Analysis of Various Assembly System Configurations with Respect to Quality and Productivity

by

S. Jack Hu
The University of Michigan
Mechanical Engineering and
Applied Mechanics
Ann Arbor, Michigan

and

Kathryn E. Stecke
The University of Michigan
School of Business
Ann Arbor, Michigan

and

Robert Webbink
The University of Michigan
Mechanical Engineering and
Applied Mechanics
Ann Arbor, Michigan

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ABSTRACT

Traditional assembly lines have been largely serial in nature. However, advancements in controls and other technology have allowed for the implementation of alternative system configurations, including the use of parallel systems. These systems offer improvements in productivity, but their performance with regards to quality, particularly dimensional variation, is not well understood.

Several alternative system configurations presently in use are identified and their general layout determined. From these layouts, a set of four sample configurations of four stations is proposed and analyzed for performance. The traditional method of performance analysis, system reliability, is shown to be inadequate in that it overestimates the performance of some systems. In its place, expected productivity is used as a fast and simple method of estimating performance without computationally intensive simulation.

Next, the expected level of variation from each configuration is examined using a set of three basic sheet metal parts that are spot-welded together. Traditional methods of estimating variation stack-up are insufficient for use with sheet metal, as they assume rigid parts. In their place, “mechanistic variation simulation” is used to analyze the variation stackup.

From these results, it is clear that the system configuration that produces the best productivity is not the best in terms of assembly variation. These results are then used to produce some basic guidelines to aid in the selection of a system configuration that is an appropriate blend in terms of productivity and quality.

1. INTRODUCTION

A predictable sequence of parts is crucial to many different products, especially in situations where products are fully or partially customized. If every copy of a product were identical, removing parts from the line or running them through parallel machines would not be a problem. However, with products such as automobiles that are heavily customized, disrupting the sequence of parts and assemblies can result in many finished products not meeting the customer's orders. As a result, many traditional assembly lines have been of a pure serial configuration.

However, with advanced technologies, variable processing times and parallel processing workstations are now available. This enables the use of more flexible production configurations, including the implementation of both serial and parallel configurations on the same line. While the performance characteristics of such systems may be analyzed with relative ease for some products, it becomes less clear how these systems perform when considering complex structures and assemblies, particularly with assemblies consisting of compliant (non rigid) parts. In these types of assemblies, variation propagation is significantly more difficult to predict, and the tradeoffs with system performance may result in different optimal configurations than when only considering rigid structures.

Therefore, the intent of this study is to use an example of a compliant assembly to develop a method of analyzing such systems and to generate some basic conclusions on how configurations may impact product variation as well as system throughput. Such methods and conclusions could then help aid in the selection of future assembly line configurations.

1.2 Literature Review

Significant amounts of research have been done towards understanding the performance of various production system configurations. Udomkesmalee and Daganzo (1989) and Spur et al. (1986) recognize the benefits that implementation of parallel processing systems have had on several performance factors. Among these are the ability to match demand more closely, reduce work-in-process and the impact of problems in one station on the entire system, and achieve higher system utilization and shorter order flow time. In addition to these benefits, some penalties might exist with respect to cost and part quality. However, to date no literature has been found on the impact that different production system configurations may have on part quality, as defined by the overall level of variation of the finished product. Therefore, §1.2.1 focuses on the existing literature documenting the first area of interest, the impact of system configurations on system performance indices. The remaining topic of predicting part variation, specifically as it refers to the inclusion of compliant parts is covered in the literature review in §1.2.2.

1.2.1 Assembly System Configurations

Existing literature focuses primarily on improving the throughput of the system when discussing the impact various assembly system configurations have on system performance. Within this context, there are two primary approaches taken to maximize throughput: altering the layout of the machines and altering the workload assigned to each. Although alternatives to increase production exist, including subcontracting, overtime, and altering buffer sizes, the trade-offs of these methods in comparison to altering system configuration have not been explored.

The first method of improving productivity, altering the layout of the machines, has received much attention. Blumenfeld (1989) and Weber (1997) examine the effect that various configurations have on the throughput of a given system. Stecke and Solberg (1985), Dallery and Stecke (1990), Lee et al. (1991), and Magazine and Stecke (1996) examine a similar problem, and demonstrate an application of the bowl-phenomenon. That is, in order to increase productivity, the best system configuration is that with a large number of machines symmetrically placed in the middle stations of a production line. More specifically, the most desirable configuration is a pure parallel system, where all machines perform the entire set of tasks needed to complete the product, and all machines operate independently of one another. In this manner, if one machine fails, the others continue to manufacture the product, and a minimal amount of production is lost. If it is not possible to place all machines in pure parallel, they demonstrate that the optimal configuration is the most unbalanced configuration possible when the configuration is not symmetric. In this manner, the majority of the machines are placed in parallel at the center of the production line, with the workload appropriately assigned. While this method may improve production, it can result in problems with the sequencing of parts and assemblies, as addressed by Smith and Stecke (1996), Buzacott (1990), Udomkesmalee and Daganzo (1989), and Whitt (1984).

The second primary method of improving system productivity is altering the workload assigned to each station. Stecke and Solberg (1985), Ghosh and Gagnon (1989), Hackman et al. (1989), Johnson (1991), and Malakooti (1991) all address this method. In general, the best approach shown to improve the productivity is to use the bowl-phenomenon, which assigns a larger workload to the first and last stations in a line; however, these methods do not all directly address the availability of parallel machines. Pinto et al. (1975) provide a more direct look at the inclusion of parallel machines when considering workload allocation. Furthermore, assigning workload is in many cases a discrete optimization problem, rather than continuous. For example, when spot-welding sheet metal parts, a weld is either completed or it is not. If a product needs five spot welds to complete the assembly, then the workload is only assignable in increments of 20% of the total tasks, or one weld. The advantages of the bowl phenomenon and purposefully unbalancing the workload are partially lost when the workload must be assigned in large increments.

Lee and Stecke (1996, 1998) provide a more direct approach to the discrete nature of many of these problems. Given a set of machine types and characteristics, details on the products, including task times and precedence, and details on possible material handling systems, their models help predict an optimal assembly configuration to meet product demands and maximize throughput.

Overall, the selection of an assembly system configuration depends mainly on one primary variable: cost. Improvements in productivity are desirable as they directly reduce the unit cost of the product. Likewise, improving product quality reduces rework costs, warranty expenses, and improves customer satisfaction, all of which can impact the overall cost and therefore the profitability of the operation. Daganzo and Blumenfeld (1994) address this cost aspect by introducing analytical models that demonstrate that the optimal assembly system design (serial, parallel, or hybrid) is dependent primarily upon the ratio of labor to equipment costs. Karmarkar and Kekre (1987) and Rachamadugu and Shanthikumar (1991) address other factors that may impact capacity and mix decisions, and therefore system configuration, such as inventory holding costs, lead times, batch sizes, and the amount of workspace.

1.2.2 Variation Simulation

Part variation is one of the key aspects of product quality. A product with low levels of variation is in many cases significantly less likely to have warranty claims or other failures, and may also result in higher levels of customer satisfaction. For example, if the level of variation in an automobile body can be controlled tightly, the nominal gaps between panels can be reduced, thus lowering wind noise, road noise, and water leak problems, all of which greatly impact the customer's image of quality. Therefore it is extremely important to be able to accurately predict the level of variation which can be expected from a given assembly system and set of part designs.

The process of predicting variation, known as variation analysis, historically relies on the ability to produce a function $y = f(x_1, x_2, \ldots\ldots, x_n)$ to relate the final product dimension, y, to critical dimensions, x_n, on the parts which make up the assembly. When a suitable function has been determined, the variation in the final dimension is usually predicted in one of three manners: worst case analysis, root sum squares (RSS), and Monte-Carlo simulation. The worst-case method (Chase and Greenwood (1987), Dong et al. (1994), and Dong and Soom (1990)) operates under the assumption that all parts are produced with their extreme values. The result of this assumption is a set of assembly tolerance bands that are unrealistic, as the probability that all parts will come in with worst-case dimensions is extremely small. This in turn causes the tolerances assigned to the parts to become too small in an effort to control assembly variation, and thus results in extreme costs.

The root sum squares (RSS) method is a more accurate method of predicting overall variation. This method relies on the assumption that the distributions of the incoming parts are known or can be estimated accurately. The overall variation in the product is then based simply on the square root of the sum of the square of these values. If the assembly function is nonlinear, but can be linearized without great loss of accuracy, RSS can still be used simply by multiplying the standard deviation of each part by a sensitivity coefficient. This method results in a more accurate estimate of assembly variation, as it accounts for the unlikely possibility that all parts will be at their extreme values (Lee and Woo (1990) and Treacy et al. (1991)). However, both the worst case and RSS methods are difficult to apply to complex two-dimensional and three-dimensional assemblies (Juster (1992) and Chase and Parkinson (1991)).

A more robust method of predicting variation for complex assemblies is Monte-Carlo analysis. As in RSS, this method requires accurate knowledge of the distributions of the dimensions of the incoming parts. However, instead of directly applying this knowledge, random values are selected from each distribution, and the dimension of the resulting assembly is calculated using the assembly function y(x). This process is repeated many times, and the overall level of variation can then be calculated from these "sample" assemblies (Craig (1989) and Early and Thompson (1989)).

Two problems exist with the implementation of many of these models as they are commonly used: without modification, most do not account for the fact that parts are compliant, and they do not typically include the tooling that is required to compensate for the flexibility of these parts. Under the assumption that parts are rigid, the tolerance of the individual parts should be tightened to achieve a lower level of assembly variation. Therefore, the tolerances on individual parts may be economically unrealistic. Takezawa (1980) first proposed that parts in sheet metal assembly cannot be treated as rigid bodies. Components with low rigidity are less likely to contribute to variation in the final assembly if they are mated to parts with higher rigidity. Liu and Hu (1997) demonstrate that the manner in which these parts are attached also has an impact on the level of variation in the final assembly.

Likewise, the type of, and variation within the tooling used to locate these compliant parts also impact the level of variation in the final assembly. If a part is not sufficiently supported, it is conceivable that the closing force of the clamps may be strong enough to cause distortion in the part, thus impacting the dimensions of the final assembly. Furthermore, the exact location of the fixtures can have a great impact on the variation of the product. Several methods for selecting better locating points were proposed by Mani and Wilson (1988). In order to estimate the impact of a given design on product variation, Lee and Haynes (1987) developed a finite element model for fixture system analysis. Workpiece deformation, clamping forces, and the resulting stress distribution can be calculated from this model. In combination with methods proposed by Youcef-Toumi et al. (1988) and Rearich et al. (1993), these fixtures can be evaluated accurately for cost and performance, and then be used to aid in the prediction of the final level of variation in a given assembly. Fixture faults have been identified as the major cause of dimensional variation in autobodies. As this is a classic example of the use of compliant parts, fully understanding the impact of tooling on product quality is clearly very important.

2. MOTIVATION FROM EXISTING ASSEMBLY SYSTEMS

Traditionally, most assembly lines have been serial in nature. With the advancement of control technology, it has become possible to implement alternative configurations. These configurations have begun to appear in many different settings, including automotive body assembly. Lines that have historically been pure serial in nature are now often more complex hybrid configurations. The motivations behind implementing these configurations vary from case to case. In some instances, increased throughput may be an objective. In other instances, a restriction on floor space may be the instigator. In still other cases, it may be improved product quality through lower variation that is the aim. Through examination of three example lines in this section, it is clear there is a wide variance of configurations, even for the same product type, which then leads to the question of how configuration impacts part variation.

The first step in examining existing assembly lines is to attempt to determine exactly what types of configurations have been implemented. Other than the pure serial design, most common manufacturing systems have a hybrid configuration. One such example is a system of several duplicated serial lines. These identical lines are connected in parallel, i.e., they share the same source of incoming parts and their products are mixed at the end of the system (see Figure 2). Such a configuration is also known as a parallel-lines configuration.

Hybrid systems may be difficult to identify. For example, turn-tables are common in automotive body assembly systems. These turn-tables, along with their supporting equipment, operate as a single production unit which has a hybrid system configuration. When multiple turn-tables are placed in an assembly line, the control algorithm used on the tables can actually change the effective system configuration. For example, assume two turn-tables with two operators are placed in serial in an assembly system (Figure 1). Both turn-tables have four identical fixtures (labeled 1-4). Furthermore, they always rotate counter-clockwise and remain synchronous, i.e., when one rotates by a given amount, the second rotates in an identical fashion. At the left-hand (LH) turn-table, the operator loads a part onto an empty fixture, while robots A and B simultaneously weld parts that are rotated into their respective working areas. At the same time, robot C picks one part from the LH turn-table and loads it onto an empty fixture on the right-hand (RH) turn-table. Simultaneously, robots D and E weld parts that are rotated into their respective working areas at the RH turn-table. At the final stage, an operator unloads the finished part from the RH turn-table, thus freeing a fixture for the next part to be transferred from the LH to the RH turn-table.

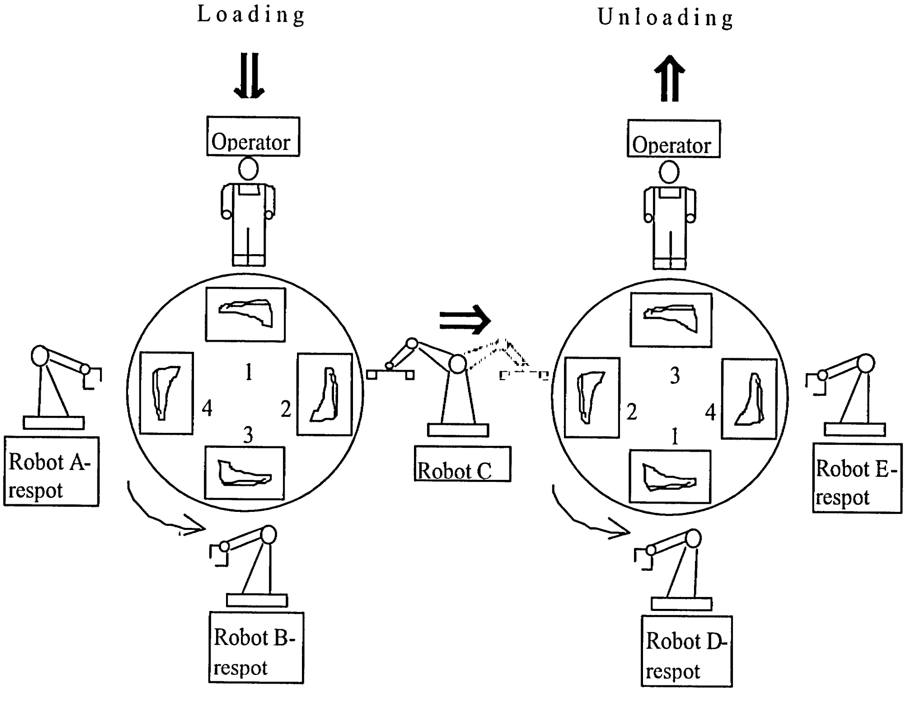


Figure 1. Two turn-tables with operators and robots.

This process is an example of a hybrid system configuration. Both turn-tables are effectively a system of parallel stations. Because the two turn-tables are synchronized, any part processed on fixture 1 of the LH table will always be processed by the fixture 1 on the RH table. Thus, there are four possible paths for the parts to follow. Within each path, the value adding processes are in a serial order. Figure 2 illustrates this configuration: A, B, D, and E denote the labels of the robots in Figure 1: 1-4 designates which set of fixtures is used.

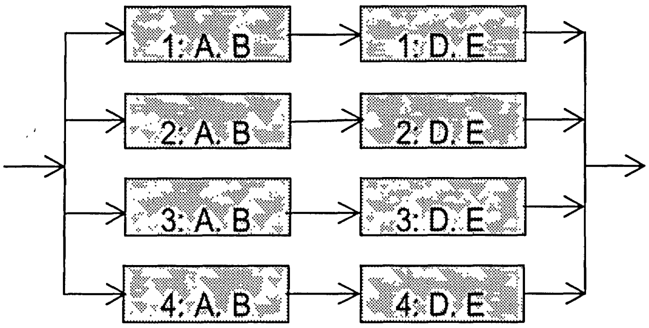


Figure 2. A parallel-lines hybrid system configuration.

Alternately, if the two turn-tables are *not* synchronized, then robot C may place the part coming from the LH turn-table on any of the fixtures on the RH turn-table. If both tables are operating normally, they may remain synchronized over a short period; however, if one fails or is advanced for some reason without loading parts, the two are no longer synchronized. Because of this change in the control method, the number of possible value-adding paths is increased from 4 to 16, with the parts exiting the LH table effectively mixing before entering the right table (Figure 3). This type of configuration is known as a serial-groups system.

Each of these two similar, but different, configurations have different performance characteristics. We demonstrate and investigate these differences with similar configurations, only with fewer machines, in §3.1.3 and §§4.4-4.6.

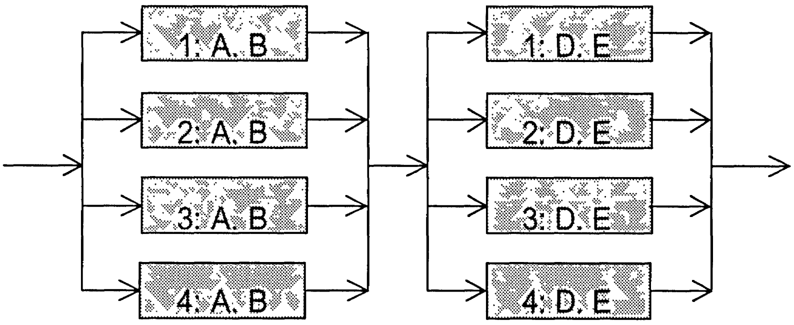


Figure 3. A serial-groups hybrid system configuration.

2.1 Example #1 – Automobile Underbody

The underbody of a car (Figure 4) consists of three main components: the engine compartment, floor pan, and rear compartment pan. The system configuration (Figure 5) consists of three smaller lines, each building a specific component, which are then joined and the product sent on through re-spot lines. Of these lines, all have a serial configuration, with the exception of the engine compartment. This component is built on two identical lines in parallel, thus giving it a parallel-lines configuration.

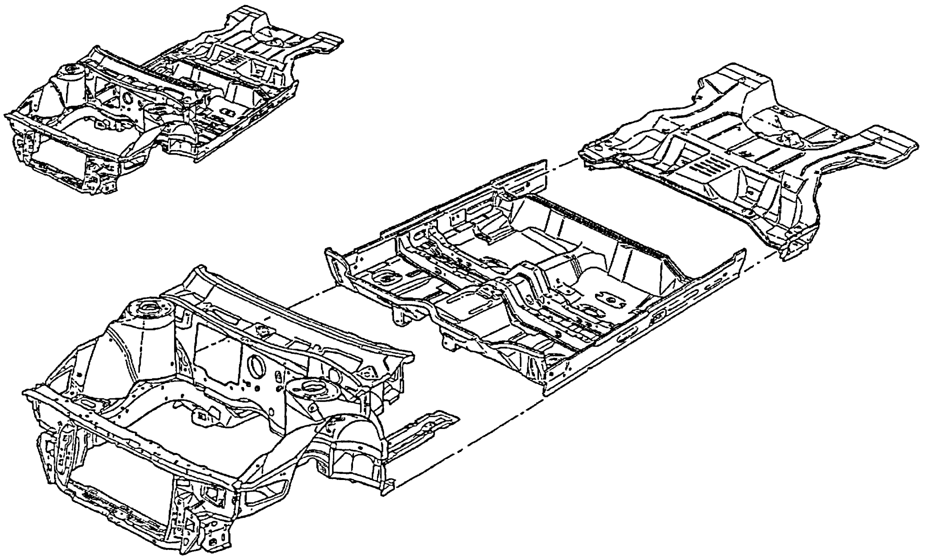


Figure 4. Automobile Underbody (model A).

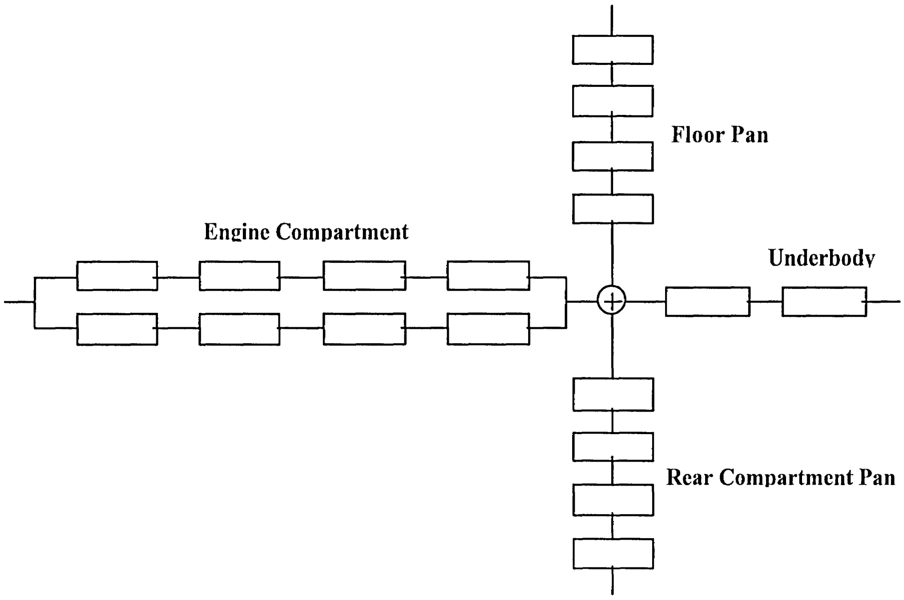


Figure 5. The assembly system configuration block-diagram for an underbody (model A).

2.2 Example #2 – Truck Cab

This example of a truck cab (Figure 6) is built on an assembly line in a more traditional manner. The cab itself consists of six subcomponents: a floor panel, back panel, dash, two side apertures, and a roof. All of the subcomponents are assembled on purely serial assembly lines (Figure 7), and joined in a framer.

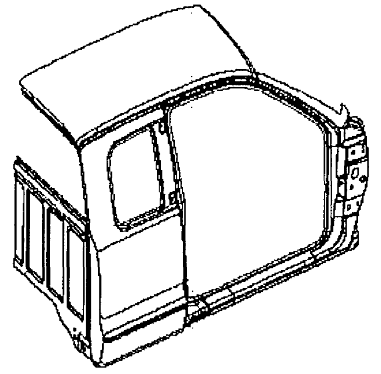


Figure 6. A cab (model B).

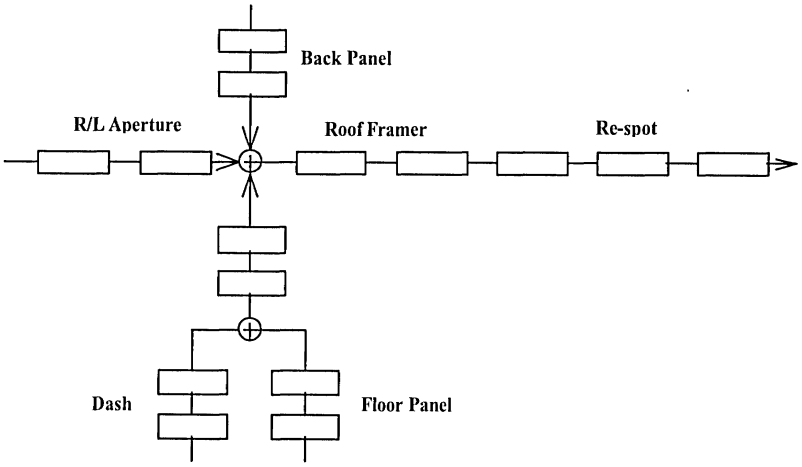


Figure 7. The assembly system configuration block-diagram for a truck cab (model B).

2.3 Example #3 – Truck Cab #2

While some truck cabs are assembled in a serial fashion, this is not true in all cases. A second model of truck cab (Figure 8) is built on a hybrid line. For this product, the system loads one component at a time, and has multiple processors at most stages, complete with mixing (Figure 9). Therefore, the configuration for this line is that of a serial-groups system.

Despite these examples, most common body assembly systems have serial configurations. Of the three examples, most are either completely serial, or largely serial to a certain level. However, in recent years, parallel-lines and serial-groups have become more common. Yet the question remains as to how the selection of different configurations impacts part quality and system productivity.

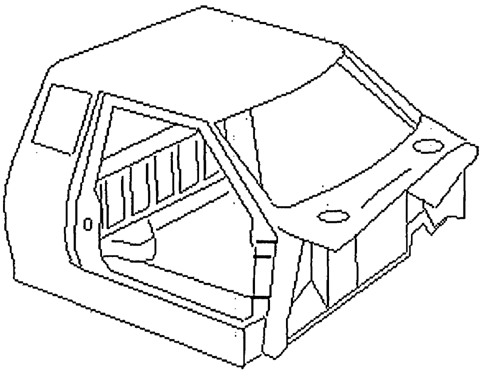


Figure 8. A truck cab (model C).

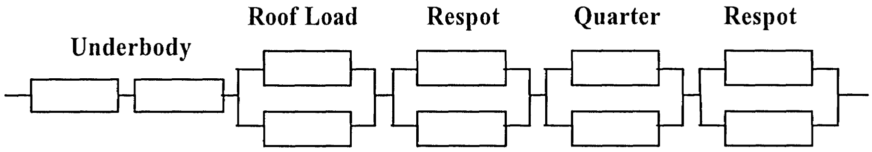


Figure 9. The assembly system configuration block-diagram for a truck cab (model C).

3. ANALYSIS OF PRODUCTIVITY

System reliability has been used often as a descriptor of the performance of a given system configuration. This index simply estimates the probability, R_s, that a given system is producing parts at any time. Calculation of this parameter relies on the given probabilities that the i-th machine in the system is capable of performing its task at any given time, R_i, for all i. Any numerical statement of reliability (e.g., R_i=.8) should be accompanied by the definition of the operating conditions, the required function, and the mission duration (Birolini, 1994). Higher reliability results in less system failure on average and consequently less downtime and loss of production.

Productivity, another performance parameter, is closely related to reliability. However, whereas reliability measures only the probability that the system is producing parts, productivity estimates the percentage of the maximum, or design, throughput that the system is able to achieve. For example, a simple parallel system comprised of two machines, both with $R_i = 0.9$, would have a reliability of $R_s = 1- (1-R_1)(1-R_2) = 0.99$. However, if one of the machines failed, the system throughput would be cut in half. This loss of production is accounted for in the productivity estimate. Calculation of this parameter is dependent upon close examination of every possible state of the system (S_j), and the percentage of the design throughput achieved in that state (t_j). Taking the product of these percentages and the probability of being in that given state (p_j) and summing over all states, gives the expected value for the percentage of design throughput that the system can achieve. That is: $P = \sum_{\forall s_j} t_j p_j$. Therefore, for the simple system of two identical parallel machines, there are four possible states for the system to be in; both machines running, in which case design throughput is met; two states where one machine is functioning but the other has failed, in which case half of the design throughput is met; and a final state where both machines have failed and no parts are being produced. For the two identical machines given above, this gives:

$$P = 1 \cdot R \cdot R + \binom{2}{1} \cdot 0.5 \cdot R(1-R) + 0 \cdot (1-R)(1-R) = 0.9 .$$

Use of this parameter in place of system reliability reduces the tendency to overstate the performance capabilities of parallel systems. This, in turn, results in a more precise comparison between systems and allows selection of a configuration based on more accurate estimates of production and quality.

3.1 Analysis of the Example Systems

Consider a system consisting of four independent stations A, B, C, and D connected in various manners. Let the reliabilities of these stations be R_A, R_B, R_C, and R_D, respectively. Assume that R_A = 0.85, R_B = 0.60, R_C = 0.75, and R_D = 0.80. It is then possible to estimate the productivity for various system configurations using these four machines.

3.1.1 Serial System

The simplest of all system configurations for four machines is the pure serial configuration (Figure 10). Given the reliabilities of the individual machines, it is simple to calculate the productivity of the system as a whole. For this system, there are a total of sixteen different possible states:

$j = \sum \begin{pmatrix} \text{number of machines} \\ \text{number operational} \end{pmatrix} = \begin{pmatrix} 4 \\ 0 \end{pmatrix} + \begin{pmatrix} 4 \\ 1 \end{pmatrix} + \begin{pmatrix} 4 \\ 2 \end{pmatrix} + \begin{pmatrix} 4 \\ 3 \end{pmatrix} + \begin{pmatrix} 4 \\ 4 \end{pmatrix} = 16$. However, production of parts occurs only in the state in which all machines are operational. If any single machine fails, all production ceases, as every remaining machine is either blocked or starved. Therefore, in the case of a serial system, the productivity is equal to the probability of being in this one state, or: $P_S = \prod_i R_i = R_A R_B R_C R_D$. This is identical to the reliability of the system. Given the reliabilities from §3.1, the productivity of the pure serial configuration is: $P_S = 0.85 \cdot 0.60 \cdot 0.75 \cdot 0.80 = 0.306$, and is independent of the order in sequence in which the machines are arranged; that is, switching the positions of machines B and A has no effect on the productivity of the system.

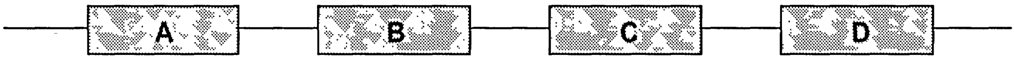


Figure 10. An example of a serial configuration.

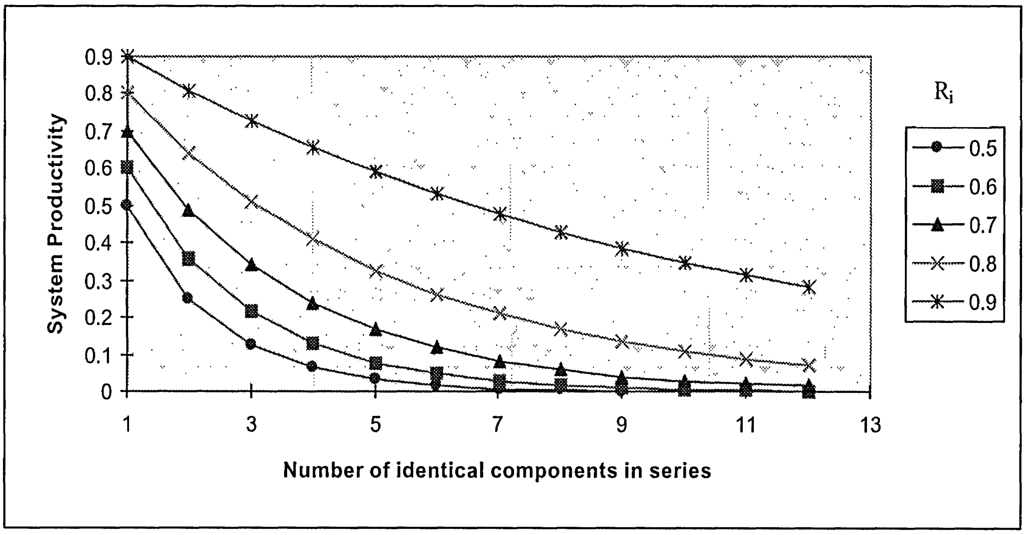


Figure 11. Effects of increasing the number of identical series components having reliability R.

Because of the fact that each station has a probability of working that is less than unity, the system reliability is less than the reliability of any one station. As the number of stations in series increases and as the station reliability decreases, the system reliability, and therefore the system productivity, also decreases. This is illustrated in Figure 11. It shows that the productivity of a serial system containing identical stations is a function of the number of stations and the station reliability. This figure shows that system productivity drops rapidly as the number of series stations increases, especially for a system in which stations do not have very high individual reliability.

3.1.2 Parallel System

Consider the system of four independent stations connected in a pure parallel fashion (Figure 12). According to the classical definition of reliability, the system is successful and operational if one or more stations is operating. In other words, the system fails only if all its stations fail. However, this fails to account for the loss of production that occurs when one, two, or three stations fail. The productivity estimate more accurately represents such a system's performance. For this system, there are once again a total of 16 possible states. However, as opposed to the serial case, all *but* one of the states result in production at some level. Assuming that each machine is designed to account for an equal amount of the total throughput (i.e., 0.25), and all machines have equal reliability, productivity of this system can be expressed as:

$$P_S = 1 \cdot R^4 + 0.75 \cdot \binom{4}{3} \cdot R^3 \cdot (1-R) + 0.5\binom{4}{2} \cdot R^2 \cdot (1-R)^2 + 0.25\binom{4}{1} \cdot R \cdot (1-R)^3 + 0 \cdot (1-R)^4.$$

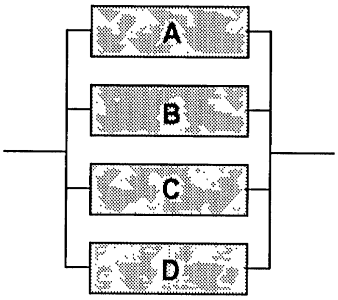


Figure 12. An example of a parallel configuration.

For the case where the reliabilities are not all equal, evaluation of productivity will be a slightly more complex task. However, because the machines are independent in a pure parallel system, their probabilities of being operational are independent, and the analysis can be simplified to:

$$P_S = 0.25 \cdot R_A + 0.25 \cdot R_B + 0.25 \cdot R_C + 0.25 \cdot R_D.$$

Therefore, using the previously stated reliabilities for these four machines, the productivity is given as: $P_S = 0.75$.

In general, as the number of stations in parallel increases and/or the station reliability increases, the system reliability also increases (Figure 13). However, the independence of the machines in parallel results in the conclusion that productivity in a pure parallel system of identical components is equal to the average reliability of the components, independent of the number present. This is counter to the trend shown by system reliability and demonstrates how using system reliability to guide configuration selection can lead to a non-optimal solution.

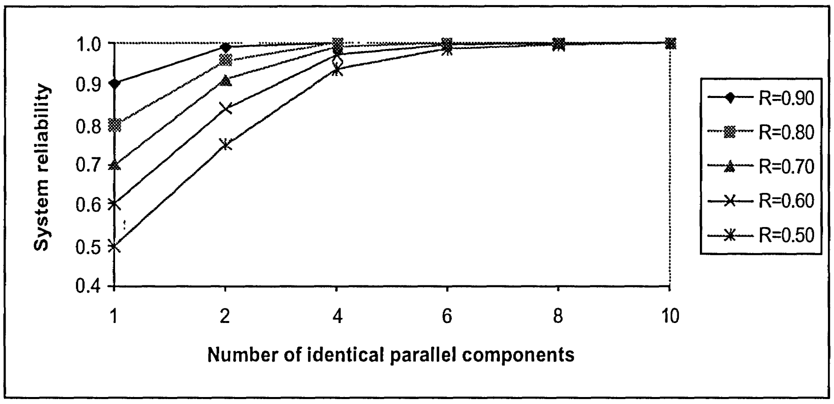


Figure 13. Effects of increasing the number of identical parallel components having reliability R.

3.1.3 Hybrid Systems

Hybrid systems are combinations of serial and parallel systems. The number of possible hybrid configurations grows rapidly as the number of stations increases. However, for this study, two specific types are examined: parallel lines and serial groups. When a hybrid system is arranged so that there is more than one branch in the system, and each branch has more than one station connected in series, then it is defined as a parallel-lines system (Figure 14).

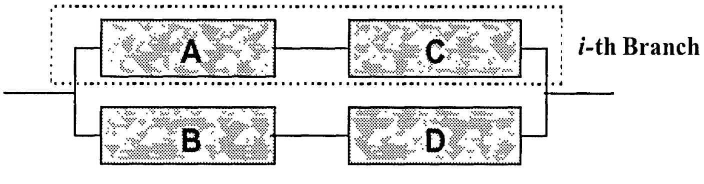


Figure 14. An example of a parallel-lines configuration.

For a parallel-lines configuration, the number of possible paths of material flow is equal to the number of branches in the system. As in the case of a pure parallel system, use of system reliability to characterize performance may result in overly optimistic projections. In this configuration, if all machines have equal throughput, 50% will pass through A and C, and the remaining 50% through B and D. Therefore, the productivity of this system is simply: $P_S = 0.5R_AR_C + 0.5R_BR_D$. It is of note that if $R_A \neq R_B \neq R_C \neq R_D$, the productivity is not necessarily optimized for that particular configuration. Using the previous values for machine reliability for comparison purposes, it is clear that the productivity of the system in Figure 14 is 0.559. However, by switching the positions of machines C and D, productivity can rise to 0.565. For either arrangement of this configuration, the system reliability is 0.824, which clearly exaggerates the difference between this configuration and the pure serial configuration.

When a hybrid system is arranged so that there is more than one group of stations in the system, and each group has several stations connected in parallel, then it is defined as a serial groups system (Figure 15).

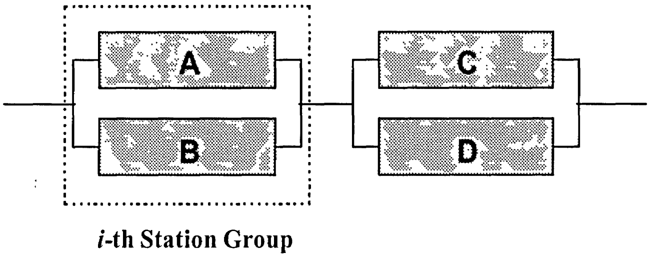


Figure 15. An example of a serial-groups configuration.

The expression for productivity of this system is slightly more complex than the previous configurations. Once again, there are 16 possible system states. However, any state that has more than two machines down or the set of {AB} or {CD} down results in no production. Assuming each machine has equal throughput, all other states produce 0.5 of the design throughput, with the exception of all machines running, which produces the full amount. Therefore, the expression for productivity is:

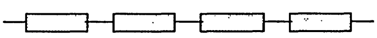
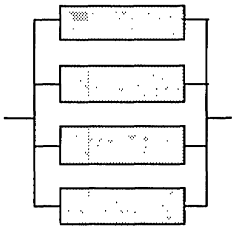
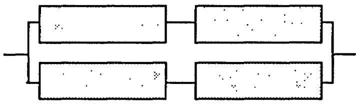
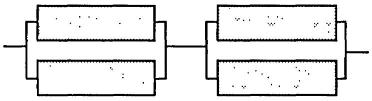
$$= R_B\left(R_C(0.5-0.5R_D)+0.5R_D\right)+R_A\left((0.5-0.5R_B)R_D+R_C(0.5-0.5R_B-0.5R_D+R_BR_D)\right) .$$

Once again, it is clear that if the machines are not of equal reliability, their exact placement within the configuration impacts productivity. However, using the same values as before, in this case it is the optimal placement, and the productivity is 0.5995.

3.4 Comparison and Discussion

Table 1 summarizes the results of the system reliability and productivity analyses in §§3.1 - 3.3. It is clear that different system configurations have a strong impact on the productivity of assembly systems. The system having four stations connected in a series has the lowest system productivity among the four systems. If the stations are rearranged and connected in parallel, the system productivity is maximized. Hybrid systems offer productivity greater than serial, but slightly less than parallel systems. Furthermore, within the hybrid groups, the serial groups system appears to have a slightly higher productivity than the parallel-lines configuration.

Table 1. Reliability and productivity of different system configurations.

System Configuration	Block Diagram	System Reliability	Probability of System Failure	Expected Productivity
Serial		.306	.694	.306
Parallel		.997	.003	.75
Parallel-lines		.824	.176	.565
Serial-groups		.893	.107	.5995

In general, the greater the number of possible paths of material flow a system has, the greater its productivity becomes. A serial system has only one possible path of material flow, so the system shuts down if only one machine fails. A parallel-lines system offers more redundancy than a serial system, and therefore exhibits a great increase in productivity. This trend follows in the serial-groups system, which has four possible flow paths, and therefore even greater redundancy and improved productivity. The pure parallel configuration offers the most redundancy. This configuration has no more possible flow paths than the serial-groups configuration. However, failure of a machine in the serial-groups configuration reduces production by 50%. In the pure parallel system, any machine failure only cuts production 25%, as the machines are completely independent of each other. Thus, not only is there a benefit for increased flow paths with respect to productivity, but the number of independent flow paths also is an important factor for increased productivity.

Some operational implications of these observations are as follows: It may be possible to purchase better machines with higher reliability to increase the productivity of some critical continuous processes, but the costs may become too high. If several similar tasks can be combined on a single station and several of these stations combined to form a parallel system, high system productivity is possible without the need to purchase complex, expensive machines.

4. VARIATION SIMULATION

There are many ways in which to define the overall quality of a product. Main concerns of customers may be looks, feel, or even sound. If a product looks, feels, and sounds right, and runs properly, consumers tend to consider it to be of high quality. While many different parameters may influence these qualities, if the product is not built or assembled well, there is little way of guaranteeing a high quality result. Producing well-built parts in many instances is a challenge in controlling dimensional variation. If the parts can be produced and assembled to within specifications, then the result should be a high quality product, assuming a good product design. If, on the other hand, a product cannot be built within specifications, a great overall product design may not be able to prevent consumers from labeling the product as "poor quality". This is especially true in many sheet metal assembly tasks, such as building automotive bodies. Poor dimensional control, or large variation, can adversely affect many aspects of the vehicle which the customer uses to define high and low quality, such as door closing effort, wind noise, water leakage, and gap and flush problems.

This brings the question of how assembly variation tends to vary with system configuration. There are several methods that are useful for predicting or simulating assembly variation. The most commonly used of these are worst-case analysis, root sum squares, and Monte Carlo simulation. In all of these methods, the parts are considered to be rigid bodies. However, for sheet metal assemblies, these methods cannot correctly predict the variation of the assembly without modification because flexible sheet metal parts can deform during assembly.

An alternative to these statistical approaches is variation simulation using mechanistic models, or "mechanistic variation simulation". This method, initially presented by Liu and Hu (1997), combines engineering structural models with statistical techniques for better analysis of the variation stack-up of deformable sheet metal part assemblies.

Mechanistic variation simulation uses a mathematical relation (Figure 16) to predict variation in the final assembly. This relation uses the deviation of the i-th part from nominal, v_i (i = 1, 2,...,M), and the deviation of the j-th tooling element, u_j (j = 1, 2,...,N), to determine the deviation in the final assembly, v. The coefficients by which these deviations are multiplied, S_i and S_j, are known as sensitivity coefficients. In a traditional worst-case analysis, these coefficients are taken as ±1. However, this ignores the intricacies involved in predicting the variation of deformable assemblies.

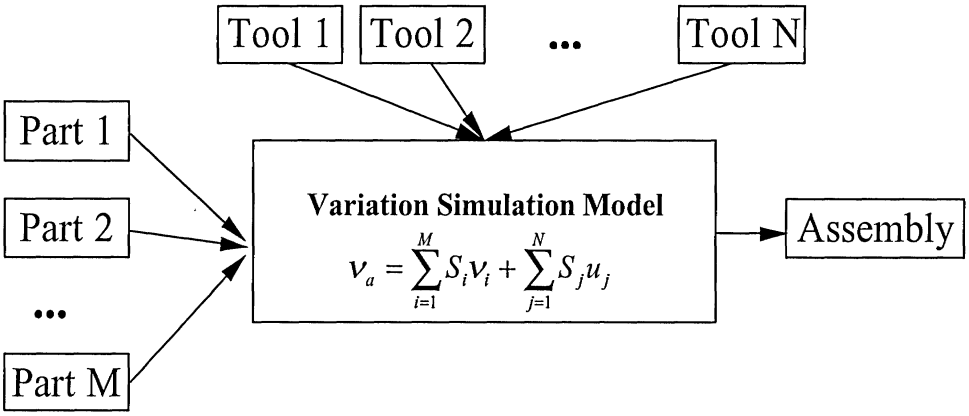


Figure 16. Variation simulation modeling (Liu and Hu, 1997).

In mechanistic variation simulation, part deformations during assembly processes are no longer ignored. The sensitivity coefficients (S_i and S_j) are not simply ±1, but are complicated functions of geometrical dimensions and material properties of the components, plus the work-holding fixturing (constraints) and joining (welding) schemes. These sensitivity coefficients can be determined using offset finite element models as proposed in Liu and Hu (1997). CAVA, a computer program developed in the S.M. Wu Manufacturing Research Center at The University of Michigan, uses this method to determine a more accurate estimate of variation than available in traditional models. CAVA is now described in §4.1.

4.1 Simulation Setup

In order to determine the performance of different system configurations in terms of product quality and variation, it is necessary to know the types of parts that are being assembled. Every set of parts will produce its own unique results for any given configuration. However, the general trends of the results remain the same, with scaling the main difference. For example, as we see in §4.6, a parallel configuration will almost always produce lower mean deviations than a serial line, but at the cost of higher 6-sigma variations, with the size of these gaps in performance varying with the parts.

Three identical sheet metal parts are used to test the four system configurations and serve as examples of the quality differences. Each of these parts has a length of 600 mm, a width of 400 mm, and a thickness of 1 mm. The assembly task is simply to weld the three parts into one continuous part. In a normal operation, a 3-2-1 locating scheme is used. A 3-2-1 scheme uses 3 pads to locate the part in a plane perpendicular to the z-axis, a 4-way pin to fix the translation of the part in the plane, and a two-way pin to fix the last degree of freedom, the rotation of the part about the four-way pin. This is the minimum number of locators needed to fully constrain a rigid part. However, with compliant parts, an extra locating pad is introduced to reduce deformation under self-weight and clamping loads, resulting in a 4-2-1 scheme (Figure 17). This additional locator helps reduce product variation by fixing the flexible parts more accurately. The assembled part, as shown in Figure 18, is built with four spot welds, located at the Xs. During final audit, the part is located with a 4-2-1 locating scheme as represented by the triangles, and the rear-corner point is audited for deviation from nominal, in the Z-direction only.

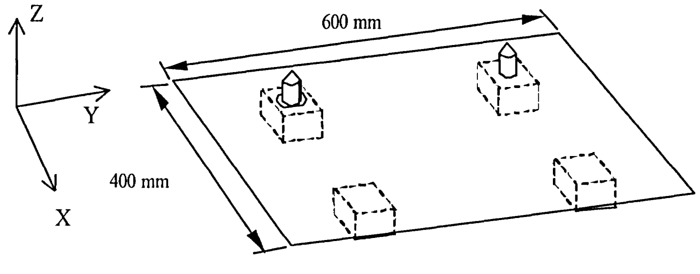


Figure 17. Four constraints (4-2-1 locating scheme) of an individual sheet metal part.

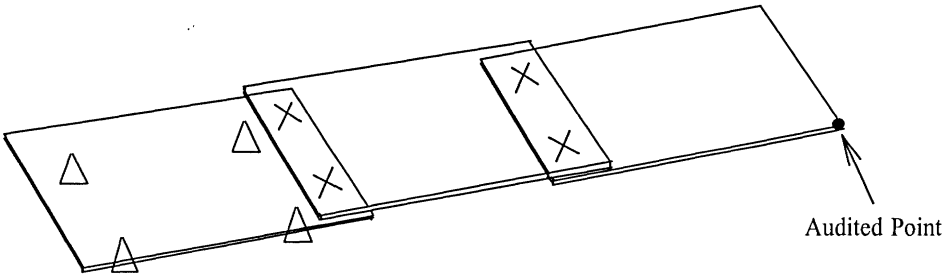
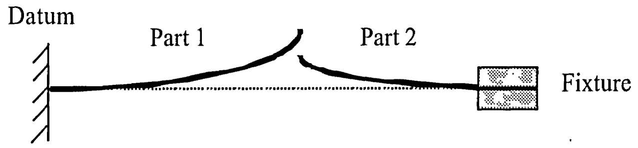


Figure 18. Final sheet metal assembly.

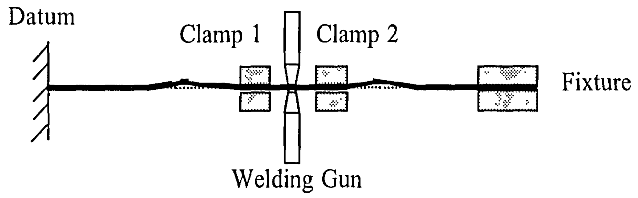
CAVA, the computer program used to simulate the product variation, takes into account the dimensional variation of both the parts and the fixtures to determine the "variation stack-up" of the assembly. The variation stack-up in an assembly is essentially a relationship of how the individual sources of variation contribute to the variation in the final assembly. To simulate this, each part coming into the fixtures is assumed to have a deviation from nominal only in the Z-direction at each corner prior to welding. The magnitude of these deformations is normally distributed with 6-sigma values of 1 mm, as are the deviations in the locations of the fixtures. The normal process that the simulation uses to simulate the variation (Figure 19) is as follows: The incoming parts are first located using the fixture. A series of clamps then forces the two parts together, at which point they are welded in the specified locations. Once the designated welds have been made, the clamps are released and the part springs back.

After the clamps are released, the program audits the parts for mean deviation and 6-sigma values. If another part is to be welded to the assembly (i.e., if only two plates are welded in one station, and a third still needs to be welded), these audited values are used as the sources of variation for the next step in the assembly.

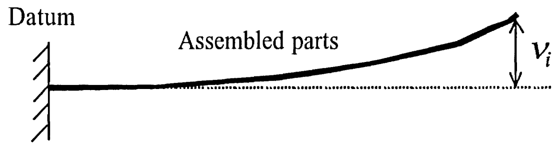
The simulations run used the same four system configurations as in the productivity analysis in §3.1. The example system has a total of four welding robots, each of which is capable of performing its task with acceptable quality. Furthermore, the incoming part variations are sampled from the same random number stream; i.e., the set of parts used to test one configuration are the exact same set of parts used to test all other configurations. The same logic is applied to the deviations in the fixturing in that essentially the same set of four fixtures is used across all configurations. Finally, it is assumed that all materials are of acceptable quality. Therefore, the only design variable to be addressed is the actual system configuration.



(a) Variation of parts before welding



(b) Tooling and welding



(c) Assembly variation due to material spring-back

Figure 19. Variation stack-up in a sheet metal assembly process [Liu, et.al. 1996]

As described in §§4.2-4.5, each system configuration assumes slightly different details for the actual welding process (§4.6 gives the actual results). However, for all systems, a throughput of 1200 parts per day is required. Each machine is capable of performing a single weld at a time, similar to welding robots, and the throughput of each machine is assumed to be approximately 1200 welds per day.

4.2 Serial System

In a serial assembly system, the machines make each weld sequentially, one spot at a time, until all four spots have been welded (Figure 20). Each station in the system performs the task shown in the system diagram in the figure (i.e., spot weld #1 in the first station).

The first two parts are put on the first fixture, and the first spot weld is performed. Then the assembled parts are transferred to the next fixture, and the second spot weld is done. For welding the third and fourth spots, the parts are transferred to fixtures three and four, respectively.

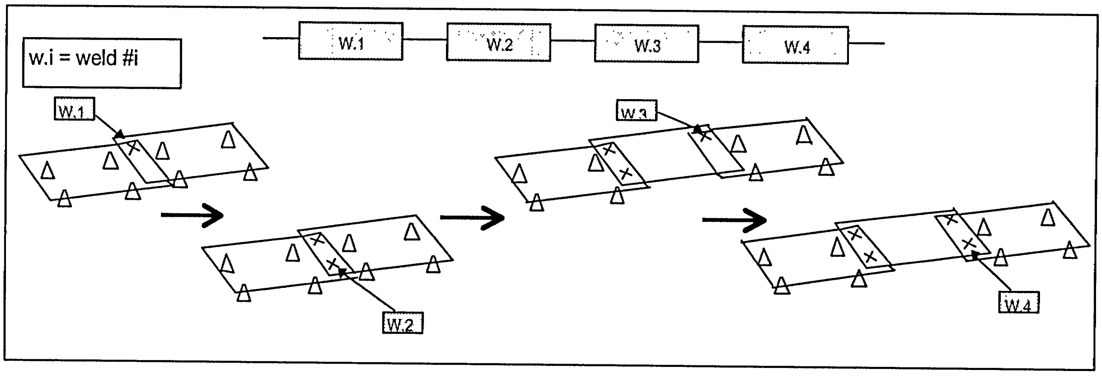


Figure 20. Simulation for a serial system configuration.

The production from this system is 1,200 assemblies per day, maximizing the throughput of the individual machines. From the results of the variation simulation (i.e., mean deviation and 6-sigma values of the audited point), the deviations of the audited point in the Z-direction can be plotted. A typical result for such a serial system (Figure 21) shows a normal distribution because only one material-flow path exists in a serial assembly system.

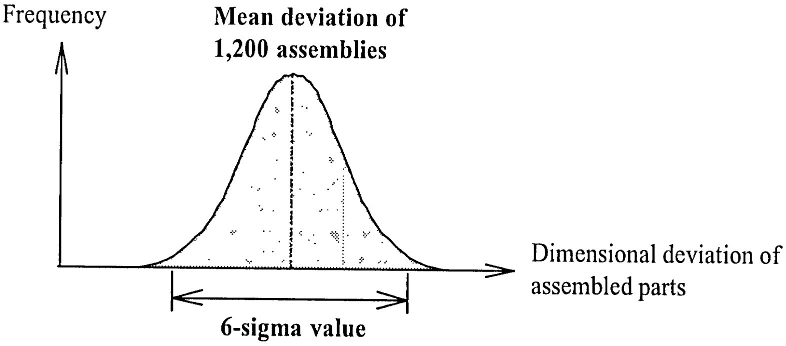


Figure 21. An example of a histogram of dimensional deviation for the serial system configuration.

4.3 Parallel System

In the parallel assembly system, four spots are welded sequentially (Figure 22). However, each station in the system performs all four tasks (i.e., welding 4 spots), and the clamps are not released between welds. Therefore, as each machine has four times as many tasks, and is capable of performing only one at a time, the cycle time on each machine is approximately four times as long. Thus, in order to maintain the same throughput as the serial assembly system, the four stations must be connected in parallel.

In the real world, it is impossible for these four stations to be perfectly identical in terms of the setup conditions. As a result, the dimensions of the products produced by these four stations may show four different distributions, even though the incoming parts have a common distribution. This problem is addressed by the incorporation of tool variation in the mathematical model. Each station has its own unique set of tooling with deviations from nominal sampled from a random distribution, as previously described. Thus, none of the four stations will produce parts with the exact same distribution as another station. As the deviations for the tooling are taken from the same stream as for the serial system, the differences in setup do not artificially create a bias towards either system.

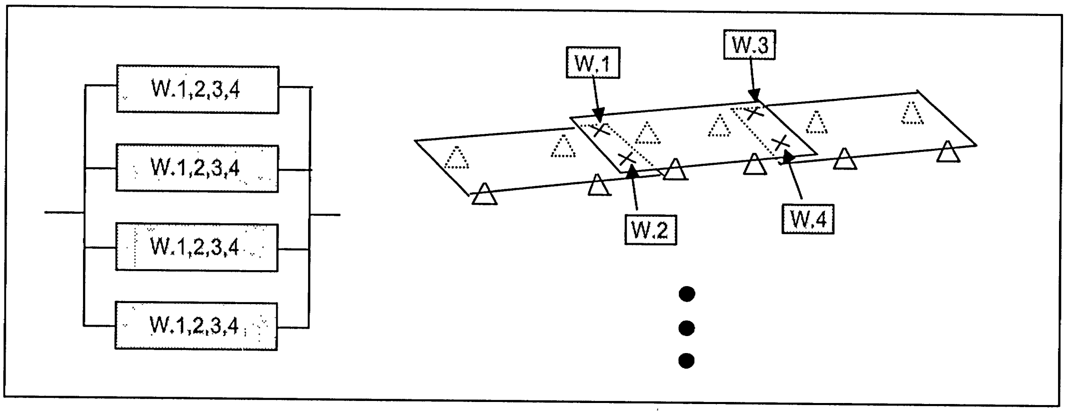


Figure 22. Simulation for the parallel system configuration.

The four stations produce a total of 1200 assemblies each day. As each station produces 300 assemblies per day, at 4 welds per assembly, the throughput for each individual station is maximized, and the overall system meets system throughput targets. Figure 23 demonstrates an example of the deviations produced by such a system. With different setup misalignments, each station produces its own unique distribution, resulting in an overall product distribution with 4 local concentrations of part deviations, which may or may not be closely spaced, depending upon the degree of misalignment.

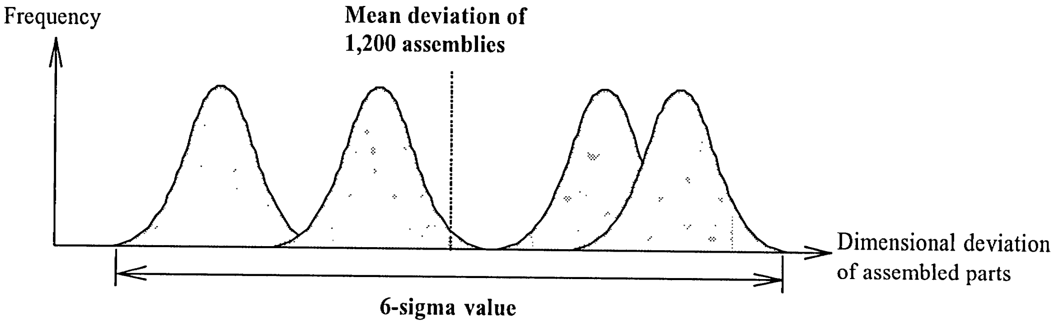


Figure 23. An example of a histogram of dimensional deviation for a parallel system configuration.

4.4 Parallel-lines System

In a parallel-lines assembly system, two spots are welded at each station, until all four spots have been welded (Figure 24). As each machine performs two welds, its part throughput is cut to 600 parts per day (600 parts/day * 2 welds/part = 1200 welds/day). As a result, each branch of the system is capable of producing only 600 parts per day, so two branches must be used to produce the required throughput.

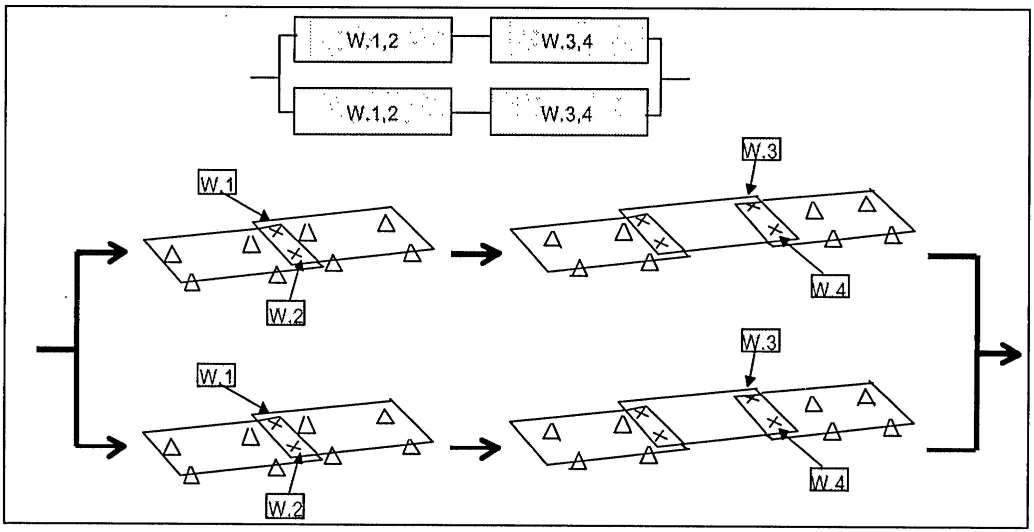


Figure 24. Simulation for the parallel-lines system configuration.

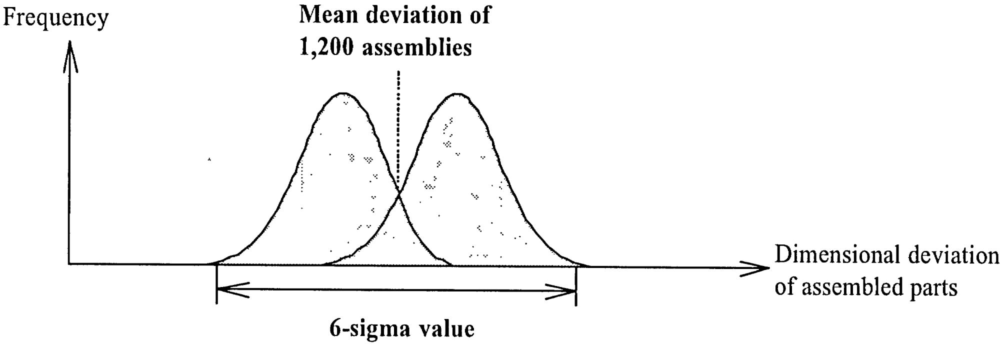


Figure 25. An example of a histogram of dimensional deviation for the parallel-lines system configuration.

Again, the same levels of misalignment are used for the up/down datums (random numbers between -1 mm to 1 mm), and therefore the products passing through these two different assembly paths may have different dimensional distributions. A typical example of the output of such a system (Figure 25) contains two distinct distributions for part deviation. The 6-sigma values for each of these distributions tend to be narrower than in the serial system, with overall system six-sigma dependent upon the amount of misalignment between the two paths. Unlike the parallel system, this configuration does not show four unique distributions because no product mixing is allowed during transfer from the first to the second stage of assembly; i.e., parts may not be taken from the first machine in one branch and transferred to the second machine in the other branch.

4.5 Serial-groups System

A serial-groups system is set up in a manner almost identical to a parallel-lines configuration. Two spots are welded in each station, until all four spots have been welded as shown in Figure 26. Two stations connected in parallel form a station group, and there are two station groups connected in a series in the system. This system has the same design throughput as that of a parallel-lines assembly system, as each station is performing the same number of tasks.

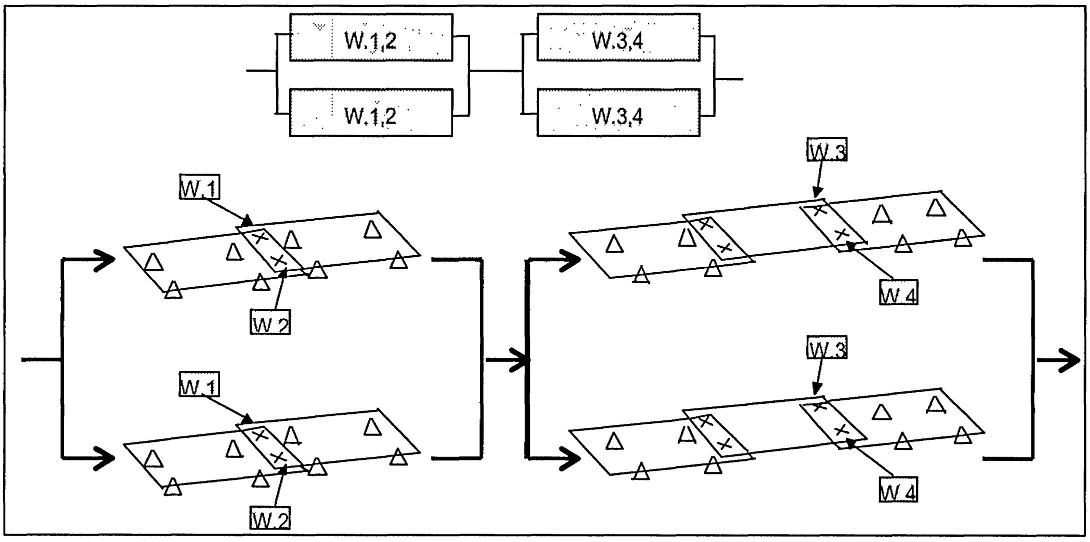


Figure 26. Simulation for the serial-groups system configuration.

The difference between the serial-groups system and the parallel-lines configuration is with the allowing of product mixing after the first two welds are completed. Therefore, there are 4 possible paths of material flows in the system, and 1,200 assemblies are produced evenly through these 4 paths (i.e., 300 assemblies for each path). Because of the different levels of misalignment assigned to the tooling, the products passing through these four different assembly paths may have four different local dimensional distributions (Figure 27). Once again, the overall distribution is determined largely by the degree of misalignment. To prevent artificial bias, the same misalignments as used in the serial system were used once again for this configuration.

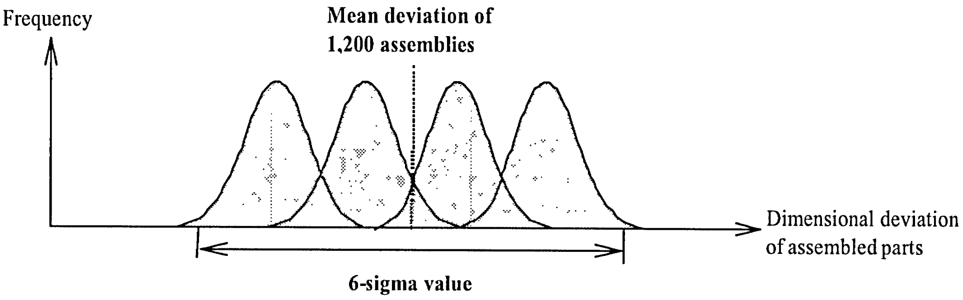


Figure 27. An example of a histogram of dimensional deviation for a serial-groups system configuration.

4.6 Simulation Results

For the all the tested system configurations, CAVA gave a histogram of the deviation of the simulated 1,200 parts (Figure 30). While the overall variation may be considered extreme for some purposes, such as automobile body assembly, the dimensions of the parts and the tooling variations were taken at large values. This, combined with none of the parts causing an increase stiffness in the final assembly, thereby decreasing variation (Liu, et. al. 1996), result in these large deviations. Testing of the CAVA algorithms against industry data has shown good results. Therefore, these values should be taken to show the scaling of the problem. In terms of individual results, the serial configuration demonstrates the expected single distribution with relatively large 6-sigma deviation. Overall mean deviation is 17.45 mm and the 6-sigma variation is 65.80 mm.

For the parallel assembly system, the overall mean deviation is 2.01 mm and 6-sigma value is 101.18 mm. Although the histogram appears to be composed of just two distributions, examination of the plot reveals that the left distribution consists of approximately 75% of the total parts. That reveals the underlying cause of this uneven "dual" distribution as being three of the four stations having similar deviation in tooling, with the fourth having a setup leading to a significantly different distribution.

The parallel-lines assembly system shows that the tooling setups result in fairly similar distributions, and thus the appearance of a single distribution. In this case, the overall mean deviation is 4.46 mm and 6-sigma value is 23.25 mm.

Finally, the serial-groups assembly system simulation results in an overall mean deviation of 4.39 mm and 6-sigma value of 56.57 mm. In this case, it is clear that there are multiple distributions combining to form the overall distribution. One appears to be centered around 20 mm, one around –7 mm, and the two corresponding to the remaining two paths through the system are near 5 mm.

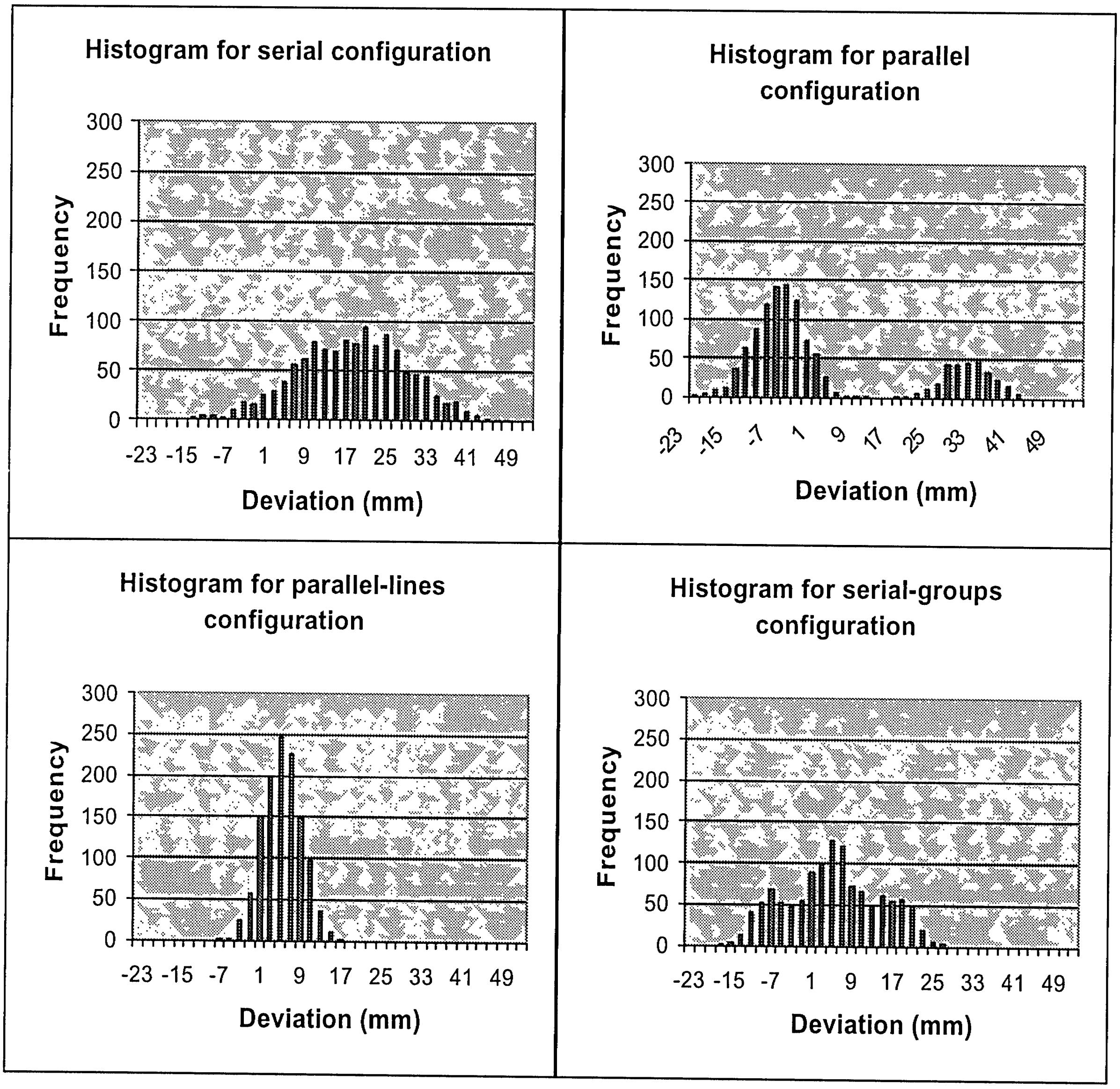


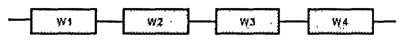
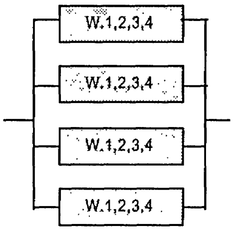
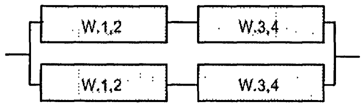
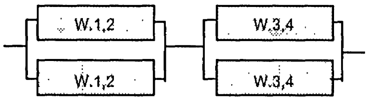
Figure 30. Histogram results from the simulations

4.7 Comparison and Discussion

Close analysis of the simulation results presents some basic relations between the number of flow paths, number of machines passed through, setup errors, mean deviation, and six-sigma variation (Table 2). As the number of flow paths increases, the six-sigma level of variation tends to increase. This is evident when comparing the serial system to the parallel, and the parallel-lines configuration to the serial-groups. In both instances, the number of possible flow paths increase, from 1 to 4 and from 2 to 4, respectively. These increases result in the six-sigma variation increasing by at least 53.7%.

This is largely a result of the setup errors and misalignment between paths. For example, if the setup errors for the four paths in the parallel system were –1 mm, -0.33 mm, +0.33mm, and +1 mm, the distribution of parts might look somewhat similar to Figure 27. In this case, although the variation for parts coming from each path may be small, the six-sigma for the entire product line would be very large. If the individual lines could be made more similar in terms of setup errors, the four distributions might converge to form a single, narrow distribution, and thus have a lower level of variation. The same holds true for the serial-groups and parallel-lines combination.

Table 2. Variability of different system configurations.

System Configuration	Block Diagram	Mean Deviation of Audited Point	6 Sigma of Audited Point
Serial		17.45 mm	65.80 mm
Parallel		2.01 mm	101.18 mm
Parallel-lines		4.46 mm	23.25 mm
Serial-groups		4.39 mm	56.57 mm

Despite this, there is a drop in the variation between the serial line and the parallel-lines configurations, even though the number of possible flow paths increase. This is a reflection of the number of machines the parts pass through. Every time a part is moved from one fixture to another, a stack-up of variation from tooling occurs. If all the processing were done on a single fixture, such as the case in a pure-parallel system, the major contributors to variation would be the deviation of the fixture from nominal and the incoming part variation. For each additional machine added to the line, an additional source of error is introduced, and therefore variation increases. Thus, this effect tends to offset the negative impact which increasing the number of flow paths might have, as can be seen from the change between the pure-serial line and the parallel-lines configuration. Although the number of flow paths doubles, the tooling variation stack-up from two machines is far less than from four, thus actually resulting in a decrease in the six-sigma level.

As configuration pertains to mean deviation, a similar effect is evident. Each distribution caused by a flow path has its own separate mean and standard deviation. With a single flow path, there is only one distribution present. Therefore, the mean deviation of all assemblies is subject to that single case created from a single set of misalignment problems in the individual machines. Thus, if the misalignments cause the assemblies to have large deviations from the nominal, the configuration as a whole shows this deviation. However, if there are two flow paths, then there are two individual distributions. These distributions will tend to offset each other if there is no consistent problem causing the fixtures to tend to near identical misalignments. Therefore, the overall mean deviation tends to decrease with an increase in the number of flow paths. Similarly, a decrease in the number of machines on a given path will result in lower mean deviations. Therefore, in terms of mean deviation, it appears as if a pure-parallel configuration is the optimal choice. As the system becomes more serial in nature, selection of configurations such as serial-groups over parallel-lines is also preferred to control mean deviation, as such configurations offer more flow paths. Clearly, the popular pure serial line is the worst of the options, and is only desirable if the process can be controlled to center the distribution of assemblies around the nominal, which is very difficult to ensure.

5. SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

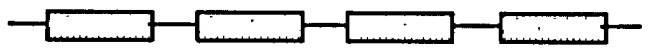
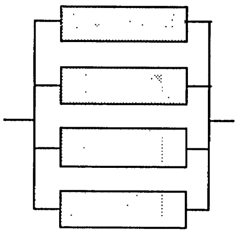
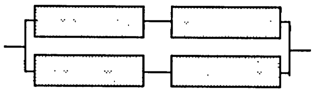
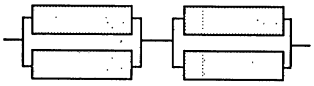
Advancements in control technology have led to the implementation of system configurations other than traditional pure-serial lines in the assembly of many sheet metal products, including automobiles. These configurations have been implemented for various reasons, including increased productivity and improved quality, but the tradeoffs between various configurations to this point have not been well documented and are not well-understood. The purpose of this work was to begin to qualitatively build some relations and understanding between system configurations and performance parameters by looking at a small case study of a four machine system, charged with the task of welding three sheet metal parts together via four welds.

System reliability has traditionally been a well-used index of overall system performance. However, as shown in §3, system reliability is often an inaccurate and misleading representation of the performance of the system, as it does not account for the loss in production that occurs if, for example, one station in a pure-parallel system fails. In its place, the system productivity was examined in §§3.1.1-3.1.3. This measure simply uses the reliability of the individual stations to predict the percentage of the design throughput that the system will be able to achieve in operation. From the results of this analysis, it is clear that the trends follow those set by the system reliability, but with smaller differences between the various systems. As in the case of system reliability, in the pure serial configuration, as the number of stations increases, the system productivity drops sharply, especially if individual machine reliability is low. In the pure-parallel system, however, a different effect is realized than that given by system reliability. As the number of stations increases, the system reliability increases sharply, especially when the individual machines have low reliability. This does not hold for system productivity, as for this case productivity is essentially the mean of the individual machine reliabilities. Thus, such a system will not look as attractive when considering productivity as when considering reliability (Table 3).

For hybrid configurations, the two main contributing factors to both system reliability and system productivity are the number of flow paths and the number of groups/stations in serial. As the number of flow paths increases, the likelihood that the system will be operating increases, and therefore so does the expected productivity. However, just as in the case of the pure parallel system, using system reliability as a measure of system performance can exaggerate this improvement, as can be seen from the difference between the parallel-lines and serial-groups configurations. Furthermore, as the number of groups or stations in serial increases, the expected productivity decreases rather sharply.

System productivity and reliability are not the only performance measures affected by system configuration; as shown in §4, product quality, as defined by both the mean deviation and the 6σ level of variation, is similarly impacted. The system of three parts was examined using mechanistic variation simulation, which uses both incoming part variation and tooling variation in its mathematical models to predict the level of variation of the assembled product. Assuming that the accuracy with which the fixtures could be set up was independent of the system configuration, several clear trends appear in the resulting part quality. As the number of stations in serial increases, the individual setup errors from the fixtures stack up and cause a large amount of variation in the assembled product. As a pure serial line has only one flow path, the resulting assemblies have only one characteristic distribution, which is subject to a large amount of deviation from the nominal in addition to its large standard deviation.

Table 3. Summary of Results.

System Configuration	Block Diagram	Mean Deviation	6-Sigma Deviation	Reliability	Expected Productivity (parts per day)
Serial		17.45 mm	65.80 mm	.306	.306 (367)
Parallel		2.01 mm	101.18 mm	.997	.75 (900)
Parallel-lines		4.46 mm	23.25 mm	.824	.565 (678)
Serial-groups		4.39 mm	56.57 mm	.893	.5995 (719)

As the number of flow paths increases in a system configuration, two primary trends become evident. First, for each unique flow path in a system, there is a characteristic distribution for the assembled products. Therefore, for a system with four flow paths, there are four unique distributions which combine to form the overall distribution for the product. The result is a set of assemblies which may on average be significantly closer to the nominal, as one distribution which is biased to the negative side of the nominal may offset one to the positive side. In contrast, if the four distributions are not nearly identical, the standard deviation of the combined distribution is significantly larger, as previously demonstrated with Figure 27. Thus, an increase in the flow paths tends to have a negative impact on the standard deviation.

Therefore, the general effects of changes in system configuration on performance are as given in Table 4. The magnitudes of these trends depend on particulars, such as the parts, fixtures, station repeatability, etc. All things being equal, these trends are as given in Table 4.

Table 4. Impact of System Trends on Performance.

System Trend	Impact on Productivity	Impact on Product Mean	Impact on Product Standard Deviation
Increase in # of Flow Paths	Increases productivity, especially for low station reliability **Positive**	Brings the products closer to nominal **Positive**	Increases the standard deviation of the assemblies **Negative**
Increase in # of Stations in Serial	Decreases productivity, especially with low station reliability **Negative**	Results in larger deviation from the mean **Negative**	Results in a larger standard deviation from more stack-up **Negative**

These trends can be verified to hold for the case studies relatively easily. Starting with the case of the pure serial, any of the three remaining configurations results in both an increase in the number of flow paths as well as a reduction in the number of stations in serial. In this case, the trends would lead to the conclusion that any of the other systems would have higher productivity, and an improvement in the mean dimension of the assembled product. The impact on standard deviation is more difficult to predict, as the change in number of flow paths and the number of stations in serial tend to give opposing effects. In this case, it is clear that a reduction in number of stations in serial from four to two results in a significantly larger reduction in error resulting from stack-up than the corresponding increase in error resulting from mixing. However, by proceeding to the pure parallel configuration, the number of stations in serial is cut by 75% but the number of flow paths quadruples. In this case, the effect of the increase in flow paths outweighs the reduction in stack-up error, and therefore, the net is an increase in standard deviation.

Continuing with the parallel-lines configuration, a switch to serial groups configuration results in no change in the number of stations in parallel. Therefore, the only change is in the number of flow paths. As this is an increase, the expected result is an improvement in productivity and product mean, and an increase in standard deviation. Clearly, all of these expectations hold. Furthermore, changing from parallel-lines to pure parallel incorporates a reduction in the number of stations in serial as well as an increase in the number of flow paths. Therefore, the expectation is for improvements in productivity and product mean, and conflicting effects on standard deviation. Once again, these expectations hold with the simulation and analysis results, with the increase in standard deviation caused by the increase in flow paths outweighing the decrease in standard deviation caused by stack-up error.

Finally, for the case of serial-groups, the change to a pure parallel configuration results in a reduction in the number of stations in serial from two to one, with no accompanying change in the number of paths. Therefore, the expected result is for an improvement in all three performance aspects. From the case study, it is clear that this holds for system productivity and product mean, but the effect on standard deviation is opposite of that which is expected. This can be explained by the fact that the four paths in the serial-groups configuration are *not* in fact *independent*. That is, of the four paths, two use the same station in the first group and the other two use the second station, and therefore the four paths are in fact related. Thus, these four paths do not act in the same manner as four independent paths. As a result, the change from serial groups to a pure parallel configuration effectively includes an increase in the number of paths. This would not change expectations with regards to productivity or product mean, but could allow for an increase in standard deviation, as is seen in the test results. Therefore, the effect of changes in system configuration on system performance does seem to follow the trends presented in Table 4, with the addition of the effect of a change in the number of independent flow paths.

By considering both productivity and quality output of a system configuration, we conclude that with careful design, implementing a parallel-lines system configuration into existing serial assembly lines could help to improve both system productivity and output quality, as measured by the 6σ level of variation. By providing more system redundancy, a parallel-lines system can improve the productivity of a system using unreliable stations. Also, the output quality of the system can be improved because the number of serial fixtures is reduced in each processing path. However, the number of parallel lines should not be too large because assembly quality may start to deteriorate with too many possible processing paths (e.g., parallel systems).

Results from queueing theory propose that parallel systems are the best with respect to productivity. More specifically, larger parallel stations and fewer stations in series are better (Stecke and Solberg (1985), Dallery and Stecke (1990), Lee et al. (1991), Magazine and Stecke (1996)). However, we show here that these system configurations also result in larger 6ó variation in the output, especially for a pure-parallel system.

From this basic understanding about how different system configurations affect system productivity and quality variation, we can further study other performance characteristics of various assembly line configurations. For example, the analysis of changeover times of different system configurations is an important issue. The ideal production system is one that can adjust quickly and efficiently to maintain a continuous flow of product to the market. Choosing a configuration which has a shorter changeover time is vital for many industries, especially when competition is intense and market forces demanding, such as in automotive assembly.

Furthermore, the combined effect and trade-offs between all system performance measures should be studied. Here we addressed system performance measures individually. However, in most assembly systems, variation, productivity, changeover response, and throughput are all inter-related. No models yet exist to analyze these performance measures in an integrated manner. Therefore, it is necessary to establish a theory and methodology for modeling assembly system configurations and their performance in an integrated manner.

Finally, the link effect of varying capabilities among stations and their impact on system performance should be studied. That is, when each individual station has different performance parameters and capabilities, the placement of these stations within the configuration is expected to impact the overall system performance. In this study, all stations were assumed to be identical in all aspects except reliability.

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