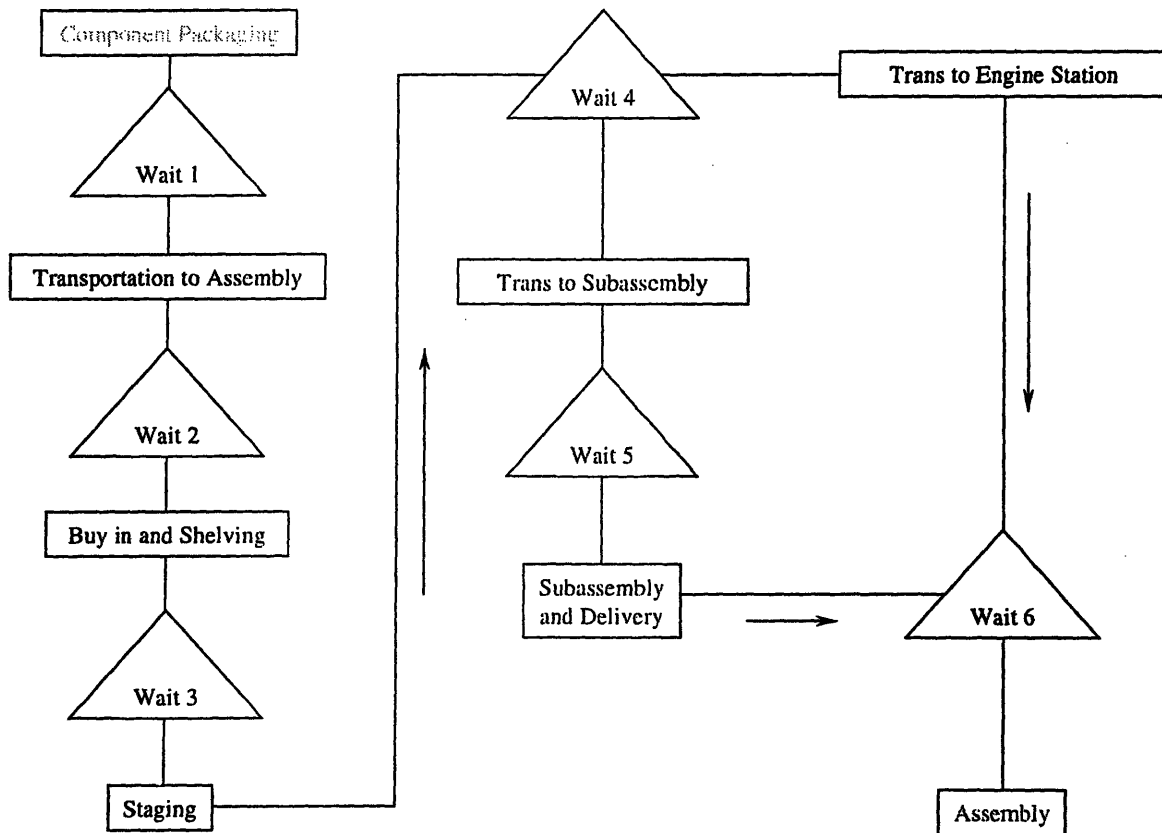


Figure 4.2-1 Production-Assembly Process Flow: This figure shows the flow of individual gears from packaging through assembly. Note that after Wait 4 there are two possible locations for transport – either directly to an engine station and a wait for assembly, or to subassembly and even greater time waiting.

Average times for each step are shown below:

- Component Packaging: 2 hours
- Wait 1: 2 hours
- Transportation to Assembly: 15 minutes
- Wait 2: 6 hours
- Buy in and Shelving: 30 minutes
- Wait 3: 1 week
- Staging (complete engine): 6 hours
- Wait 4: 3 days
- Transportation to Subassembly: 10 minutes
- Wait 5: 2 days
- Subassembly and Delivery: 4 hours
- Transportation to Engine Station: 10 minutes
- Wait 6: 2 days
- Assembly: 8 hours

All of these steps are important parts of the process map, but for simplicity of further discussion transportation delays will be neglected and only processing and waiting times will be discussed. The reason for this is that transportation deals only with material movement, and with or without a component kit plan material will still travel the same path. Also, the travel times are insignificant compared to the sum of waiting and processing times of the rest of the system. With that in mind, discussion turns to the mechanics, advantages and disadvantages of the component kit plan.

Once individual components are shelved in the assembly warehouse they wait until picked for an engine, kit or spare parts order. They are grouped in trays by engine family and part number. This seems efficient on the surface; but further inspection revealed some disturbing issues. Although each tray contained a certain number of identical parts, which aided in visual inventory count, multiple trays of the same part number were found in several different locations on the engine family rack, as well in several different engine family locations. Shown in Figure 4.2-2 is schematic of the layout of the assembly warehouse, and close-ups of an engine rack and part tray are presented in Figure 4.2-3.

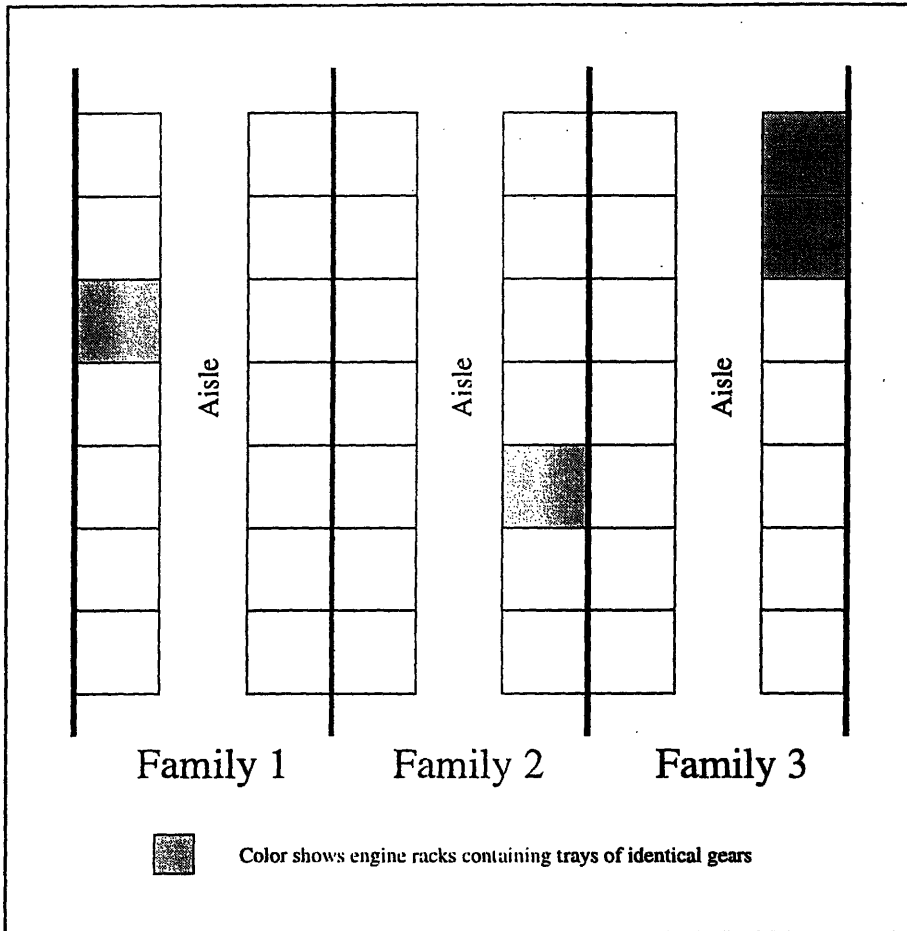


Figure 4.2-3 Engine Rack and Part Tray: Engine racks and part trays containing identical gears.

As gears were taken from a tray, additional time was not spent to rearrange all other gears on the rack to backfill the vacant spot. When a tray emptied, it was immediately replaced by a full tray, which had just been bought into the facility. As new trays of like gears were bought in, individual gears were not removed from that tray to backfill vacant spots, but the entire full tray was placed in an open location in the rack. Then, by separating components by engine family, the facility was able to save travel time during the picking and staging process. Although at the tray and rack level there was some disorganization, the time spent not rearranging individual components made the buy in and shelving process very smooth. In short, warehouse personnel became much more efficient through time saved in shelving, picking and staging due to the reduced travel and shopping time. Finally, after installing the WMS system to electronically monitor inventory levels, the facility was able to jump from an inventory accuracy level of 70% to over 95%.

So why kit gears at the COE level? With a system this efficient, wouldn't it be easier just to fix the information system to more accurately reflect inventory levels at real time speed rather than creating the chaos of physically relocating entire sections of the original warehouse? Maybe, but remember that the long-term goal was to build complete gear modules at the component level. To build them there inventory must be there, and for the inventory to be there it must be moved from its current location. So the logic follows: If the Gear COE was not looking to build complete modules, the system need not change and resources could be dedicated to improving the information and material flow between the component facilities and assembly. However, if complete modules are to be built prior to shipment to a customer then the *entire system* to support that must be co-located.

4.3 Pros and Cons

The entire system? In fact, the entire system necessary build complete modules prior to shipment involves not just component manufacturing and on-site inventory management, it involves purchasing (for raw materials and purchased components), finance (to track cost performance), and an assembly section to actually assembly the parts into modules. Fortunately, the move to a COE structure provided the foundation for integrating all

necessary support functions. There is still work to be done determining the exact organization structure of the COE, as well as defining roles and responsibilities, but the groundwork has been laid for this type of restructuring. But what about someone to actually assemble the parts? This is skilled work requiring special qualifications, and as luck would have it the subassembly section in the assembly facility is its own organization, structurally separate from the engine assemblers. When the decision is finally made to produce complete modules, moving the subassembly section can be accomplished with little difficulty.

Arguments against such a drastic change include the fact that subassembly and assembly associates are mutually supporting. Although subassemblers cannot replace engine assemblers (engine assembly requires a higher level of certification), engine assemblers can and do fill in to complete subassembly work when necessary. After physically moving the subassembly section to a different location a measure of mutual support will be lost, but this step is far into the future and will get due attention long before a move is made. Another argument is that physically moving the inventory will mean less visibility for engine coordinators who must have accurate, up to date information on material status in order to properly adjust the engine production schedule. Later, an attempt will be made to show the futility of such an argument, and possibly even the irrelevance of engine coordinators altogether with a new system. Finally, it was noted that creating a separate warehouse might compromise the physical security of the components. While it is true that multiple facilities increase the need for prudent (and possibly costly) security measures, this issue must be included in any future study.

Why is so much emphasis placed on the above arguments? It was mentioned earlier that this facility was not ready to support such a radical organizational change. Having been through a company-side restructuring, a voluntary retirement and a reduction in force, opposition to change was well understood. The arguments above were heard most frequently during interviews and presentations, and they are presented here to show the level of resistance under which this kit plan was being developed.

After identifying the process steps and their approximate times, the kit plan was developed to reduce or eliminate some of the non-value added time and to bring some of the value added steps further upstream in the manufacturing process. Specifically, concentration centers first on the break between Wait 4 and Transportation to Subassembly,

then on the break between Subassembly and Delivery, and Wait 6. These are the two locations where future kitting, and then complete production of subassemblies will integrate into the assembly process.

The mechanics of the kit plan do not differ significantly from the inventory flow seen in the original assembly system, but there are differences. Many steps originally accomplished at the assembly level will now be completed at the component level, and the effect on the process steps and waiting time will be noted.

Component packaging will not change. Parts will continue to move from the production floor to the packaging area upon completion. The first change, then, is what happens at Wait 1. Although not so significant in relation to the total time, this is actually a step which can be eliminated altogether. When parts are moved from the component facility to assembly, travel time and additional resources are necessary. Trucks are used to make runs throughout the day, and packaged parts wait for each of those runs. Therefore, a tradeoff is made between holding inventory and efficiently loading a truck. By moving inventory closer to the component facility, however, packaged components can be immediately moved to a storage location. In fact, during development of the kit plan a new storage location was identified in the same building, just down the hall. In relation to the total movement and processing time, transportation to the storage facility is almost instantaneous.

Once transportation is complete, the old system required a waiting period (along with incoming components from two other facilities) before buy-in and shelving could occur. Again, this waiting time was not great but could be reduced or even eliminated in the new system. If a part was moved directly from packaging, through transportation and immediately shelved, Wait 1 and Wait 2 would be completely eliminated. A manpower issue might exist, however, if one person was not able to adequately cover the amount of incoming orders. Although this issue was noted during kit plan development, it was not investigated further. It was agreed that this issue would be solved during the construction of the new warehouse, after testing during various incoming order levels. It made no sense at this stage to try and replicate the system.

Between shelving and staging, an unavoidable wait occurs. Given the constraints of the MRP system under which the assembly facility operated, the Gear COE was susceptible to engine production schedule variability. Even if all components were built to order, and

completed just in time for staging and transportation to assembly, the production schedule could at any minute change and force components to be re-shelved in favor of other, more critical parts. This wait, producing the first significant amount of inventory, was able to be reduced but not eliminated altogether. Therefore, allowances were made to hold certain amounts of inventory in this buffer to not only protect the Gear COE from assembly variability, but also to maintain adequate delivery performance for kit and spare part orders.

Looking next to staging, the old system required a wait before transportation to either subassembly of an engine station. Due to production schedule variability mentioned above, this was unavoidable in some circumstances. Also, at some points during the quarterly production cycle there were discrepancies between the workload in subassembly and at engine stations. Usually, the subassembly section ran short of work and was idle. To balance holding inventory and keep subassembly gainfully employed, certain components were split from a staged engine and transported to subassemblies. Although this kept the section busy, it is obvious that once the work was complete it again sat (although now on the shop floor) waiting for the rest of the engine components to be released into production.

What happens if engine components are staged at the component facility? First, components for an engine can remain on the shelves until a concrete decision has been made to release an engine to the production floor. Since this decision is made days in advance of staging the parts, the component facility has plenty of time to react and can assemble kits in a just-in-time fashion for transportation to assembly. The next logical step after kitting, and this may prematurely jump to the punchline, is that complete modules are assembled in a just-in-time fashion and are transported directly to the engine station. Was it mentioned earlier that engine coordinators, who are responsible for tracking all component order status, might be irrelevant when complete kits (and then complete modules) are shipped, complete, on the day of engine release?

4.4 What to Kit?

The first step in developing a kit plan was to determine exactly what to kit depending on type of order (engine, kit or spare parts). For engines and rebuild kits, the bills of materials had already been developed including both purchased parts and manufactured components from all three component facilities. Spare parts orders were not standard, so they were not included in this study. Only engines and kits, then, were considered for

kitting. Note: Spare parts would still be included in developing production schedules, and the variance of these orders taken into account in figuring optimum batch size and production runs, but after production they would be separated from components marked for kits and held separately.

There were approximately 150 different engine builds and kits (including both parent engine families and derivatives). Space was limited for additional warehouses on the campus, and attempting to kit each one would be wasteful. Many of these builds were similar, so it did not make sense to develop individual kits for all 150 cases. Instead, kits with similar (or even identical) components were grouped into one kit. Only 51 kits were required to cover the original 150 possible kit configurations, saving space.

At the Gear COE, kits would be comprised of only manufactured gears and shafts. Since the COE was already using cell based manufacturing for different components, it made sense to further break the kit bill of materials into cell groups. This would first aid in visual inspection of inventory in each kit, and would allow cell managers to more proactively adjust their production schedules to produce necessary components in time for delivery. By identifying each kit by engine family and then break them into different cells, visibility on the components for any order would be brought to the absolute lowest level, the cell manager. Whereas in the original production system COE Directors and the Vice President of Manufacturing made decisions about delivery of individual components, now the responsibility for components rested with the first line manager. COE directors could then concentrate on subassembly and engine kits, and senior executives could track engine orders, instead of individual parts.

Shown in Figure 4.4-1 is a representative kit for a single engine order. Not that the bill contains all the manufactured parts from a component facility broken down by manufacturing cell.

85-180C	3800272-1	02	3604090-1	1
			698195-6	1
		22	371551	1
			75283	3
		23	76389-1	1
Organized by:		24	372420	1
- Engine			372822-2	1
- Build Number			73749-6	1
- Cell		29	75282	1
			75285-4	1

Figure 4.4-1 Representative Kit: This shows (by part number and manufacturing cell) the gear products proposed for one engine kit. It is a representative kit of the 85-180C engine, Build Number 3800272-1. Products from cells 02, 22-24 and 29 are shown. This kit currently includes only internally manufactured parts. Future kitting will include both internally and externally sourced gear products.

It was mentioned earlier that certain engine families contained not only the parent engine but also derivatives of that engine. The kit above shows not only the engine number (85-180C), but also the build number (3800272-1). Some engines had up to a dozen different build numbers. At the component level, kits were grouped according to similarity, meaning that one kit contained the identical parts for a number of different engine builds. Although that makes the build number meaningless in maintaining kit inventory, it seemed appropriate to include this additional step during explanation.

To avoid confusion between engines and build numbers, interim part numbers would be made for each of the 50 kits. At the component level, these interim numbers would be used to track specific kits, replacing the need for a complete bill of materials for the kit. No change would be seen at the assembly facility, since the tray would be delivered as a mix of individual part numbers, and the interim number would no longer be necessary. Additionally, the build number would be included with the delivered kit, along with the appropriate order number, in order to ensure accuracy of the transaction and accountability of all gears.

This accuracy and accountability may seem like common sense, but it was a vital step in ensuring the success of the kit plan. As the assembly facility was currently laid out, both original equipment assemblers and rebuild technicians were located under the same roof.

Communication between these two groups was frequent, but unfortunately it was normally to secure needed parts that were not readily available in inventory. Earlier it was mentioned that often engines were released onto the shop floor without a complete bill of parts. Also, subassemblies were released prior to engine release in order to keep the subassembly section in work. Sometimes, even these subassemblies were released without a complete bill preventing any work. So, many times both engine and subassembly carts waited for assembly for days on the shop floor. The best way to explain the issues that developed is to tell a story.

If a rebuild technician did not have a certain part, he or she would first look to inventory to find the part. If the part was not in stock and the order was critical, the next step was to go onto the OEM assembly floor to find the part. If lucky, the technician would find the part on an engine or subassembly rack that was waiting for assembly, but without a complete bill. The managers compared order completion dates, and parts were routinely given away. This worked both ways, when OEM assemblers were short parts that they could find in rebuild. What is confusing here is that this type of transaction is the best way for the assembly managers to maintain smooth flow of engines through the facility. If an OEM order did not have a complete bill, and the necessary components would take many days to arrive, it did not make sense to sit on other components which could be used somewhere else to get engines out the door. If studied only within the scope of the assembly facility, this procedure was an important and necessary part of coordinating completion times to meet end-of-quarter production quotas.

The problem arises when these parts, having been identified at the component level as being released to the floor with an order, turn up missing as a result of a unknown transaction made at assembly. Unfortunately, the information about that part's location flows very slowly back to the production facility, and when it finally arrives it is usually in the form of an expedited order. The component production schedule, which worked adequately to get the part to assembly on time, now has to scramble and disrupt current production to expedite a small batch to meet this "new" critical engine assembly. A vicious cycle is generated when other components, forced to wait for the expedited order, fall behind in the schedule and are delivered late to assembly. As one part is expedited, others wait and become critical, only to be then expedited to meet new critical engines.

4.5 New System Layout

So how can a kit plan solve these issues? Shown below are two diagrams. Figure 4.5-1 shows the existing production and assembly system, and Figure 4.5-2 shows a new system with kitting.

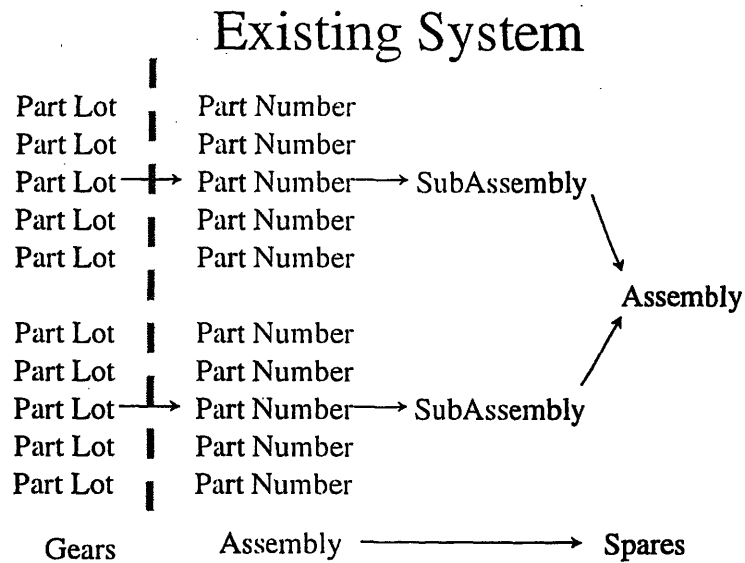


Figure 4.5-1 Existing System without Kitting: The cutoff of gear product visibility occurs as parts are shipped to the assembly warehouse. This significantly increases the information feedback loop involving order processing and status.

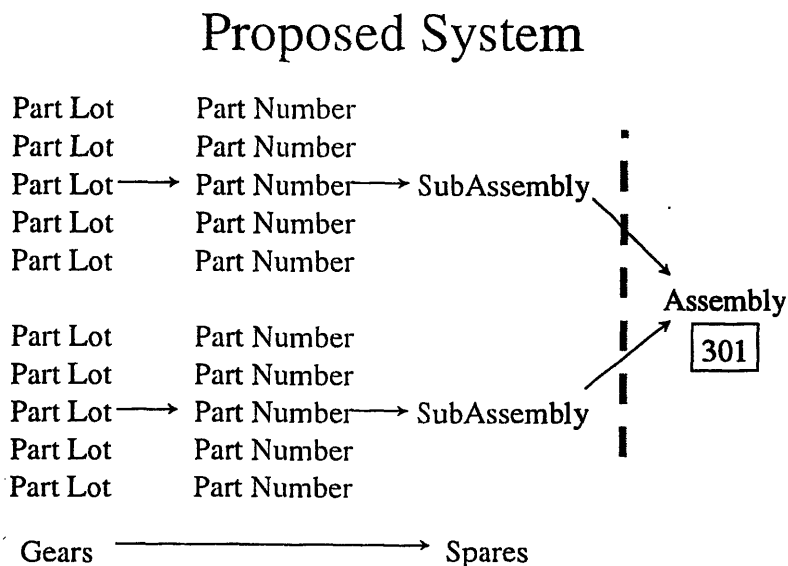


Figure 4.5-2 Proposed System with Kitting: By maintaining gear product visibility until the final assembly step, the feedback loop is dramatically decreased.

Note first that the two flows are not significantly different. However, the difference lies in the position of the dashed line, denoting the cutoff of visibility from the component level. In the first figure, as parts are completed in lots, they are packaged and delivered to assembly as individual part numbers and stocked on shelves for later use in either an engine, kit or spare part order. Although the information system tracks inventory levels through production and in the assembly warehouse, knowledge of where that order will be used is lost to components. Additionally, as parts are shifted between OEM and rebuild, real time inventory status is non-existent.

In the proposed system, the cutoff line shifts much further to the right, allowing visibility and control of components through the entire process until they are delivered as a kit to assembly. Each tray is bought in as a complete kit, and component manufacturing has a concrete record of deliver performance right down to the individual order number. Only when the complete kit is delivered to assembly is control lost, but if a kit is delivered complete, any discrepancies that arise later are quickly noted and corrected. Also, accountability for exchanging components between OEM and rebuild is established.

So how does the help both assembly and component manufacturing to better track inventory and ensure orders arrive complete and on time? The answer lies in shifting value added process further upstream in the distribution chain. Component facilities can track individual parts through manufacture, completing all parts necessary and assembling the kit in time for delivery, and assembly buys in a complete kit ready for staging. Released engines now have complete bills of materials and assembly can start immediately. Also, the necessity for engines to wait (sometimes days) in the assembly staging area is eliminated since kits can now be delivered at exactly the correct time.

Chapter 5 Integrating Product Ownership

5.1 Background

The previous chapters focused mostly on the mathematical development of a model that mirrors historical assembly and production behavior. The bullwhip and hockey stick effects have been developed, and an understanding of the variables that affect the actual production and assembly systems is complete. However, this explanation is too narrow in the larger context of material and information flow throughout the entire organization. An analogy to where this thesis now stands would be like discussing the growth of a plant only in terms of cell reproduction, without any mention of food, water and sunlight. In this thesis, only the most tactical issues have been developed, without regard for systems operations or strategy. The link between manufacturing and marketing must in some way be addressed. This allows a full appreciation for the development and execution of the production schedule, and allows the presentation of a unified argument for process improvements across the entire supply chain, not just in the manufacturing sector.

This section is not meant to be quantitative. Instead, the goal is to present a framework for developing a material and information flow management system in the Case and Gear COE given the current management structure, exploiting the roles and responsibilities outlined during the business reorganization. Specifically, as the COE assumes a greater role in designing and producing complete gear modules and separates from the volatility associated with the assembly schedule, a higher level of customer service, lower inventory and higher turns can be achieved, and the enterprise and manufacturing goals can be more closely aligned.

Looking back at causal loop development, the primary driver of the system was a revenue target. This target determined the number of engines built in a production quarter, and the number of spare parts orders that would be filled. The model itself did not include this revenue variable, but instead concentrated on the behavior of the system after being motivated by a revenue target (i.e. it met an artificial engine quota that was developed based on historical data). Now, by looking more at the manufacturing-marketing linkage, it will be possible to suggest different information and material flow options to improve system performance, lower inventory and increase customer responsiveness.

A plethora of material and information management tools abound. Material Requirements Planning (MRP), Just-in-Time (JIT), Kanban, CONWIP, and Lean Manufacturing are only a few such tools which provide managers ways to match demand and operate at the lowest cost structure possible in terms of inventory, labor, and capital. An additional tool is presented here, called Demand Flow Technology (DFT), which is simply a western approach to Japanese Just-in-Time manufacturing. DFT, however, includes certain aspects that aid its applicability to the traditional western manufacturing philosophy of scheduled manufacturing systems.

Demand Flow Technology is a business tool that allows companies to more effectively track material and information flow, and continually adjust daily and weekly production based on actual customer demand. The reliance on schedules for individual components and subassemblies is eliminated, and individual components are manufactured to meet specific orders and delivery dates, without lost time in raw material, WIP and finished goods inventories. If this sounds suspiciously like Japanese Kanban techniques, well, it should. However, DFT goes far beyond pull processes and machine cells. It incorporates a strategic link between marketing and manufacturing, refocusing the manufacturing process on takt time, cost, quality and inventory turns.

In a traditional scheduled manufacturing environment, marketing and manufacturing are forever at odds. Manufacturing managers complain that marketing always asks for more than they can offer in both volume and speed. Marketing complains of missed orders, unresponsive design changes and quality problems. Understanding that the incentives of each organization are not necessarily linked, it is inevitable that such tension arises (Porteus & Whang, 1989). As discussed earlier in this work, marketing drove the need to ship a quota of engines. Manufacturing managers resorted to extraordinary measures of expediting engines and components to meet demand, and often achieved production goals with a reliance on overtime labor.

The primary marketing goal was to ship as many engines as possible in a production quarter to meet revenue targets. Manufacturing managers, on the other hand, were much more interested in production efficiency, and scheduled production runs to optimize labor and time in the process. Because the original Gear Production Center operated solely on a cost basis, many times these priorities did not match. The necessity to ship orders, in many cases, overrode production efficiency and process cost. Manufacturing managers were in a

race to not only produce scheduled components, but also to meet the additional demand of expedited orders.

Scheduled manufacturing also necessitated a large and complex storage facility for raw materials, work in process and finished goods. Since components were not necessarily produced at the pull of an engine but rather to a production schedule, many pieces waited in finished goods for engine release (which was often changed to suit completion and delivery of priority orders). Raw materials waited in bulk for release to the production floor (which were purchased in quantity as a tradeoff to reduce shipping expense). Finally, inventory turns ranged between four and seven. Long lead times and excess work in process inventory contributed to quality exposure of each lot of gear products. Although defect rates were fairly constant and the sources of the defects could be found, aggressive process improvement methods were met with some resistance.

The organizational shift to the COE concept was the first step toward creating an organization that could operate independently and not remain tied to assembly volatility. The new COE included the functional expertise to design and manufacture complete gear modules, and also would be in a position to control the entire value chain from raw material procurement to delivery of complete modules. Cellular manufacturing was already in place, and a vigorous attempt was underway by supply chain management to optimize product lot sizes to minimize inventory and reduce cycle times. However, the Case and Gear COE was still invariably linked to the production processes of the three other component facilities, and was still under the control of assembly for delivery performance.

5.2 Application

Demand Flow Technology is surprisingly simple. In fact, its tenets may be too simplistic to find their way into this type of literature. The basic philosophy is nothing more than fundamental industrial engineering concepts appropriately matched with consistent manufacturing metrics. More importantly, however, DFT provides a framework to align necessary support functions around the manufacturing process capability yet retain their own inherent goals and metrics.

John Costanza's book, The Quantum Leap, explains the mechanics of DFT in much greater detail than is possible here. Relevant examples allow the reader to understand the most basic production schedule inefficiencies and to establish conclusions about its worth as

not only a production scheduling technique, but as a tool for capacity planning and inventory control. Costanza then discusses product design, total employee and total quality involvement, and financial management. Finally, issues are outlined that are relevant to implementing the DFT strategy and technology.

The point of introducing DFT in this context is not to develop its mechanics. The point is to discuss its relevance in the overall supply chain, of which the COE is only a small part. A quote from a Compaq Computer Corporation senior manager says, "There is only so much that can be done to affect costs within 4-wall manufacturing. The real payoff is going to come from the supply chain as a whole, and we must all look outside our own organizations to reap these benefits." The model developed in this work seeks to understand the flow of gear products across the entire chain from raw materials to engine shipment. This type of system thinking is absolutely critical in implementing any type of change involving two or more elements of a value chain.

The aspect of DFT most relevant to this discussion is the link between manufacturing and marketing. In the model presented here, that link started with a revenue target driving engine and parts orders and ended with shipped orders. Tension existed within manufacturing to meet orders levels that were consistently higher than current process capability. Marketing, or Enterprise, was concerned with meeting quarterly demand regardless of costs. Somewhere in starting and ending this link, ownership for the product was lost and information and material flow suffered.

The first step in DFT is to gain control of both orders and the manufacturing process, and force continued ownership of the product throughout the value chain. In this case, the break in ownership occurred once the product was complete. Enterprise forecasts were inaccurate and manufacturing was left to sort through excess finished goods inventory meant for a lost order. The bullwhip of randomly fluctuating orders caused continual production schedule disruption, and as was proven in the system model, that fluctuation amplified as it moved back through the value chain. Assembly reacted to changing engine orders, but the component centers bore the brunt of the effect with two levels of amplification and the combined variability of both OEM, kit and spare parts orders.

To improve forecasting accuracy would seem like throwing good money after bad. In fact, the first rule of forecasting is that they are inherently inaccurate. Additionally, trying to artificially "freeze" a production schedule at a certain time limit severely limits the hands

of marketing to meet rapidly changing customer requirements. Therefore, it is necessary to look to other variables in the system which can indirectly drive forecasting accuracy (yet maintain flexibility) and allow for smooth, level-loaded production (yet still be responsive to changing market demands) and minimize the bullwhip effect.

DFT addresses both forecasting accuracy and production efficiency through the medium of ownership. In the case of the manufacturing facility in this study, ownership of the product was lost between order entry and production, and between completion and order shipment. Marketing owned nothing in production, and manufacturing owned no outstanding orders. To suggest a remedy would be to develop continuous ownership, or a set of linkages, of production from order entry through shipment, by both marketing and production (Hausman & Montgomery, 1997).

Specifically, manufacturing would own all outstanding orders and in-process inventory to maximize process efficiency. This way, marketing would not be able to change the production schedule except in the most extreme circumstances, and manufacturing would look much further out on the production horizon to more efficiently use the resources at hand to effectively meet customer demand in the right amount, at the right time. Marketing, on the other hand, would immediately take ownership of all completed orders, whether firm orders existed or not. To meet aggressive inventory metrics, marketing would have to become much more proactive about determining the status of each order, and about entering that order into the system. No longer would manufacturing be left holding excess inventory for which orders never existed, and marketing would no longer be apt to artificially inflate orders based on inaccurate forecasts.

Currently, marketing and manufacturing are separate functions in the manufacturing environment in this company. Although linking marketing and manufacturing would certainly be possible, geographical and functional separation make the task much more difficult. As the COE further defines its place in the organization, and roles and responsibilities become clearer, linking the marketing and manufacturing functions will be of prime importance in achieving the greatest improvements across the entire supply chain. Co-location of both functions, a resolution to production ownership and aligned metrics should be long term goals in support of Demand Flow Technology implementation.

Chapter 6 Conclusion

6.1 Integration

Feedback systems with few variables are easily understood through inspection, common sense and basic mathematics. Simple cause-and-effect relationships directly affect flows to produce net increases and/or decreases in the stocks in an environment. However, as those systems become more complex, adding more variables and multiple cause-and-effect relationships, it is nearly impossible to accurately determine the net effect in an environment from a change in any single variable. Inspection is confusing, common sense often leads to incorrect conclusions, and the mathematical representations become complicated sets of equations necessitating advanced solving techniques. Modeling is a way to create a mathematical representation of a system to determine the net effect from a change in specific variables.

In a manufacturing system, there exist countless material and information feedback systems that can dramatically affect system performance. At all levels, in all functions, policy differences contribute to inefficiencies in transmitting information and material, resulting in a bullwhip effect. This bullwhip effect, as shown by Jay Forrester, can have significant impacts on a supply chain. As separate policies are implemented, and managers make sound decisions affecting their own piece of the chain, the overall effect can be detrimental.

In the manufacturing environment studied in this work, many information and material feedback loops combined between component production and turbine engine assembly. These feedback loops (and the inherent variability of demand forecasting) produced increasing amplitude of response to production changes. As demand fluctuated, so too did the manufacturing process supporting it, but at a much more aggressive rate. Forrester's step and sine inputs showed only either a one-time change in demand or a constant, predictable cyclicity. As shown, however, very rarely was demand fluctuation either predictable or singular in this industry. Instead, managers had to cope with consistent step inputs (and accompanying noise) overlying inherent cyclicity.

Additionally, the concept of a production gap (a result of MRP type systems which rely on sequential scheduling of components, subassemblies and complete assemblies) was introduced to show its importance in the feedback race between the stock of engines actually

complete and the desired level of engines to be completed in a production quarter. Many of the management incentives in this type of system revolve around this production gap, sometimes driving undesirable side effects like expediting in order to meet arbitrary production quotas at the expense of process efficiency. A delicate balance must be maintained between the manufacturing process and marketing flexibility, but often maximizing the performance of one for short-term gain happens only at the long-term expense of the other.

The manufacturing model presented in Chapter 3 builds on the bullwhip effect development of Chapter 2. Forrester's work showed the amplification of response and delay of information transmissions with each step back from an end consumer, and also showed the delay in increasing or decreasing material flow. In this manufacturing system, the delays of information and material flow operate similarly. With each step back, changes in demand are learned later, and the speed necessary to increase or decrease production to account for that demand change (and either backorders or cancelled orders) is directly a function of the time delay in transmission of the information.

Many variables affected the manufacturing system in this study. Each variable tested represented some type of controllable delay, and the sensitivity of each was used to then determine appropriate management actions to take in improving material and information flow. Interpretation of the results highlighted the most important variables affecting delays, and this study was able to suggest a kit plan (at the component level) which would significantly shorten the feedback loops between assembly and component production. By maintaining a dedicated gear product finished goods inventory, more immediate decisions could be made about product flow through the factory. Also, by kitting the gears by order number prior to shipment to assembly, each component facility could make more proactive adjustments to production schedules to improve delivery performance and maintain less inventory. Said another way - the component facilities could be lean.

Demand Flow Technology (DFT) was then introduced to provide a framework for integrating other functions in the organization that were not directly involved in the manufacturing process. Marketing, specifically, was identified because of their fundamental interest in outstanding orders at the facilities and in complete orders to be shipped. Unfortunately, in many circumstances manufacturing and marketing metrics are at odds about product mix, volume and flexibility. Using DFT, a more efficient method to link

manufacturing and marketing incentives through product ownership was introduced. The point was to look outside the four walls of a manufacturing facility and seek process improvement over an entire supply chain, rather than only in the production process.

To conclude, this main emphasis of this work was to introduce a problem solving approach, using system dynamics modeling, to suggest policy improvements in a specific manufacturing environment. The basics of modeling were presented to inspire confidence in the process and an understanding of the results obtained in a production-distribution setting. Then, using the same piecewise approach, a manufacturing model was developed to mirror the information and material delays inherent in a production-assembly system. While the most intricate details of creating a mathematical representation of the production system were deliberately minimized, causal loop development was instead highlighted. As a first step in determining the cause-and-effect relationships in any system, it can be implemented by anyone at any level of an organization. It does not take extraordinary skill to decide that one variable affects another, and this step alone can become a powerful management tool to uncover basic misconceptions about business processes, whether they be in the manufacturing industry, finance, service or research.

6.2 Future Work

The variables modeled in this work represent a study at one point in time. This company, and the industry as a whole, is in a state of flux. Business reorganization contributed to many changes over the course of the internship, and continued improvements have altered the system since. Although an attempt was made in this study to generalize the relationships between key variables and the results of their interactions, the system is now fundamentally different. As the kit plan is developed in the future, then, a look back at the cause-and-effect relationships of this study must be performed. Although the relationships may seem similar, subtle changes from updated management policies alter even the most basic interactions. Additionally, the reference modes associated with those variables could significantly change which may impact the initial conditions of a mathematical representation. In short, the same process outlined in this study must be followed to develop a new, improved model of system performance.

The kit plan was a first pass attempt to define a solution to the information and material feedback delays noted in the system. Although it represents an in-depth look at

inventory control across the production-assembly value chain, its tactical implementation was not fully outlined. To implement such a plan in the future, then, will require a more thorough development of the operational and tactical elements necessary to support this type of organizational change. This study looked to kit current engine configurations, and exploited the tremendous overlap of components to minimize the space required to house such a finished goods inventory. Engine configuration and component overlap must be again researched to determine appropriate inventory levels and kit configurations.

Finally, a more thorough cost/benefit analysis must be conducted to determine the true economic benefit of such a plan. During the internship, the study was able to adequately outline the material and information flow efficiencies that could be created with a kit plan, but the cost drivers (and their overall effect on the system) were not fully examined. Using the same causal loop development process used for the production process, the interactions of product mix and volume, quality, delivery and flexibility can be weighed against the costs incurred by the system.

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Appendix A

Manufacturing Model Documentation

- (01) $AR1 = \text{Engines } 1 / (\text{Assembly Delay} / 3)$
Units: engine/Month
Engine completion rate after one delay period.
- (02) $AR2 = \text{Engines } 2 / (\text{Assembly Delay} / 3)$
Units: engine/Month
Engine completion rate after two delay periods.
- (03) $AR3 = \text{Engines } 3 / (\text{Assembly Delay} / 3)$
Units: engine/Month
Engine completion rate after three delay periods.
- (04) $\text{Assembly Delay} = \max(2 * \text{Time to Target}, 3)$
Units: Month
Represents pressure felt to complete engines as the target time approaches. Begins with a linear delay until a theoretical minimum delay is reached, representing the fastest rate at which an engine can be completed.
- (05) $\text{Decision Rate} = \text{Desired Assembly Rate} + (\text{Expedited Infusion} * \text{Switch})$
Units: engine/Month
Desired rate at which engines are assembled developed as a function of the difference between actual and desired WIP, the difference between normal and actual stocks of unfilled orders, the order introduction rate and the WIP Adjustment Time.
- (06) $\text{Delay in Filling Orders} = \text{Gear Handling} + (\text{Gear Out of Stock} * (\text{Desired Inventory} / \text{Stores Inventory}))$
Units: Month
Time lag as a result of raw material stockout or material handling.
- (07) $\text{Desired Assembly Rate} = \text{UC Inc} + (((\text{Normal UC} - \text{UC Engines}) + (\text{Desired WIP} - \text{Engine WIP})) / \text{WIP Adjustment})$
Units: engine/Month
Desired rate at which engines are assembled.

- (08) $\text{Desired Gear Rate} = \text{Gear Inc} + (((\text{Normal UC Gears} - \text{UC Gears}) + (\text{Desired Gear WIP} - \text{Gear WIP})) / \text{Gear WIP Adjustment})$
 Units: gear/Month
 The desired rate at which gear/shaft orders will be processed.
- (09) $\text{Desired Gear WIP} = \text{Smoothed Gears} * \text{Gear Assembly Delay}$
 Units: gear
 Desired WIP level based on smoothed orders.
- (10) $\text{Desired Inventory} = \text{"Inventory/Orders Constant"} * \text{Smoothed Gears}$
 Units: gear
 Desired finished goods inventory available to fill orders.
- (11) $\text{Desired WIP} = \text{Smoothed Orders} * \text{Assembly Delay}$
 Units: engine
 Desired engine WIP.
- (12) $\text{Engine WIP} = \text{Engines 1} + \text{Engines 2} + \text{Engines 3}$
 Units: engine
 Total actual WIP level in the assembly system.
- (13) $\text{Engines 1} = \text{INTEG}(\text{Decision Rate} - \text{AR1}, 250)$
 Units: engine
 WIP level in first delay period.
- (14) $\text{Engines 2} = \text{INTEG}(\text{AR1} - \text{AR2}, 250)$
 Units: engine
 WIP level in second delay period.
- (15) $\text{Engines 3} = \text{INTEG}(\text{AR2} - \text{AR3}, 250)$
 Units: engine
 WIP level in third delay period.
- (16) $\text{Expedited Infusion} = \text{IF THEN ELSE}(\text{WIP Delta} > 0, \text{WIP Delta} * 4, 0)$
 Units: engine/Month
 Represents engines needing rework or expedited through the system.

- (17) $\text{External Orders} = \text{Orders} * \text{Input Modification}$
 Units: gear/Month
 This is the modified kit/spares order variable.
- (18) $\text{Feasible Shipments} = \text{Stores Inventory} / \text{Delay in Filling Orders}$
 Units: gear/Month
 Shipment rate at which the current system is able to support.
- (19) $\text{FINAL TIME} = 3$
 Units: Month
 The final time for the simulation.
- (20) $\text{Gear Assembly Delay} = \max(\text{Gear Time to Target}, 1)$
 Units: Month
 Used to determine the pressure felt as the target time approaches.
- (21) $\text{Gear Dec} = \text{GR3}$
 Units: gear/Month
 Completed gear/shaft orders leaving the system.
- (22) $\text{Gear Decision Rate} = \text{Desired Gear Rate}$
 Units: gear/Month
 The desired rate at which gear/shaft orders will be processed.
- (23) $\text{Gear Exp Rate} = \text{Gear Infusion}$
 Units: gear/Month
 Amount of gear orders which are targeted for expedition through the system.
- (24) $\text{Gear Handling} = 1$
 Units: Month
 Delay in handling raw material for production.
- (25) $\text{Gear Inc} = \text{External Orders} + \text{OEM Orders}$
 Units: gear/Month
 This is the total inflow of gear/shaft orders to the Gear Production Center.

- (26) $\text{Gear Infusion} = \max(\text{Expedited Infusion} * \text{Gears/engine}, (\text{Gear WIP} - \text{Desired Gear WIP}) / \text{Time})$
 Units: gear/Month
 Decision variable which can add gear/shaft orders into the system. Represents effect of rework or expediting.
- (27) $\text{Gear Out of Stock} = 1$
 Units: Month
 Time necessary to obtain raw material when out of stock.
- (28) $\text{Gear Smoothing Delay} = 8$
 Units: Month
 Smoothing constant for gear/shaft orders.
- (29) $\text{Gear Target Time} = 3$
 Units: Month
 Production time for revenue purposes.
- (30) $\text{Gear Time to Target} = \text{Gear Target Time} - \text{Time}$
 Units: Month
 Time left in production cycle until target time is reached.
- (31) $\text{Gear WIP} = \text{Gears 1} + \text{Gears 2} + \text{Gears 3}$
 Units: gear
 Total actual WIP in the Gear Production Center.
- (32) $\text{Gear WIP Adjustment} = 2$
 Units: Month
 Represents the time factor to adjust gear/shaft WIP levels.
- (33) $\text{Gears 1} = \text{INTEG}(\text{Gear Decision Rate} + \text{Gear Exp Rate} - \text{GR1}, 6000)$
 Units: gear
 Level 1 WIP.
- (34) $\text{Gears 2} = \text{INTEG}(\text{GR1} - \text{GR2}, 6000)$
 Units: gear
 Level 2 WIP.

- (35) $Gears\ 3 = INTEG\ (GR2 - GR3,\ 6000)$
 Units: gear
 Level 3 WIP.
- (36) "Gears/engine" = 9
 Units: gear/engine
 Average gear/shaft products per engine
- (37) $GR1 = Gears\ 1 / (Gear\ Assembly\ Delay / 3)$
 Units: gear/Month
 Gear production rate after one delay cycle.
- (38) $GR2 = Gears\ 2 / (Gear\ Assembly\ Delay / 3)$
 Units: gear/Month
 Gear production rate after two delay cycles.
- (39) $GR3 = Gears\ 3 / (Gear\ Assembly\ Delay / 3)$
 Units: gear/Month
 Final gear production rate.
- (40) Handling = 1
 Units: Month
 Delay resulting from component handling.
- (41) INITIAL TIME = 0.001
 Units: Month
 The initial time for the simulation.
- (42) Input Modification =
 $1 + STEP(Step\ Height, Step\ Time) + STEP(Step\ Height2, Step\ Time2) +$
 $(Pulse\ Quantity / TIME\ STEP) * PULSE(Pulse\ Time, TIME\ STEP) +$
 $RAMP(Ramp\ Slope, Ramp\ Start\ Time, Ramp\ End\ Time) +$
 $Sine\ Amplitude * SIN(2 * 3.14159 * Time / Sine\ Period) +$
 $STEP(1, Noise\ Start\ Time) * Noise\ Amplitude * (RANDOM(0, 1) - 0.5)$
 Units: dimensionless
 This is a tool that allows quick access to a variety of input patterns.

- (43) "Inventory/Orders Constant"= 2
Units: Month
Represents the desired time amount of inventory in the system.
- (44) MACPAC= 200
Units: engine/Month
Engine orders through MACPAC.
- (45) Noise Amplitude= 0
Units: dimensionless
Magnitude of the random input, as a fraction of the base value of the input.
- (46) Noise Start Time= 1
Units: Week
Start time for the random input.
- (47) Normal UO= Smoothed Orders*(Handling+Out of Stock)
Units: engine
Normal stock of unfilled orders in the system.
- (48) Normal UO Gears= Smoothed Gears*(Gear Handling+Gear Out of Stock)
Units: gear
The normal amount of unfilled orders reflected by smoothed orders.
- (49) OEM Orders= Decision Rate*"Gears/engine"
Units: gear/Month
The number of OEM engine orders.
- (50) Orders= 4200
Units: gear/Month
This represents the number of kit/spares orders.
- (51) Out of Stock= 1
Units: Month
Delay time as a result of out of stock components.

- (52) Pulse Quantity= 0
Units: dimensionless*Week
The quantity to be added to the delay in the pulse input, as a fraction of the base value of Input. For example, to pulse in a quantity equal to 50% of the current value of input, set to .50.
- (53) Pulse Time= 50
Units: Week
Time at which the pulse in Input occurs.
- (54) Ramp End Time= 1e+009
Units: Week
End time for the ramp input.
- (55) Ramp Slope= 0
Units: 1/Week
Slope of the ramp input, as a fraction of the base value.
- (56) Ramp Start Time= 10
Units: Week
Start time for the ramp input.
- (57) SAVEPER = TIME STEP
Units: Month
The frequency with which output is stored.
- (58) Shipments= Shipments Sent From Stores
Units: gear/Month
Shipments sent from the Gear Production center to spares orders and stores.
- (59) Shipments Sent From Stores= MIN(Feasible Shipments,Gear Inc)
Units: gear/Month
Actual shipments which can be shipped from the Gear Production center. Moderated by the negative hold variable to prevent shipments without material.
- (60) Sine Amplitude= 0
Units: dimensionless
Amplitude of the sinc wave in Input, as a fraction of the base value.

- (61) Sine Period= 52
Units: Week
Periodicity of the sine wave in Input.
- (62) Smoothed Gears= SMOOTH(Gear Inc,Gear Smoothing Delay)
Units: gear/Month
Resulting smoothed gear/shaft order into the system.
- (63) Smoothed Orders= SMOOTH(UO Inc,Smoothing Delay)
Units: engine/Month
Smoothed engine orders.
- (64) Smoothing Delay= 8
Units: Month
Smoothing constant for engine orders.
- (65) Step Height= 0
Units: dimensionless
Height of the step input, as a fraction of the base value.
- (66) Step Height2= 0
Units: dimensionless
- (67) Step Time= 1
Units: Week
Time for the step input.
- (68) Step Time2= 48
Units: Week
- (69) Stores Inventory= INTEG (GR3-Shipments, 6000)
Units: gear
Gear products in storage at assembly warehouse
- (70) Switch= 1
Units: dimensionless
Turns expediting on and off.

- (71) Target Time= 3
 Units: Month
 Production time for revenue purposes.
- (72) TIME STEP = 0.015625
 Units: Month
 The time step for the simulation.
- (73) Time to Target= Target Time-Time
 Units: Month
 Time left in production cycle until target time is reached.
- (74) UO Dec= AR3
 Units: engine/Month
 Completion rate of engines.
- (75) UO Engines= INTEG (+UO Inc-UO Dec, 600)
 Units: engine
 Number of outstanding engine orders.
- (76) UO Gears= INTEG (+Gear Inc-Gear Dec, 10000)
 Units: gear
 Stock of outstanding gear/shaft orders.
- (77) UO Inc= MACPAC
 Units: engine/Month
 Inflow of engine orders.
- (78) WIP Adjustment= 1.5
 Units: Month
 Time required to adjust WIP in the Engine Assembly facility.
- (79) WIP Delta= Engine WIP-Desired WIP
 Units: engine
 Difference between actual and desired WIP levels.

Industrial Dynamics Model Documentation

(Note: Most variables in this model include explanations for clarity. A more detailed explanation can be found in Chapter 15 of Industrial Dynamics)

- (001) $AID = 6$
Units: Week
Proportionality constant between Inventory and Average Sales at Distributor
- (002) $AIF = 4$
Units: Week
Proportionality constant between Inventory and Average Sales at Factory
- (003) $AIR = 8$
Units: Week
Proportionality constant between Inventory and Average Sales at Retail
- (004) $ALF = 1e+006$
Units: units/Week
Constant specifying manufacturing capacity limit at factory
- (005) $CPD = CPD1 + CPD2 + CPD3$
Units: units
Clerical in-process orders at distributor.
- (006) $CPD1 = INTEG (PDD - PSD1, 667)$
Units: units
Level 1 clerical in-process.
- (007) $CPD2 = INTEG (PSD1 - PSD2, 667)$
Units: units
Level 2 clerical in-process.
- (008) $CPD3 = INTEG (PSD2 - PSD3, 667)$
Units: units
Level 3 clerical in-process.

- (009) $CPF = CPF1 + CPF2 + CPF3$
Units: units
Clerical in-process orders at factory.
- (010) $CPF1 = \text{INTEG} (MDF - MOF1, 333)$
Units: units
Level 1 factory in-process.
- (011) $CPF2 = \text{INTEG} (MOF1 - MOF2, 333)$
Units: units
Level 2 factory in-process.
- (012) $CPF3 = \text{INTEG} (MOF2 - MOF3, 333)$
Units: units
Level 3 factory in-process.
- (013) $CPR = CPR1 + CPR2 + CPR3$
Units: units
Clerical in-process at retailer.
- (014) $CPR1 = \text{INTEG} (PDR - PSR1, 1000)$
Units: units
Level 1 retail in-process.
- (015) $CPR2 = \text{INTEG} (PSR1 - PSR2, 1000)$
Units: units
Level 2 retail in-process.
- (016) $CPR3 = \text{INTEG} (PSR2 - PSR3, 1000)$
Units: units
Level 3 retail in-process.
- (017) $DCD = 2$
Units: Week
Delay in Clerical Order Placing at Distributor

- (018) $DCF = 1$
 Units: Week
 Delay in Clerical Order Placing at Factory
- (019) $DCR = 3$
 Units: Week
 Delay in Clerical Order Placing at Retailer
- (020) $DFD = DHD + DUD * (IDD / "IAD, Inventory")$
 Units: Week
 Delay in filling orders at Distributor
- (021) $DFH = DHF + DUH * (IDH / "IAF, Inventory")$
 Units: Week
 Delay in filling orders at Distributor
- (022) $DFR = DHR + DUR * (IDR / "IAR, Inventory")$
 Units: Week
 Delay in filling orders at Retail
- (023) $DHD = 1$
 Units: Week
 Delay in handling time at Distributor
- (024) $DHF = 1$
 Units: Week
 Delay in handling time at Factory
- (025) $DHR = 1$
 Units: Week
 Delay in handling time at Retail
- (026) $DID = 4$
 Units: Week
 Delay in Inventory (and Pipeline) adjustment at Distributor

- (027) DIF= 4
Units: Week
Delay in Inventory (and Pipeline) adjustment at Factory
- (028) DIR= 4
Units: Week
Delay in Inventory (and Pipeline) adjustment at Retail
- (029) DMD= 0.5
Units: Week
Delay in order mailing from Distributor
- (030) DMR= 0.5
Units: Week
Delay in order mailing from retailer
- (031) DPF= 6
Units: Week
Delay in order mailing from Factory
- (032) DRD= 8
Units: Week
Delay in smoothing requisitions at Distributor, the smoothing time constant
- (033) DRF= 8
Units: Week
Delay in smoothing requisitions at Factory, the smoothing time constant
- (034) DRR= 8
Units: Week
Delay in smoothing requisitions at Retail, the smoothing time constant
- (035) DTD= 2
Units: Week
Delay in Transportation of goods to Distributor

- (036) DTR= 1
 Units: Week
 Delay in Transportation of goods to Retail
- (037) DUD= 0.6
 Units: Week
 Delay in Unfilled Orders at Distributor from out-of-stock items at normal inventory
- (038) DUF= 1
 Units: Week
 Delay in Unfilled Orders at Factory from out-of-stock items at normal inventory
- (039) DUR= 0.8
 Units: Week
 Delay in Unfilled Orders at Retail from out-of-stock items at normal inventory
- (040) FINAL TIME = 120
 Units: Week
 The final time for the simulation.
- (041) "IAD, Inventory"= INTEG (SRD3-SSD, 6000)
 Units: units
 Actual Inventory at Distributor
- (042) "IAF, Inventory"= INTEG (SRF3-SSF, 4000)
 Units: units
 Actual Inventory at Factory
- (043) "IAR, Inventory"= INTEG (SRR3-"SSR, Shipments", 8000)
 Units: units
 Actual Inventory at Retail
- (044) IDD= AID*RSD
 Units: units
 Inventory Desired at Distributor

- (045) $IDF = AIF + RSF$
 Units: units
 Inventory Desired at Factory
- (046) $IDR = AIR + RSR$
 Units: units
 Inventory Desired at Retail
- (047) $INITIAL\ TIME = 0.001$
 Units: Week
 The initial time for the simulation.
- (048) Input Modification=
 $1 + STEP(\text{Step Height}, \text{Step Time}) + STEP(\text{Step Height2}, \text{Step Time2}) +$
 $(\text{Pulse Quantity} / \text{TIME STEP}) * PULSE(\text{Pulse Time}, \text{TIME STEP}) +$
 $RAMP(\text{Ramp Slope}, \text{Ramp Start Time}, \text{Ramp End Time}) +$
 $\text{Sine Amplitude} * SIN(2 * 3.14159 * \text{Time} / \text{Sine Period}) +$
 $STEP(1, \text{Noise Start Time}) * \text{Noise Amplitude} * (\text{RANDOM } 0\ 1() - 0.5)$
 Units: dimensionless
 This is a tool which allows quick access to a variety of input patterns.
- (049) $LAD = CPD + PMD + "UOF, Unfilled Orders" + MTD$
 Units: units
 Pipeline Orders Actually in Transit to Retail
- (050) $LAF = CPF + OPF$
 Units: units
 Pipeline Orders Actually in Transit through Factory
- (051) $LAR = CPR + PMR + "UOD, Unfilled Orders" + MTR$
 Units: units
 Pipeline Orders Actually in Transit to Retail
- (052) $LDD = RSD * (DCD + DMD + DFF + DTD)$
 Units: units
 Pipeline Orders desired (necessary) in transit to distributor

- (053) $LDF = RSI * (DCI + DPF)$
 Units: units
 Pipeline Orders desired (necessary) in transit through factory
- (054) $LDR = RSR * (DCR + DMR + DFD + DTR)$
 Units: units
 Pipeline Orders desired (or necessary) to supply Retail
- (055) $MDF = IF THEN ELSE(ALI < MWF, ALF, MVI)$
 Units: units/Week
 Manufacturing rate decision at factory
- (056) $MOF1 = CPF1 / (DCF / 3)$
 Units: units/Week
 Manufacturing order rate into factory Level 1
- (057) $MOF2 = CPF2 / (DCF / 3)$
 Units: units/Week
 Manufacturing order rate into factory Level 2
- (058) $MOF3 = CPF3 / (DCF / 3)$
 Units: units/Week
 Manufacturing order rate into factory Level 3
- (059) $MTD = MTD1 + MTD2 + MTD3$
 Units: units
 Material in transit to distributor
- (060) $MTD1 = INTEG (SRD - SRD1, 667)$
 Units: units
 Level 1 material to distributor
- (061) $MTD2 = INTEG (SRD1 - SRD2, 667)$
 Units: units
 Level 2 material to distributor

- (062) $MTD3 = INTEG (SRD2 - SRD3, 667)$
 Units: units
 Level 3 material to distributor
- (063) $MTR = MTR1 + MTR2 + MTR3$
 Units: units
 Material in transit to retail
- (064) $MTR1 = INTEG (+SSID - SRR1, 333)$
 Units: units
 Level 1 material to retail
- (065) $MTR2 = INTEG (SRR1 - SRR2, 333)$
 Units: units
 Level 2 material to retail
- (066) $MTR3 = INTEG (SRR2 - SRR3, 333)$
 Units: units
 Level 3 material to retail
- (067) $MWF = RRF3 + (((IDF - "IAF, Inventory") + (LDF - LAF) + ("UOF, Unfilled Orders" - UNF)) / DIF)$
 Units: units/Week
 Manufacturing rate wanted at factory
- (068) $NID = "IAD, Inventory" / TIME STEP$
 Units: units/Week
 Negative Inventory limit rate at Distributor
- (069) $NIF = "IAF, Inventory" / TIME STEP$
 Units: units/Week
 Negative Inventory limit rate at Factory
- (070) $NIR = "IAR, Inventory" / TIME STEP$
 Units: units/Week
 Negative Inventory limit rate at Retail

- (071) Noise Amplitude= 0
 Units: dimensionless
 Magnitude of the random input, as a **fraction** of the base value of the input.
- (072) Noise Start Time= 1
 Units: Week
 Start time for the random input.
- (073) OPF= OPF1+OPF2+OPF3
 Units: units
 Orders in production at factory
- (074) OPF1= INTEG (MOF3-SRF1, 2000)
 Units: units
 Level 1 production at factory
- (075) OPF2= INTEG (SRF1-SRF2, 2000)
 Units: units
 Level 2 production at factory
- (076) OPF3= INTEG (SRF2-SRF3, 2000)
 Units: units
 Level 3 production at factory
- (077) Order Introduction= 1000
 Units: units/Week
 Constant introduction of orders, **will be modified** by "Input Modification" variable
- (078) Orders= Input Modification*Order Introduction
 Units: units/Week
 Rate at which orders are introduced into the system
- (079) Outs D= SSD
 Units: units/Week
 Same variable as SSD

- (080) Outs F= SSF
 Units: units/Week
 Same variable as SSF
- (081) Outs R= "SSR, Shipments"
 Units: units/Week
 Same variable as SSR
- (082) $PDD = RRD3 + (((IDD - "IAD, Inventory") + (LDD - LAD) + ("UOD, Unfilled Orders" - \dot{U}ND)) / DID)$
 Units: units/Week
 Purchase rate decision at distributor
- (083) $PDR = "RRR, Orders" + (((IDR - "IAR, Inventory") + (LDR - LAR) + ("UOR, Unfilled Orders" - UNR)) / DIR)$
 Units: units/Week
 Purchase rate decision at retailer
- (084) $PMD = PMD1 + PMD2 + PMD3$
 Units: units
 Purchase orders in mail from distributor
- (085) $PMD1 = INTEG (PSD3 - RRF1, 167)$
 Units: units
 Level 1 mail from distributor
- (086) $PMD2 = INTEG (RRF1 - RRF2, 167)$
 Units: units
 Level 2 mail from distributor
- (087) $PMD3 = INTEG (RRF2 - RRF3, 167)$
 Units: units
 Level 3 mail from distributor
- (088) $PMR = PMR1 + PMR2 + PMR3$
 Units: units
 Purchase orders in mail from retailer

- (089) $PMR1 = INTEG (PSR3-RRD1, 167)$
Units: units
Level 1 mail from retailer
- (090) $PMR2 = INTEG (RRD1-RRD2, 167)$
Units: units
Level 2 mail from retailer
- (091) $PMR3 = INTEG (RRD2-RRD3, 167)$
Units: units
Level 3 mail from retailer
- (092) $PSD1 = CPD1 / (DCD / 3)$
Units: units/Week
Level 1 purchase orders sent from distributor
- (093) $PSD2 = CPD2 / (DCD / 3)$
Units: units/Week
Level 2 purchase orders sent from distributor
- (094) $PSD3 = CPD3 / (DCD / 3)$
Units: units/Week
Level 3 purchase orders sent from distributor
- (095) $PSR1 = CPR1 / (DCR / 3)$
Units: units/Week
Level 1 purchase orders sent from retailer
- (096) $PSR2 = CPR2 / (DCR / 3)$
Units: units/Week
Level 2 purchase orders sent from retailer
- (097) $PSR3 = CPR3 / (DCR / 3)$
Units: units/Week
Level 3 purchase orders sent from retailer

- (098) Pulse Quantity= 0
 Units: dimensionless*Week
 The quantity to be added to the delay in the pulse input, as a fraction of the base value of Input. For example, to pulse in a quantity equal to 50% of the current value of input, set to .50.
- (099) Pulse Time= 50
 Units: Week
 Time at which the pulse in Input occurs.
- (100) Ramp End Time= 1e+009
 Units: Week
 End time for the ramp input.
- (101) Ramp Slope= 0
 Units: 1/Week
 Slope of the ramp input, as a fraction of the base value.
- (102) Ramp Start Time= 10
 Units: Week
 Start time for the ramp input.
- (103) $RRD1 = PMR1 / (DMR / 3)$
 Units: units/Week
 Level 1 reqs received at distributor
- (104) $RRD2 = PMR2 / (DMR / 3)$
 Units: units/Week
 Level 2 reqs received at distributor
- (105) $RRD3 = PMR3 / (DMR / 3)$
 Units: units/Week
 Level 3 reqs received at distributor
- (106) $RRF1 = PMD1 / (DMD / 3)$
 Units: units/Week
 Level 1 reqs received at factory

- (107) $RRF2 = PMD2 / (DMD / 3)$
 Units: units/Week
 Level 2 reqs received at factory
- (108) $RRF3 = PMD3 / (DMD / 3)$
 Units: units/Week
 Level 3 reqs received at factory
- (109) "RRR, Orders" = Order Introduction * Input Modification
 Units: units/Week
 Modified order introduction rate
- (110) $RSD = SMOOTH(RRD3, DRD)$
 Units: units/Week
 Reqs smoothed at distributor
- (111) $RSF = SMOOTH(RRF3, DRI)$
 Units: units/Week
 Reqs smoothed at factory
- (112) $RSR = SMOOTH("RRR, Orders", DRR)$
 Units: units/Week
 Reqs smoothed at retailer
- (113) SAVEPER = TIME STEP
 Units: Week
 The frequency with which output is stored.
- (114) Sine Amplitude = 0.1
 Units: dimensionless
 Amplitude of the sine wave in Input, as a fraction of the base value.
- (115) Sine Period = 52
 Units: Week
 Periodicity of the sine wave in Input.

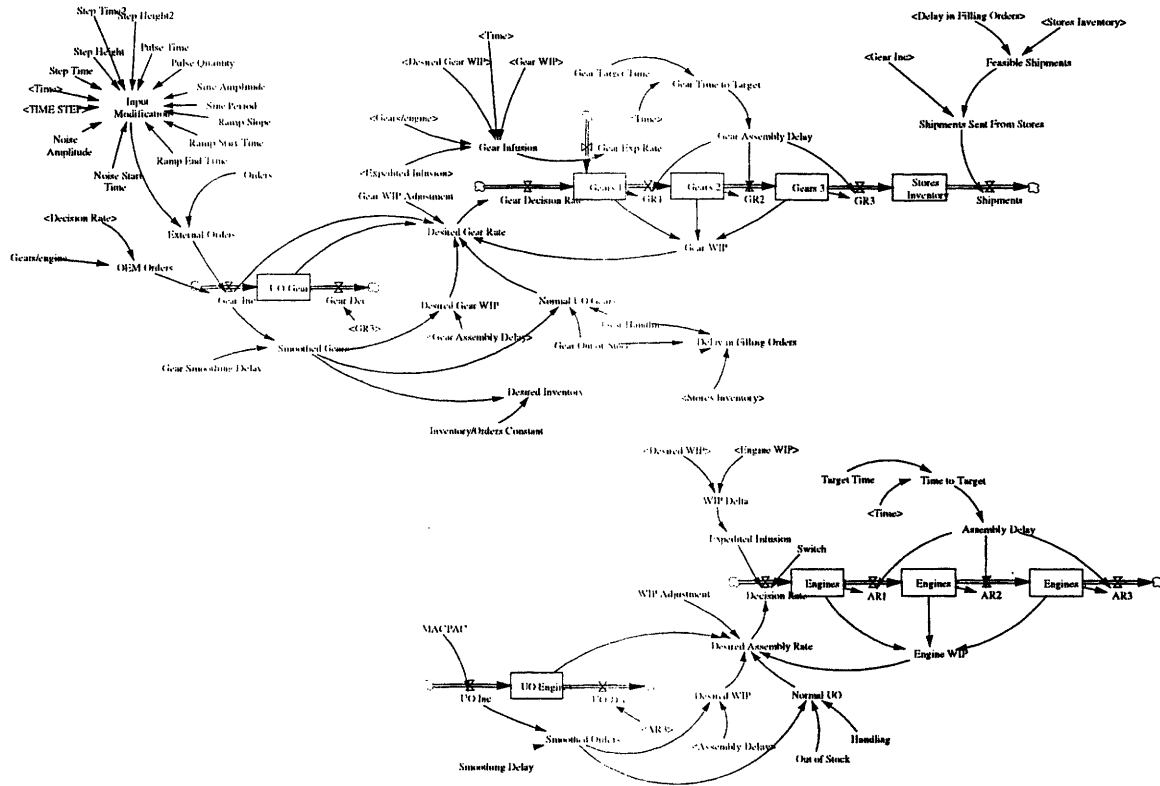
- (116) $SRD1 = MTD1 / (DTD / 3)$
Units: units/Week
Level 1 shipments received at distributor
- (117) $SRD2 = MTD2 / (DTD / 3)$
Units: units/Week
Level 2 shipments received at distributor
- (118) $SRD3 = MTD3 / (DTD / 3)$
Units: units/Week
Level 3 shipments received at distributor
- (119) $SRF1 = OPF1 / (DPF / 3)$
Units: units/Week
Level 1 shipments received at factory
- (120) $SRF2 = OPF2 / (DPF / 3)$
Units: units/Week
Level 2 shipments received at factory
- (121) $SRF3 = OPF3 / (DPF / 3)$
Units: units/Week
Level 3 shipments received at factory
- (122) $SRR1 = MTR1 / (DTR / 3)$
Units: units/Week
Level 1 shipments received at retailer
- (123) $SRR2 = MTR2 / (DTR / 3)$
Units: units/Week
Level 2 shipments received at retailer
- (124) $SRR3 = MTR3 / (DTR / 3)$
Units: units/Week
Level 3 shipments received at retailer

- (125) $SSD = \text{IF THEN ELSE}(NID < STD, NID, STD)$
 Units: units/Week
 Shipments sent from distributor
- (126) $SSF = \text{IF THEN ELSE}(NIF < STF, NIF, STF)$
 Units: units/Week
 Shipments sent from factory
- (127) "SSR, Shipments" = $\text{IF THEN ELSE}(NIR < STR, NIR, STR)$
 Units: units/Week
 Shipments sent from Retail
- (128) $STD = \text{"UOD, Unfilled Orders"}/DFD$
 Units: units/Week
 Shipping Rate to be tried at Distributor
- (129) Step Height = 0
 Units: dimensionless
 Height of the step input, as a fraction of the base value.
- (130) Step Height2 = 0
 Units: dimensionless
- (131) Step Time = 1
 Units: Week
 Time for the step input.
- (132) Step Time2 = 48
 Units: Week
- (133) $STF = \text{"UOF, Unfilled Orders"}/DFF$
 Units: units/Week
 Shipping Rate to be tried at Factory
- (134) $STR = \text{"UOR, Unfilled Orders"}/DFR$
 Units: units/Week
 Shipping Rate to be tried at Retail

- (135) $\text{TIME STEP} = 0.0625$
Units: Week
- (136) $\text{UND} = \text{RSD} * (\text{DHD} + \text{DUD})$
Units: units
Unfilled Normal level of orders at **Distributor**
- (137) $\text{UNF} = \text{RSF} * (\text{DHF} + \text{DUF})$
Units: units
Unfilled Normal level of orders at **Factory**
- (138) $\text{UNR} = \text{RSR} * (\text{DHR} + \text{DUR})$
Units: units
Unfilled Normal level of orders at **Retail**
- (139) "UOD, Unfilled Orders" = INTEG (RRD3-Outs D, 1600)
Units: units
Stock of Unfilled Orders at **Distributor**
- (140) "UOF, Unfilled Orders" = INTEG (RRF3-Outs F, 2000)
Units: units
Stock of Unfilled Orders at **Factory**
- (141) "UOR, Unfilled Orders" = INTEG (+ "RRR, Orders" - Outs R, 1400)
Units: units
Stock of Unfilled Orders at **Retail**

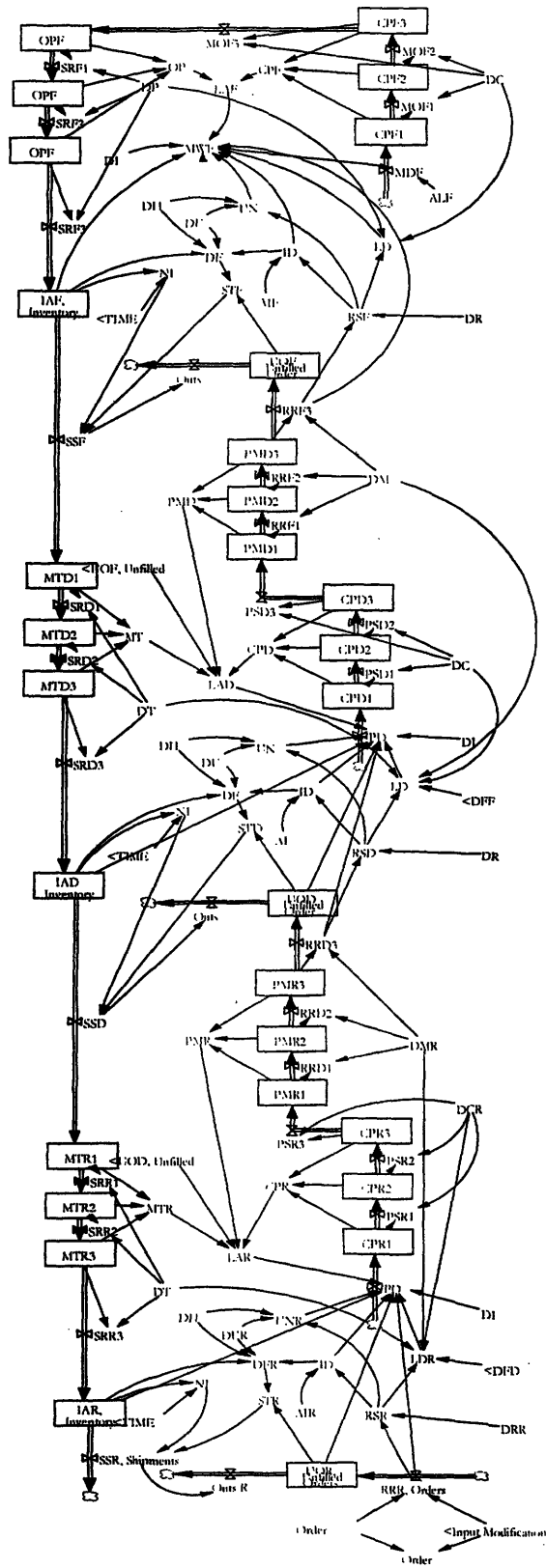
Appendix B

Manufacturing Model

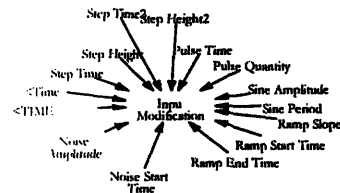


This figure is the actual model developed with Vensim simulation software. Graphically, it represents a system of equations which, when repeatedly run through many cycles, yields the systems results referred to in this work.

Industrial Dynamics Model



This figure is the model developed by Forrester in Industrial Dynamics. Further study is directed to that work for a more thorough discussion of its development.





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