Managing Product Variety in Automobile Assembly: The Importance of the Sequencing Point

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In recent years, globalization of markets and increased consumer sophistication have led to an increase in the variety of products that customers demand and a consequent increase in the number of variants of any given product line that a manufacturer must supply. At the same time, an increasing number of companies have pushed the task of accommodating product variety up the supply chain to suppliers. This makes it increasingly difficult to understand where and how variety is accommodated. Based on our study of the automotive industry, we introduce the concept of a sequencing point, which we define as where component variants are placed in the sequence that final assembly requires. We discuss the implications of alternative sequencing-point-location strategy on management of product variety. For each strategy, we discuss associated trade-offs and provide short case studies.

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Internationalization of markets and increased consumer sophistication have led to an increase in the variety of products demanded. The Dell example has clearly demonstrated that it is possible to deliver a high degree of customization at low cost. Together with the Internet, which provides the customer interface, this has put the pressure on companies to respond to the increased variety that customers demand (Swaminathan and Tayur 2003, Swaminathan and Lee 2003).

Analyzing the automobile industry, MacDuffie et al. (1996) argue that companies can no longer stay profitable by producing large volumes of a standardized product. Clark and Fujimoto (1991) state that changes in energy prices and trade structures, internationalization of markets, and increased consumer sophistication are sources for increasing product variety. The average annual sales per passenger-car model dropped by 34 percent in the United States from 1973 to 1989, while model count increased from 84 to 142 during this period (Womack et al. 1990). Abernathy and Wayne (1974) warn manufacturers that consistently choosing a "focus" strategy will result in a reduced ability to respond to market changes.

There are different ways to address this increase in variety. One popular approach is to shift part of the responsibility of accommodating product variety upstream to suppliers. For example, Delphi Automotive Systems delivers the entire driver's cockpit to DaimlerChrysler's Tuscalousa plant in Alabama. The automotive industry pioneered the earliest form of such a strategy, often called just-in-time (JIT) delivery, where parts were delivered at the right time to the manufacturing facility. The main benefit of such an approach was a reduction in parts inventory at the manufacturing facility. For example, recently it has been cited often that Dell mandates frequent JIT deliveries from its major suppliers, forcing them to set up dedicated stock-holding centers near Dell's facility. Academic researchers (Inman and Bulfin 1991, White et al. 1999, Drexl and Kimms 2001) have studied JIT systems. These studies have addressed implementation of JIT principles at the plant, their overall effect on manufacturing performance, and the optimization of product scheduling. The next advancement in terms of manufacturer-supplier shipment coordination that the auto industry adopted relates to JIT sequenced delivery. This takes JIT to the next level

wherein the delivery of parts is synchronized with the production schedule of the manufacturer. Therefore, when a manufacturer such as General Motors is assembling a blue car on the line, the corresponding parts such as blue seats and blue fenders are on the feeding-parts line. Such a sequenced JIT system leads to lower inventory (due to JIT delivery) and greater efficiency (in manufacturing time and overhead) because it minimizes the additional work related to sorting parts and matching them to the production schedule. Although there is abundant literature on sequencing and scheduling at a machine or plant level (Graves 1981, Baker 1995), the concept of sequenced delivery across supply chain partners has been explored less often.

Our aim in this paper is to introduce alternative strategies that enable JIT sequenced delivery, and to discuss the role of the location where the components are sequenced within stages of a supply chain. For example, Johnson Control delivers a variety of seats in the correct sequence to Toyota's Georgetown plant. In an alternative arrangement, Prince, a subsidiary of Johnson Control, delivers door panels to DaimlerChrysler's Sterling Heights Assembly Plant (SHAP). Prince manufactures the door panels in Holland, Michigan and delivers them to an intermediate sequencing center, which is fairly close to SHAP. It keeps approximately two days of inventory and brings the door panels into the required sequence before delivering them to SHAP every hour. In another arrangement, the truck line at New United Motor Manufacturing Inc. (NUMMI) in Fremont, California, which General Motors and Toyota jointly own, receives 47 different wire harnesses from one of its suppliers for the various configurations of its trucks. At a staging area within the NUMMI plant, the wire harnesses are then put in the correct sequence to match the final build sequence of the vehicles. In yet another stage of the process, the assembly-line operator at workstation "brake build" on NUMMI's final truck assembly line selects various parts from a large rack displaying seven different part numbers. Based on the brake-pedal code, which is displayed on a specification sheet (manifest) attached to the hood of each vehicle, the operator picks two, three, or four parts according to the codes listed on the manifest.

One result of these possible arrangements is that it is no longer valid to talk exclusively about the level of variety that a final assembly plant accommodates. Rather, one has to look at the whole supply chain, starting at the lowest tier of suppliers and continuing up to final assembly of a product, to get valid pictures of how the assembly plant accommodates variety. At the same time, *where* variety is accommodated has important implications on flexibility and overall cost effectiveness. In this context, we introduce the concept of a *sequencing point*. The objective of this paper is to classify and categorize the different arrangements and to discuss the associated trade-offs.

There is an abundance of operations-management literature that studies models for managing product variety. Lee and Tang (1997) analyze the impact of using standardization, modular design, and process redesign to delay the point of differentiation (PoD) for a product. Swaminathan and Tayur (1998) introduce the concept of vanilla boxes—semifinished products that can be assembled into different end products—to reduce response time when product variety increases. Jordan and Graves (1995) address the issue of how much flexibility is desirable for automobile manufacturing plants and show that limited flexibility can yield almost the same benefits as total flexibility. In comprehensive reviews, Swaminathan and Lee (2003) and Venkatesh and Swaminathan (2003) provide an exhaustive review of models and applications related to design for postponement.

A wide range of empirical studies addresses different aspects of how companies deal with demand variety. Fisher et al. (1995) compare mass production methods to craft and lean production. Consistent with the findings of MacDuffie et al. (1996), they find that lean production has enabled manufacturers to handle greater variety. Ulrich et al. (1998) study the bicycle industry and differentiate between strategic decisions—those dealing with the fundamental structure of the variety delivery system—and tactical decisions. They define a *decouple point* as the point in the supply chain where a specific customer's name is associated with a specific product. Upton (1997) looks at process range in the paper industry and uses paper weight as a unidimensional, complexity measure for process range. Swaminathan (2001) discusses how companies can deal with increasing product variety using standardization of product, parts,

procurement, and processes to help mitigate the negative impact of product variety on a firm's operations.

MacDuffie et al. (1996) introduce four complexity measures to classify and quantify manufacturing-process complexity in the automobile industry. Using this classification, they study the impact of product variety on manufacturing performance using a subset of the data from the International Motor Vehicle Program (IMVP) study of 70 assembly plants.

The focus of the work mentioned above has been the management of variety at one stage in the supply chain. The supply chain acts as a filter and determines how much complexity is imposed on different stages of the manufacturing system. Because there are limits to how much variety can be handled at any particular stage, the capability of a supply chain to reduce the impact of variety is what ultimately drives how much variety that system can handle. We will discuss the benefits of considering the entire supply chain by introducing the sequencing-point concept in the following sections.

The Sequence Point—Definition and Possible Locations

Before we can discuss our sequence-point concept, we need to define the *parts pipeline* (PP) and *parts repertory*. We define a PP as a sequence of parts or components that are in the same sequence as the vehicles in which they will be installed. The length of the PP can be given as a number of parts or in minutes of production supported.

A sequencing process, which consists of "reading" the next specified item, selecting the specified item from a repertory, and prepending the item to the current contents of the PP, feeds the PP. At final assembly, the actual build sequence determines the item to be prepended. A parts repertory, which we define as a stock of alternate items, must exist to permit selection of the correct item if the items are not produced on a mixed-model assembly line. Figure 1 illustrates the concept.

Based on this, we now define the sequence point as the beginning of the PP; the objective of the PP is the installation of the component by the assembly workstation.

The sequencing process—prepending an item to the current contents of the PP—can either be inherent in
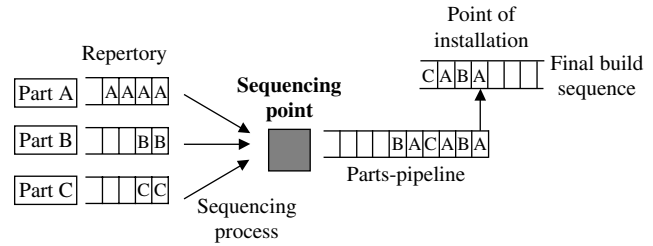

Figure 1: The sequencing process consists of "reading" the next specified item, selecting the specified item from a parts repertory, and prepending the item to the current contents of the PP.

the supplier's production process or it can take place at a later point. A mixed-model assembly line without a physical, unsequenced parts supply is an example of the first case. In the second case, items are prepended to the PP from a sequenced parts stock, which is kept at the supplier, the sequencing center, the final assembly area, or line-side. A PP cannot be longer than the upstream sequence information that the final assembly provides; this determines the *time window to installation.* This is a crucial constraint for automotive assembly because frequently there are changes to the build sequence after the paint operations; this limits the time available until a given component is installed in the vehicle.

The sequencing process can take place anywhere between component manufacturing at the supplier plant and the final assembly-line installation of the component. The ideal value of the PP length, or equivalently, the location of the sequence point for a given part, is subject to various trade-offs, which we will discuss in subsequent sections.

Note that knowing the PoD as generally discussed under delayed differentiation (Swaminathan and Lee 2003) is not the same as the sequence point we introduce here. The PoD gives an upper bound on the location of the sequence point, e.g., how far downstream the sequence point can be located, but does not specify its location. The sequence point for a given PoD can be located anywhere between the lowest-tier supplier and the PoD. Another common term used in literature is the *push-pull boundary*. This refers to the point where production switches from being a "make-to-stock" to a "make-to-order" environment. Traditionally, the PoD could be considered to represent the push-pull boundary because a firm could benefit from

mass production up to the point of differentiation. Therefore, the push-pull boundary in a sense defines the boundaries for the location of the sequence point but need not be the same as the sequence point.

Before discussing the consequences and trade-offs of a particular sequence-point location, we must first understand how product variety affects the manufacturing process. Product variety requires the line operator to deviate from the standard operating sequence (SOS), which we define as the sequence of work elements for the base model at a given workstation.

Assembling different models may require substitution, elimination, or addition of work elements to the SOS, and may possibly result in variations in cycle times for different models. On this level, it is not necessary to differentiate between intermodel and intramodel varieties because we are merely concerned with the effects of variety. It makes no difference to a line operator if he or she installs a component on a Camry or a Sienna minivan if the SOS remains unchanged. In the extreme case of assembling two models on the same line, each of which requires a completely different SOS at some workstation, we can still use the above definition.

For suppliers and assembly conveyance (note that we use the term "assembly conveyance" to denote in-plant handling of material and components including unpacking, sequencing, and delivery to the assembly line), product variety introduces complexity in the form of sequencing components, or handling and delivering additional variants of a given component. We are now ready to discuss the different possible locations of the sequence point. As we illustrate in our short examples above, the sequence point can be located inside or outside of the final manufacturing plant. If the sequence point is located outside, then sequencing can take place at the source (within the supplier plant) or at an intermediate sequencing center. If located within the final manufacturing plant, sequencing can be achieved by assembly conveyance before the product is delivered to the line, or by the line operator, in which case we have nonsequenced delivery of components to the line. For each location, we discuss the setting, give a short case example, and analyze associated costs and benefits.

Sequence Point at Supplier

If the total lead time, which comprises production, sequencing, and delivery lead times, for a given component, is shorter than the time-to-installation after the sequence information has been shared, the component supplier can perform the sequencing. This is also the only setup where the supplier can operate a mixed-model line in a JIT fashion, matching the sequence at final assembly and delivering directly to the final assembly line. Co-location of supplier and final-assembly operations is helpful in further reducing in-process inventory; however, it is not strictly necessary.

Volkswagen's Resende truck plant provides an interesting case example that combines modularized component delivery with sequenced delivery and co-location of suppliers and final-assembly operations. The Resende plant represents, at this time, the highest degree of supplier integration. In this "consorcio modular" ("modular consortium" in Portuguese), Volkswagen has gone beyond traditional outsourcing strategies and invited suppliers to assemble their component modules within its plant, where they not only assemble their own components and parts, but also actually install their modules into the vehicles.

A Brazilian supplier first welds the cabins for the trucks. The VDO Group of Germany installs seats, interior trim, and instrument panels. Cummins Engine prepares engines for assembly. Iochpe-Maxion, a Brazilian company, adds the brakes, fuel tank, and electrical and steering components after shipping the skeletal frame to the plant. An overhead conveyor takes the chassis to Rockwell-Braseixos, which adds the axle and suspension. Remon Resende Montagens adds the wheels and tires. Workers install the power train and cab after the chassis is moved to the main assembly line. Finally, at the end of the assembly line, Volkswagen's inspectors test the trucks.

The advantages of having the sequence point located at the supplier coincide with most of the JIT advantages. These include a reduction in total system inventory because the pace of production at the supplier will generally be close to the pace of production at the final assembly plant to allow sequenced delivery. The maximum amount of work-in-process inventory is limited by the information lead time—the time available between the communication of the

actual build sequence to the supplier and the installation of the part on the final assembly line. We discuss information lead time in more detail in the *Lead Time Constraint* section below. As demand variety increases, sequenced delivery becomes increasingly important because without supplier-sequenced delivery, the final manufacturers must keep safety stock for each variant.

Placing components in sequence right at the source also eliminates double handling, i.e., having to place them in the correct sequence later. This is particularly true for mixed-model assembly lines at component suppliers.

The downside of sequenced production at the supplier and the associated reduction of inventory at the final manufacturer is reduced flexibility in dealing with defects and changes in the build sequence. A defective part that is delivered to the final assembly plant cannot be easily replaced with an identical part from inventory. Rather, a replacement part must be brought in from the component supplier. Such tight coupling of the manufacturer and supplier production schedules makes sequencing and scheduling decisions at both the manufacturer and the supplier extremely critical. In addition, if the time window to installation is short, it may not be feasible to use full truckloads for component deliveries to the final manufacturing plant. However, this is a problem that companies switching to JIT manufacturing and delivery have encountered previously. "Milk-run routes," where components from multiple suppliers are pooled into one truck to avoid increased shipping costs, have largely remedied this problem. (Note that milk-run routes were introduced when supplier delivery lot sizes were reduced under the Toyota Production System (TPS) to avoid near-empty trucks.)

Intermediate Sequence Point
If total lead time, which includes production, sequencing, and delivery lead time, is longer than the time to installation after the sequence information has been communicated, JIT-based manufacturing in the correct sequence is not feasible. Consequently, components must be produced to stock, and shipped in larger quantities to the final assembly plant or to a sequencing center (SC) that is located closer to the final assembly operations. Such an intermediate SC

will typically be located near the final assembly line, with parts delivered in batches from the supplier plant to the SC, which receives the actual production sequence from the final assembly plant, and then makes frequent deliveries of these components after bringing them into the required sequence.

As we describe above, we use deliveries of door panels to DaimlerChrysler's SHAP facility to illustrate the concept of an intermediate sequencing center—Prince in Holland, Michigan manufactures door panels and then delivers them to a sequencing center, which sequences the door panels and delivers them to SHAP.

The time window to installation for door panels is too short to allow sequenced delivery directly from Prince. However, variety is too high to display all variants line-side and allow selection by the operator. Therefore, given its setup at the time of the study, an intermediate sequencing center is DaimlerChrysler's only choice—other than sequencing the door panels within its plant before delivering them to the final assembly line.

SHAP gives Prince, the door-panel supplier, a production plan specifying quantities but not a specific sequence for a three-week time horizon to enable scheduling production and securing raw materials and components.

After the car bodies leave the paint area, where considerable changes to the sequence may be necessary because of paint defects, SHAP transmits the actual build sequence to Prince. Prince then assembles the different variants of door panels in batches and ships them to the sequencing center, which keeps about two days of inventory. Prince then brings in door panels in the correct sequence according to the information from SHAP and delivers them four times per day, on average. While this example has shown that an intermediate sequencing center may sometimes be the only choice, such a center has several disadvantages. These include double handling of components, with the resulting additional inventory that the system must keep.

Introduction of an intermediate sequencing center allows the final manufacturer to operate as if the supplier were manufacturing and delivering components in sequence and in a JIT manner, while still offering a higher degree of flexibility to deal with defects or

changes to the build sequence than source sequencing at the supplier's manufacturing site would allow. Therefore, the final manufacturer can use this arrangement as a test bed to see if process stability at its site is sufficient to allow for sequenced JIT delivery. Alternatively, this setup can also serve as a transition when the component supplier is not yet capable of running a mixed-model assembly line, but the final manufacturing plant requires sequenced delivery. While rarely cited as a reason, the lower, nonunion wages at an outside sequencing center can be a significant factor. Clearly, in this setup, the requirement for coordinated sequence in production schedules between the manufacturer and the supplier is lower when compared to the previous case. Yet, they are not independent of each other.

Sequencing Point Within the Assembly Supply

In this situation, the supplier delivers the different variants of a component to the final manufacturer, and variants are then sequenced within the final assembly plant before being delivered to the line.

We use the delivery of cowl-wire harnesses at NUMMI to illustrate the concept of locating the sequence point within the final manufacturing plant. At NUMMI's truck line, 47 alternate cowl-wire harnesses may be installed in NUMMI's trucks. The cowl-wire harness installed in a particular truck depends on several truck options or factors, e.g., destination, type of transmission, optional cruise control, two- or four-wheel drive, optional anti-lock brakes, power options, and several others. Because of the large number of variants, it would not be possible to display all variants line-side, nor would it be feasible to require the operator to select from 47 possible harnesses. Instead, assembly conveyance sequences the harnesses and delivers them to the assembly line in sequenced batches of 15 harnesses.

Sequencing Point at the Assembly-Line Operator Level

In this final setup, component sequencing occurs at the assembly line. The operator receives the unsequenced parts and does the sequencing. The length of the parts pipeline is zero because variants of components are displayed line-side; the assembly-line worker is responsible for selecting and installing the correct variant. The worker either installs components on selected vehicles equipped with that option, e.g., additional brackets on brake pedals for selected models equipped with anti-lock brakes, or installs variants of a component, displayed line-side, on every vehicle. In addition to selecting the correct component, the operator also faces fluctuations, which can be significant, in the time required to complete a work cycle.

This arrangement makes sense if the component structure is fairly modular, allowing the operator to simply select different modules for the subassembly before installing the component into the vehicle. If, on the other hand, the component product structure is more integral, it is usually not feasible to accommodate all variants line-side. Seats and instrument panels are examples of a more complicated product structure.

We use the installation of brake and clutch pedals at NUMMI's final assembly line to illustrate sequencing at the line-operator level. The assembly-line operator at workstation "brake build" on NUMMI's final truck-assembly line is responsible for selecting the correct brake components. He or she must select various parts from a large rack that displays seven different part numbers. Based on the brake-pedal code, which is displayed on a specification sheet attached to each vehicle, the operator picks two, three, or four parts according to the codes listed on the manifest hanging from the hood of the car. The operator may encounter 24 different instruction sets for any particular truck. Cycle time can range from 71 seconds for the simplest variant to 110 seconds for the most complicated variant. Given the tak time of 89 seconds at the time of our study, this clearly places restrictions on feasible build sequences to ensure that the operator does not encounter too many consecutive high-work-content models.

The main disadvantage of accommodating demand variety at the level of the assembly line is that the operator has the additional task of selecting the correct component. Surely, the probability of selecting a wrong part increases with the number of variants. Furthermore, displaying more variants requires more line space and more inventory kept line-side. On the other hand, this arrangement provides the highest level of flexibility to deal with defective components because it allows replacing a faulty part with a new

Sequencing point	Impact on line operator	Impact on assembly-conveyance/ sequencing center	Impact on supplier
Supplier	Verify matching component	Deliver components	"Full blown" JIT production and delivery
Sequencing center/ assembly conveyance	Verify matching component	Sequence components and deliver small batches	Batch production and delivery
Operator	Select correct component(s) (subassemble)	Deliver components	Batch production and delivery

Table 1: The data summarizes the impact of different locations of the sequencing point on line operators, an intermediate sequencing center or assembly conveyance, and the component supplier.

Figure 2: This diagram of tak time and cycle time at the "brake-build" workstation of the NUMMI plant illustrates that weighted, average cycle time at a given work station must be less than the tak time of the production line.

part from line-side inventory. In addition, changes to the build sequence have no impact because the line operator does not receive the information about which options to install until he or she starts the work cycle for the vehicle.

Table 1 shows the impact of different locations of the sequencing point.

Key Drivers for the Location of the Sequencing Point

To fully reap the benefits of lean production in terms of cost and quality, suppliers would produce parts in the same sequence that the final manufacturer requires them, and would deliver them directly to the final assembly line at the time needed without entailing any intermediate stock. In general, it is possible to achieve this using a mixed-model assembly line at the supplier or, if respective volumes are high enough for each variant, multiple lines with adjusted tak times.

However, this ideal setup is rarely achieved. In the following sections, we discuss the factors that influence the ideal strategy and location of the sequencing point. We start with a discussion of product variety and structure and then follow with a discussion of lead-time constraints.

Product Variety and Structure

The number of variants available for a given component restricts the feasible locations for the sequencing point in multiple ways. The restriction becomes most apparent when the sequencing point is located at the
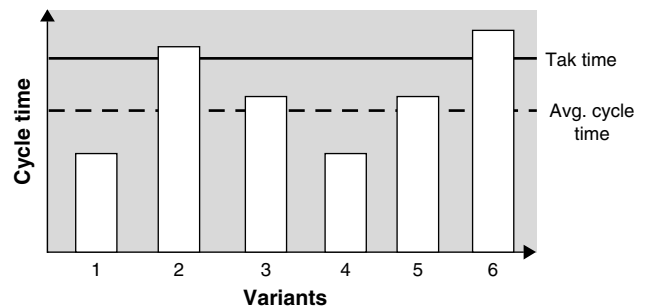
final assembly. Variants required must be displayed at or near the workstation where they will be installed (space feasibility). The operator must be able to handle the selection complexity, e.g., decoding the specifications sheet and remembering the required part picks (selection feasibility), and must install the different variants within the time available (cycle-time feasibility), which is influenced by the product structure.

Keeping sufficient inventory for a large number of variants can require too much space near the final assembly line. This can be because of the size of the component itself, e.g., seats, or the large number of variants, e.g., cowl-wire harnesses. For example, the manufacturer would need a very large amount of floor space to stock all seat variants. In addition, the line operator would need a great deal of time to retrieve the correct seat for each vehicle. There are also natural limits on the operator's ability to retrieve a required part from many variants. The line operator's ability to combine the information from different places on the specification sheet and pick the required parts accordingly drives selection feasibility.

Cycle-time feasibility is another limiting factor. Weighted-average cycle time at a given work station, i.e., the sum of the cycle times for the different variants that are required multiplied by their incidence rates, must be less than the tak time of the production line as Figure 2 illustrates. In addition, there is an upper limit on the maximum cycle time that an assembly-line operator at a given station can handle without feeling too much pressure.

We include a short discussion of product modularity because the impact of variety on cycle time varies

depending on whether components are modular or integral.

Ulrich (1995) discusses the concept of modularity; he divides product architectures into modular and integral. He examines how a product's functional elements map into its physical components and how the components interface. If components can be decoupled from each other, he terms them as modular; otherwise, he labels them as integral. For example, Specialized, a mountain-bike manufacturer, uses a modular headset design, allowing it to use third-party suspension forks. Cannondale, a competitor, uses an integrated headset design that is only compatible with Cannondale's own suspension fork.

Thus, with a modular product structure, variety has very limited impact on the line operator because the installation process is by definition unaffected for all variants. The number of variants in this case is only limited by the ability to display and select all variants. If component parts are large, this will primarily be a space constraint. If parts are small, the number of variants will be constrained by the ability of the line operator to select the correct part.

In the case of an integral product structure, the SOS for installing the part changes. Most likely, cycle time will be affected. Variety tends to be limited by the capability of the operator to perform a set of different operating steps and by the requirement that the average, weighted cycle time must be less than the tak time.

Lead-Time Constraint

Figure 3 illustrates the lead-time constraint.

Large and unpredictable transportation delays because of factors such as geographical distance between supplier and final manufacturer may make it infeasible to provide sequenced delivery if the supplier does not know the actual production sequence long enough in advance.

The delivery lead time, as well as the time between sequence broadcast and parts installation, will determine delivery lot size. While the final manufacturer will usually share the production plan with its suppliers at least one week in advance, it generally does not finalize the actual build sequence until the vehicles emerge from the paint area. Only at this point can the manufacturer forward the final build sequence to
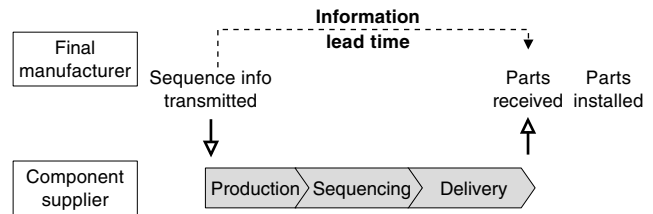

Figure 3: The information lead-time-constraint diagram shows that for sequenced delivery from the supplier to be feasible, total lead time, which comprises manufacturing, sequencing, and delivery lead times for a given component, cannot exceed the elapsed time from the point of the sequence-information transferal to the point of installation.

the supplier. The location of the workstation that will install the given component determines the lead time available to the supplier, putting an upper limit on the delivery lot size.

In addition, the required flexibility at the final manufacturing plant must be considered. On one hand, it is often necessary to resequence vehicles because of paint defects or parts shortages for certain variant combinations. On the other hand, depending on defect rates, it may be necessary to have a replacement for a faulty part or a component that was damaged in the installation process. Therefore, even if the information lead time would be long enough for supplier sequencing, these process instabilities may make it necessary to move the sequencing point closer to the final assembly point.

If the sequencing point is very close to the line worker, the flexibility to deal with these disturbances is at its highest level—the line worker can simply disregard a defective part and replace it with a new one. However, the amount of inventory required is also higher. If the sequencing point is at the supplier, flexibility to deal with disturbances is limited. For example, the necessity to reorder a defective component from the supplier will incur a significant lead time because keeping line-side backup inventory of all possible variants would defeat the purpose of locating the sequencing point at the supplier. Therefore, we would expect the flexibility in terms of reacting to defective parts to decrease as we move the sequencing point away from the manufacturer.

Table 2 illustrates the above discussion with various examples from DaimlerChrysler's SHAP. For headliner, the first component listed, the information

Component	Number of variants	Information lead time	Delivery	Sequencing point
Headliner	10	71′	Unsequenced	Line worker
Instrument panel	35	113′	Sequenced	In-house
Door panels	55	262′	Sequenced	Sequencing center
Seats	14	319′	Sequenced	Supplier

Table 2: Examples from DaimlerChrysler's SHAP illustrate factors involved in selecting a sequencing point.

Location of SP	Total system inventory	Flexibility	Delivery cost	"Possible" variety
Supplier	△	○	$$$	●
Sequencing center	△△	◔	$$	◐
Assembly conveyance	△△△	◑	$	◐
Line operator	△△△	●	$	◔

Table 3: The diagram illustrates various sequencing-point (SP) characteristics.
Note. ○ Low; ● High.

lead time of 71 minutes is too short to allow for anything other than sequencing at the workstation. The high-product variety for instrument panels prohibits sequencing at the line, and the information lead time of about 113 minutes is still too short for sequencing outside the assembly plant. Because of these constraints, SHAP uses in-house sequencing for instrument panels. The information lead time for door panels is long enough to allow outside sequencing while variety is high enough to warrant it. The high cost of seats and their bulky nature make supplier sequencing the preferred option; this is feasible because of an information lead time of about 319 minutes.

Concluding Remarks

In this paper, we have introduced and defined the concept of a sequencing point, as used in the automobile industry, as the location in the supply chain where individual components enter into the sequence that the final assembly requires. In various case studies, we discussed the trade-offs involved in locating the sequencing point at the supplier, an intermediate sequencing center, assembly conveyance, or final assembly. We also discussed the role of the sequencing point in terms of managing product variety and its implications for sequencing and scheduling.

Table 3 summarizes the characteristics of the different locations of the sequencing point as we discussed above. While a supply chain with the sequencing point located at the supplier accommodates the highest degree of variety and minimizes total system inventory, that very scenario also minimizes flexibility to respond to sequence changes and defects.

At the other extreme, locating the sequencing point at the final assembly line provides the greatest flexibility, i.e., response time in case of a defect or sequence change. It minimizes the amount of variety that can be accommodated and maximizes overall system inventory.

Locating the sequencing point at an intermediate sequencing center adds some inventory and still requires double handling. However, it improves flexibility and error-correction capability and increases the amount of variety that can be handled. Therefore, it allows a final manufacturer to operate as if it were receiving sequenced delivery from its supplier while benefiting from quicker replacement of faulty components. An intermediate sequencing center has the capability to handle a similar amount of variety with a lower overall systems inventory. As we move further away from the final assembly line, we clearly reduce flexibility.

Assuming that sequenced delivery from a supplier is feasible, as we discussed in the previous two sections, the question of whether or not it is cost effective still remains. In the ideal case, we can substantially reduce inventory when the production sequence at the supplier plant and the final manufacturer matches, and parts are transferred in small batches without intermediate storage. However, the ideal case is rarely encountered and trade-offs are frequently required. For example, the interval between sequence broadcast and parts installation may require that parts be delivered in half-empty trucks, thus incurring extra transportation costs. It is not always possible to share trucks for different components because some components require dedicated racks and target delivery-time windows may not overlap. For example, Prince delivers door panels and headliners to

DaimlerChrysler's SHAP. However, its trucks cannot accommodate both components because they require different racks.

To account for all these issues accurately, we require a more elaborate model including all cost factors and potential investments. In particular, we may utilize a combination of discrete event simulation and analytical modeling to develop a model that optimizes the location of the sequencing point taking into consideration all the factors that we have identified in this paper. This could be a rich avenue for future research in this area.

Acknowledgments

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