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ANALYSIS OF VARIOUS AUTOMOTIVE BODY ASSEMBLY SYSTEM CONFIGURATIONS WITH RESPECT TO RELIABILITY, QUALITY, AND PRODUCTIVITY

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ABSTRACT

We first develop techniques for identifying the configuration of a body assembly system. These techniques are essential because of the increasingly sophisticated hardware adopted in modern automotive assembly plants. Then we use these techniques to benchmark the system configurations of three different automotive body assembly lines.

Then we analyze the system reliability of serial, parallel, and parallel-lines and serial-groups systems. Some results are the following: with constant machine reliability, an assembly system could become more reliable if it has more possible paths of material flow. A parallel system configuration has the maximum system redundancy, and its reliability is highest. A serial system configuration has only one path of material flow, so system shutdown cannot be avoided if any of its stations fail. A serial-groups system has a slightly higher reliability than a parallel-lines system has, and both of them are much more reliable than a serial system. If we want to increase the reliability of some critical processes, we can combine several tasks and then duplicate the lines to form a parallel system with not-so-expensive machines. We then analyze the same four configurations for their expected production and present these results also.

The relationships between sheet metal assembly quality and different assembly system configurations are investigated. Four different assembly system configurations (serial, parallel, and parallel-lines and serial-groups system configurations) are designed to produce the same sheet metal product. With the same sources of variation, we simulate how the dimensional variation of assembled sheet metal parts is affected by different system configurations. "Mechanistic variation simulation" is used to analyze the variation stack-up of deformable sheet metal part assemblies.

From the simulation results, we find that the more material-flow paths an assembly system has, the distribution of its products' quality is wider. Also, the parts processed through more serial fixtures may have a higher mean deviation.

1. INTRODUCTION

Automotive body assembly lines are composed of workstations coupled together in many configurations. Traditional automotive body assembly lines are serial. Jobs are processed at a fixed rate and pass through the same sequence of workstations. With advanced technologies, concepts such as variable processing times and parallel processing workstations are now available. Many new body assembly systems have more flexible configurations, in which serial and parallel processing workstations are implemented on the same line.

1.1 System Configurations

For clarification purposes, a serial system is one in which all stations are linked in series. The stations are so interrelated that the entire system will fail if any one of the stations fail. A parallel system will fail to function only when all of its stations fail. Hybrid systems are any combination of serial and parallel systems. Figure 1 illustrates these system configurations.

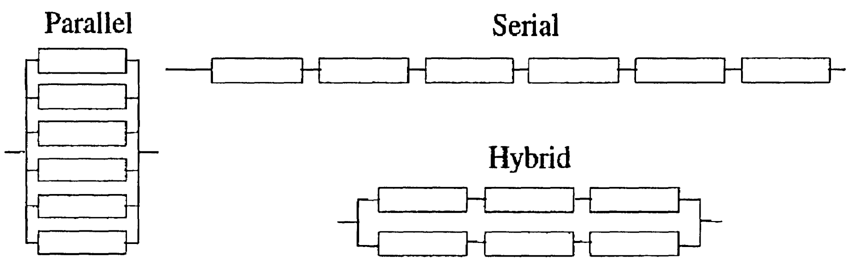


Figure 1. Serial, parallel, and hybrid system configurations.

It is generally known that configurations have significant influences on system performance in terms of reliability, maintainability, throughput, and quality variation. But to date, these performance characteristics of various assembly system configurations are not yet understood. Besides, with increased flexibility in line design, there is a need for guidelines to help choose between alternative configurations.

The plan of the paper is as follows. The literature is reviewed in the remainder of this section. In §2, we first benchmark existing body assembly system configurations in the domestic auto manufacturers. Several of these assembly lines are examined and their system configurations are plotted as block diagrams. Then we study how these configurations are implemented in the current automobile industry. In §3, we analyze and compare the reliability as well as productivity of different system configurations. Finally, in §4 we simulate and compare the quality variation of four different body assembly system configurations. Because flexible sheet metal parts are no longer considered as rigid bodies, "mechanistic variation simulation" (Liu and Hu, 1997) is used to simulate the quality variation. This paper provides information on how the performance characteristics of assembly lines are affected by different system configurations. Then guidelines for selecting assembly line configurations can be developed.

1.2 Literature Review

The literature review consists of two parts. In §1.2.1, the focus is on production system configurations. Variation simulation is reviewed in §1.2.2.

1.2.1 Production System Configurations

Understanding the production system configuration effects is important in the design of a production system because of its impact on the cost of material handling, reliability, productivity of the facility, and quality of the output. Traditionally, manufacturing systems have been divided into two categories based on their physical layout. The first category is the line (product) layout, where machines are organized in a serial manner to process a single type of part or a very limited family of part types. The second category is the functional layout (process or job shop) where the machines are organized into groups according to capabilities.

The development of parallel systems influences the implementation of manufacturing system configurations. "... parallel processing systems may be designed into flexible assembly system. A parallel processing system is a set of workstations operating in parallel. There are several benefits associated with such systems. For example, since parallel processing is designed by combining more operations into workstations and operating them in parallel to match the line speed, the production volume can be adapted to fluctuating demand by adjusting the number of parallel workstations. This design process also reduces the number of assembly stages and may help eliminate some underlying inefficiencies (e.g. idle times). Another advantage is that an individual workstation can experience problems without a major impact on the whole system" (Udomkesmalee and Daganzo, 1989). Other advantages of parallel machining are presented in Spur et al. (1986). "The advantages of simultaneous processing are: 1. High utilization of capacity units; 2. Short order flow time corresponding to a minimum of work in progress; and 3. Reduced requirements for work pieces storage."

The throughput obtained from a variety of configurations was studied using a closed queueing network model by Stecke and Solberg (1985), Dallery and Stecke (1990), and Lee et al. (1991). They showed that all possible partitions of m machines into n groups of parallel machines an be ordered according to maximum expected production. In particular, the best configuration is m parallel machines. Fewer groups of parallel machines are better than more groups. For n groups of parallel machines, the more unbalanced allocation of machines to groups is better. For example, for a system of 4 machines and 2 groups of parallel machines, the configuration of 1 and 3 machines per group is better than the configuration of 2 and 2 machines per group wrt expected production.

Blumenfeld (1989) also looks at balanced vs. unbalanced work stations. He develops an analytical model to compare throughput for various configurations. Weber (1997) investigates throughput for a variety of configurations. His application is for machining systems.

Daganzo and Blumenfeld (1994) developed an analytical model to evaluate serial, parallel, and mixed assembly system configurations. Its purpose is to identify when each configuration is cost-effective. The analysis provides preliminary results as a first step towards establishing basic principles for assembly system design. Results indicate that the optimal trade-off depends simply on the ratio of labor to equipment costs. The trade-off analysis is used to address some practical considerations in assembly system design, including ways to achieve high utilization of both labor and equipment.

Impact of parallel processing on job sequences was addressed by Smith and Stecke (1996), Buzacott (1990), Udomkesmalee and Daganzo (1989), and Whitt (1984). Parallel processing offers several advantages. However, when processing varies, it can result in unpredictable job sequences. Models were developed to illustrate these problems and the effect of alternative part delivery systems and the impact of job resequencing requirements.

There are several ways of achieving a higher production rate, e.g., the use of overtime, another assembly line, subcontracting, buffer stocks, and paralleling. Although paralleling has been suggested as a way of improving the assembly line design, it has not been explored with regard to cost trade-offs with other alternatives. An extensive review of line balancing for assembly systems is given in Ghosh and Gagnon (1989). Other papers that address line balancing issues include Hackman et al. (1989), Johnson (1988, 1991), and Malakooti (1991). Line balancing algorithms that specifically consider parallel stations are given in Pinto et al. (1975, 1981).

A methodology to design flexible assembly systems is provided in Lee and Stecke (1996, 1998). Given the input data of candidate machine types, products to be assembled (the task times and precedences among tasks), and the candidate materials handling systems, several interacting models are used to result in an assembly system configuration to meet the maximum expected demands of the products. Assembly line balancing algorithms are imbedded in the models (Lee and Johnson, 1991).

The design and configuration of a manufacturing system requires crucial decisions concerning product mix and capacity. These might involve choosing between dedicated and multi-product facilities, large capacity machines versus a pool of smaller capacity machines, etc. Models are developed which demonstrate that factors like inventory holding costs, lead times, and batch sizes of manufacture play a significant role in capacity and mix decisions (Karmarkar and Kekre, 1987). The problem of determining the optimal amount of workspace in assembly lines having a large number of variations in the product is also addressed in Rachamadugu and Shanthikumar (1991).

To date, no literature is found to investigate the relationship between quality of the output and system configurations.

1.2.2 Variation Simulation

The level of variation is one important measure of product performance. Variation levels can be predicted through models generated by variation analysis. Variation simulation analysis is a procedure which can evaluate the effect of part variation on design function. Usually it is necessary to find the variation analysis model between the design function (y) and the independent variables (x_i): $y = f(x_1, x_2, \ldots\ldots, x_n)$, where n is the number of components involved. For an assembly process, y is the assembly dimension, and the x_i's are the component dimensions. A special case is when the function f is a linear function: $y = a_1x_1 + a_2x_2 + \ldots\ldots + a_nx_n$.

Since tolerance is defined as the permissible level of variation, the techniques used for variation simulation analysis are the same as those used for tolerance analysis. There are currently three primary methods available for the analysis of assembly tolerance (variation). These methods are worst case analysis, root sum square (RSS), and simulation. The worst case method is the first method to use for one-dimensional assemblies. It evaluates the assembly under the assumption that all components are built to their extreme values (see Chase and Greenwood, 1987; Dong et al., 1994; and Dong and Soom, 1990). In practice, the worst case method will lead to tight or unrealistic tolerances for the parts in order to keep the final assembled product within the specification. In the RSS method, the variations of component parts are specified as statistical distributions. The distribution of the design function must be calculated based on part distributions. The RSS method yields a more realistic estimate and looser component tolerances than the worst case method (Greenwood and Chase, 1990; Lee and Woo, 1990; Spotts, 1978; 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. A detailed review is given in Juster (1992), Roy et al. (1991), Chase and Parkinson (1991), and Wu et al. (1987). Monte-Carlo simulation can be applied to more complex assemblies. It creates a statistical distribution of an assembly by randomly selecting values from the known distributions of the component parts and a mathematical description of how these parts are assembled (Craig, 1989; Early and Thompson, 1989).

For better assembly variation prediction, all of these variation analysis methods require information about part and tooling variation.

In the past, sheet metal parts were assumed to be rigid in the analysis of assembly variation. The assembly variation was obtained by stacking up the variation of individual "rigid" components. Under this assumption, one should tighten the tolerance of the individual parts to achieve desired assembly variation. As a result, the new designs often come with a part tolerance that is too tight to be realistic on the manufacturing floor. Takezawa (1980) first proposed that parts in sheet metal assembly cannot be treated as rigid bodies. Components with low rigidity are less elastic and such parts have little influence on the final assembly. The assembly variation can be predicted by using a linear regression model. Based on real production data, he successfully used this model to analyze the variation stack up of an automotive assembly process.

Tooling variation has strong impact on the quality of the sheet metal assembly. Tooling variation can be minimized by using robust and well-designed fixtures. Fixture designs are analyzed in terms of their ability to arrest translation and rotation, while minimizing deflection and distortion of the part during processing (Chou et al., 1989). In research that constructs force-closure grasps based on the shape of the grasped object, Nguyen (1988) classified the locators into three categories: frictionless point contact, hard-finger contact, and soft-finger contact. DeMeter (1994) extended Nguyen's research by considering the planar, spherical, and cylindrical surface contacts between workpiece and fixture elements. Kinematical and mechanical methods such as screw theory (Asada and By, 1985) and force equilibrium equations (Salisbury and Roth, 1983) are most often used for a functional configuration of the fixture. Several other approaches for synthesizing better locating points were proposed (Mani and Wilson, 1988; Menassa and DeVries, 1989). 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. Although such advances in fixture design can greatly improve fixture accuracy and repeatability, fixture faults are still the major root cause of autobody dimensional variation (ABC, 1993). Methods for the design and the evaluation of fixtures of deformable sheet metal workpieces were proposed by Youcef-Toumi et al. (1988) and Rearich et al. (1993). The results from the optimization studies have been used in a cost function analysis to determine the optimal number of fixture elements in an automotive assembly process.

2. BENCHMARKING EXISTING BODY ASSEMBLY SYSTEM CONFIGURATIONS

Now we benchmark existing body assembly system configurations that are implemented in the automotive industry. Several assembly lines are examined. Their system configurations are plotted as block diagrams. Then we study how different configurations are applied in the current automobile industry.

When examining automotive body assembly lines, the first task would be identifying what type of system configurations they are. This is not always clear since more advanced technologies are adopted in a modern automotive assembly plant. Figure 1 illustrates block diagrams for serial and parallel system configurations.

We find that other than serial configurations, most common manufacturing systems are hybrid. That is, they are the combination of interrelated serial- and parallel- subsystems. One example is a system that has several duplicated serial assembly lines. These identical assembly lines are connected in parallel, i.e., they share the same sources of incoming parts, and their products are mixed at the end of the system. Figure 1 also illustrates this typical hybrid system.

It is not always easy to identify hybrid systems. For example, turn-tables are commonly seen in body assembly lines. We can view the turn-tables along with their supporting equipment as a production unit which has a hybrid system configuration. Figure 2 shows two turn-tables that operate along with two operators and robots.

Assume that there are four identical fixtures (labeled 1 - 4) on each turn-table. These two turn-tables rotate counter-clockwise, and they always remain synchronous. At the left-hand turn-table, the operator loads a part onto an empty fixture, while robots *A* and *B* simultaneously weld parts that are rotated into their working areas. At the same time, robot *C* picks one part from the left-hand turn-table and loads it onto an empty fixture at the right-hand turn-table. Also, robots *D* and *E* weld parts that are rotated into their working areas at the right-hand turn-table. Then an operator unloads the finished part from the fixture.

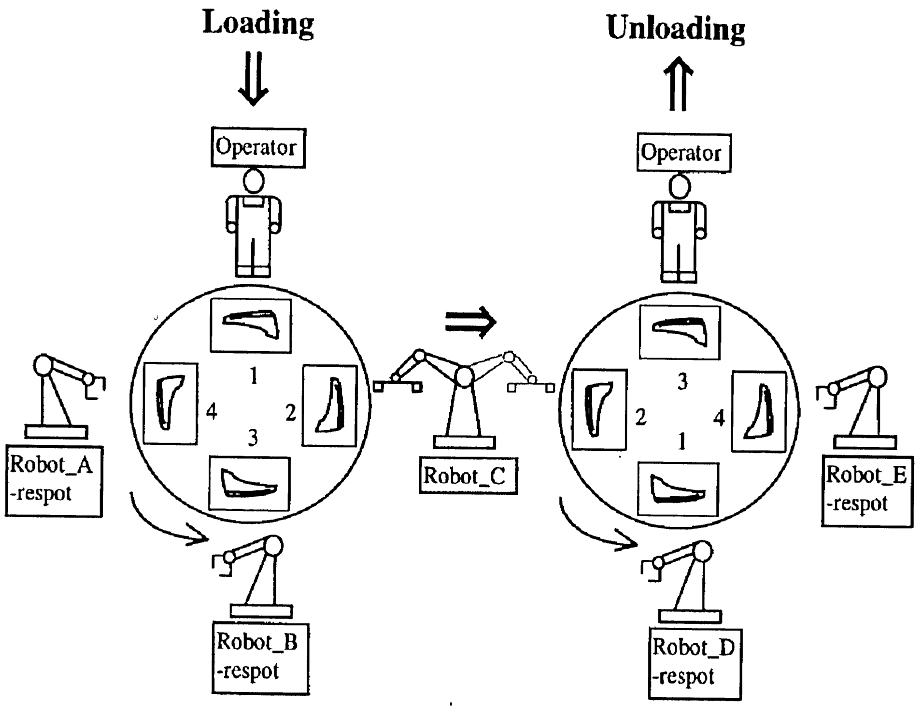


Figure 2. Two turn-tables with operators and robots.

Each part is processed in turn by robots *A* and *B* after being loaded onto one fixture. After transferring to another fixture, the part will then be processed by robots *D* and *E* before unloading. This process is an example of a hybrid system configuration. Each part has multiple value-adding paths (four identical fixtures on each turn-table). Since two turn-tables are synchronized, the number of possible paths remains four (e.g., the part loaded on fixture number 2 at the LH turn-table will only be transferred onto fixture number 2 at the RH turn-table). Within each path, the value-adding processes are in a serial order. Figure 3 illustrates the block diagram of this hybrid configuration (a parallel-lines system configuration); A, B, C, and D denote the labels of robots shown in Figure 2; 1 - 4 denote the number of the four fixtures at each turn-table.

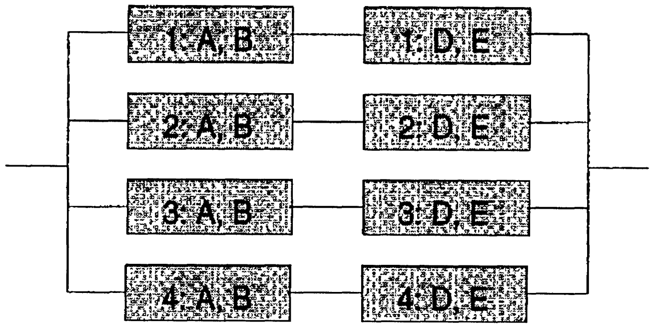


Figure 3. A parallel-lines hybrid system configuration.

If we assume that these two turn-tables are *not* synchronized, then the part coming from the LH turn-table can be randomly put on any of the fixtures on the RH turn-table. In this way, the number of value-adding paths increases from 4 to 16. Figure 4 illustrates this kind of hybrid configuration (serial-groups system configuration).

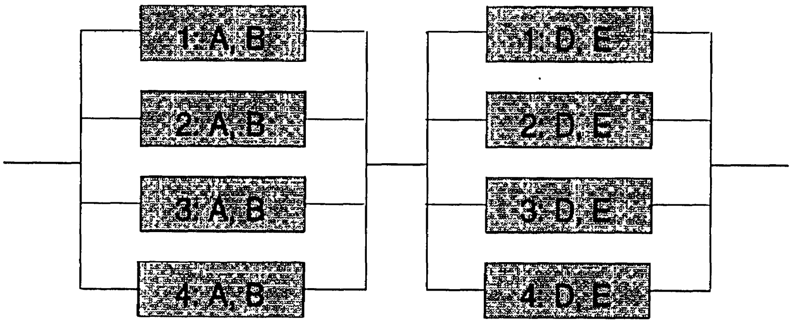


Figure 4. A serial-groups hybrid system configuration.

2.1 Benchmark #1

The assembly line of underbody (model A) is examined from a system configuration's point of view. The concepts developed earlier are applied in identifying system configurations. The underbody consists of three main components: engine compartment, floor pan, and rear compartment pan (see Figure 5).

The subassembly line for the engine compartment has a hybrid system configuration, and the other two subassembly lines have serial system configurations. The block-diagram of this assembly line is shown in Figure 6.

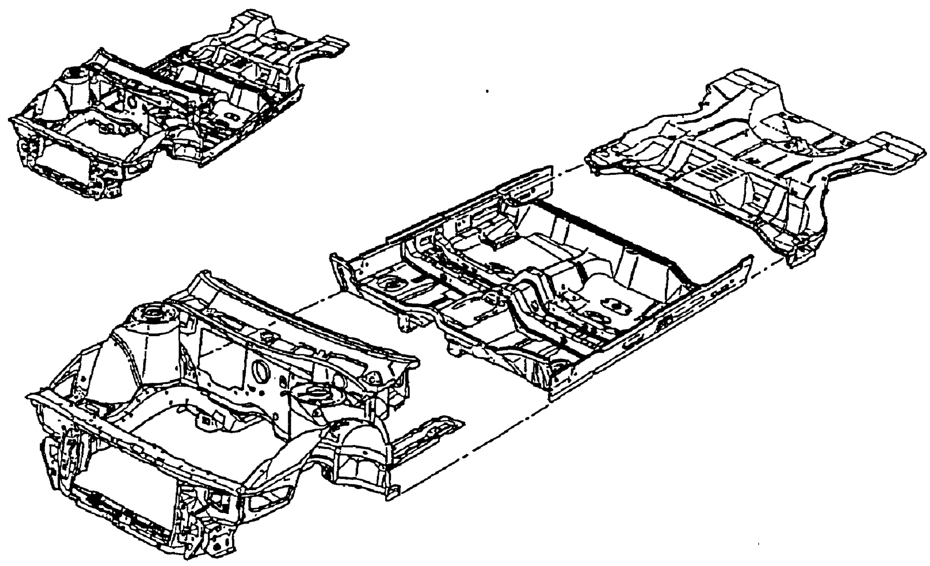


Figure 5. An underbody (model A).

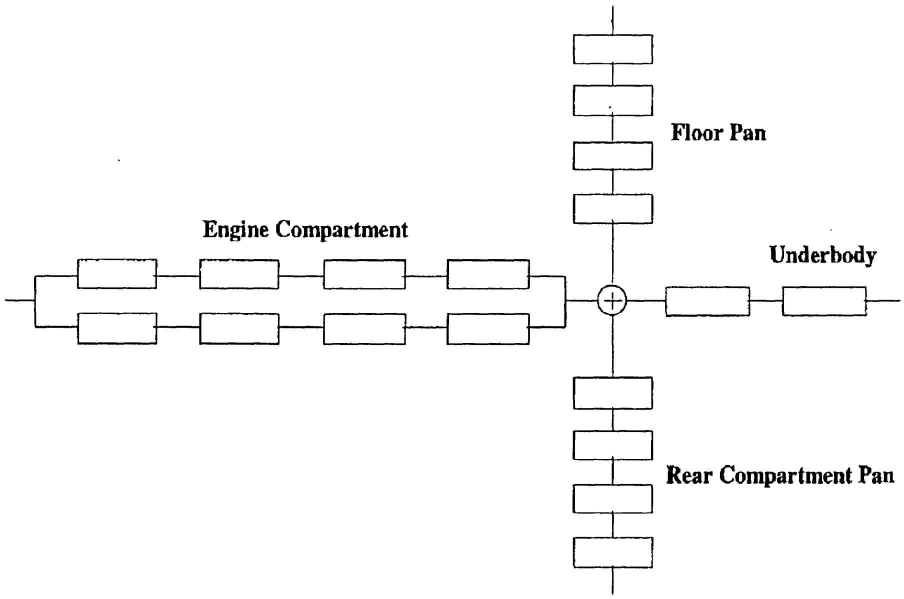


Figure 6. The assembly system configuration block-diagram for an underbody (model A).

2.2 Benchmark #2

A truck cab (model B) consists of a floor panel, back panel, dash, apertures, and roof. Figure 7 shows part of a cab (model B).

The block diagram of the assembly line is shown in Figure 8. Most of its sub-assembly lines have serial system configurations.

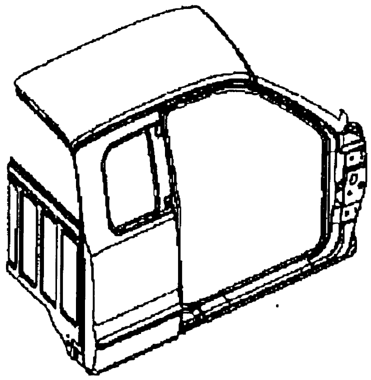


Figure 7. A cab (model B).

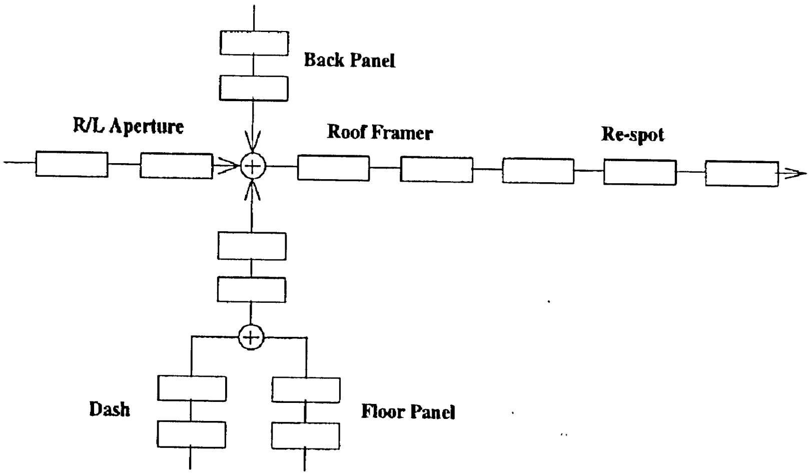


Figure 8. The assembly system configuration block-diagram for a cab (model B).

2.3 Benchmark #3

The assembly line of a truck cab (model C) is examined from the system configuration's point of view. Figure 9 shows a cab (model C).

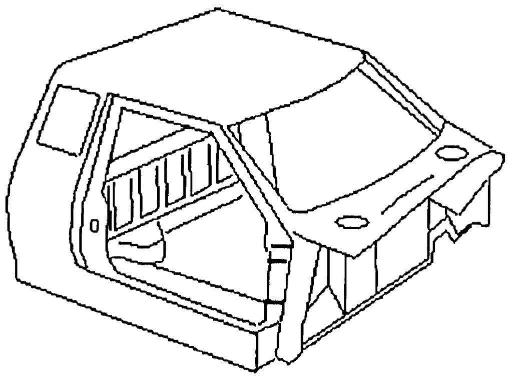


Figure 9. A cab (model C).

The block diagram of the assembly line is shown in Figure 10. This system has a serial-groups configuration.

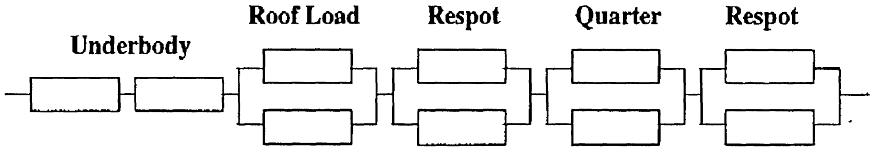


Figure 10. The assembly system configuration block-diagram for a cab (model C).

We find that most common body assembly system configurations are serial configurations. They still dominate in all three automotive body assembly lines. But more parallel-lines configurations are being adopted by car makers in recent years, as we see in Figures 6 and 10.

3. ANALYSIS OF RELIABILITYAND PRODUCTIVITY

Reliability is a characteristic of a system, generally designated by R, and expressed by the probability that an item will perform its required function under given conditions for a stated time interval. A numerical statement of reliability (e.g., R=.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 and consequently less downtime and loss of production.

There are some general reliability functions. Consider the case in which a fixed number N_0 of identical components are tested. Let $N_s(t)$ = number of components surviving at time t and $N_f(t)$ = number failed at time t. Then $N_s(t) + N_f(t) = N_0$.

At any time t, the reliability (or survivor) function R(t) is given by

$$R(t) = \frac{N_s(t)}{N_0} = \frac{N_0 - N_f(t)}{N_0} = 1 - \frac{N_f(t)}{N_0}.$$

Similarly the probability of failure F(t) is $F(t) = \dfrac{N_f(t)}{N_0}$.

A standard procedure for evaluating the reliability of a system is to decompose it into its constituent components, estimate the R of each of these components, and finally combine them using numerical techniques to estimate the reliability of the system. The level to which the decomposition is taken must be such that the reliability of the resulting components are known with reasonable and acceptable precision. It may therefore not be necessary to decompose the system into individual real components but into a set of devices or subsystems, the reliability of which is known from experience or is easy to obtain (Billinton et al., 1983).

Classically, reliability and productivity are related. However, the relationship changes when parallel machines are introduced. For example, a two-machine parallel system, when one machine fails, the reliability is still 100%, while the productivity is only 50% (see Koren et al., 1998).

3.1 Serial System

Consider a system consisting of four independent stations A, B, C, and D connected in a series (see Figure 11). This arrangement implies that all stations must work to ensure system success. Let R_A, R_B, R_C, and R_D = probability of successful operation of station A, B, C, and D, respectively. Then the system reliability (R_S) is (Sherwin and Bossche, 1993): $R_S = \prod_i R_i = R_A R_B R_C R_D$. System success and system failure are complementary events. Therefore, the probability of system failure is: $F_S = 1 - R_S = 1 - \prod_i R_i$.

Figure 11. An example of a serial configuration.

Here we give an example. Assume that R_A = .85, R_B = .60, R_C = .75, and R_D = .80. The reliability and failure probabilities of the system are $R_S = R_A R_B R_C R_D = .306$ and $F_S = 1 - R_S = .694$.

Because of the product rule and the fact that each station has a probability of success 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 also decreases. This important concept is illustrated in Figure 12. It shows that the reliability of a serial system containing identical stations is a function of the number of series stations and the station reliability. This figure suggests that system reliability drops sharply as the number of series stations increases, especially for a system in which stations do not have very high individual reliability.

Now let us look at the productivity from this serial system. The *expected productivity* from this system is: $P_S = R_A R_B R_C R_D = .306$.

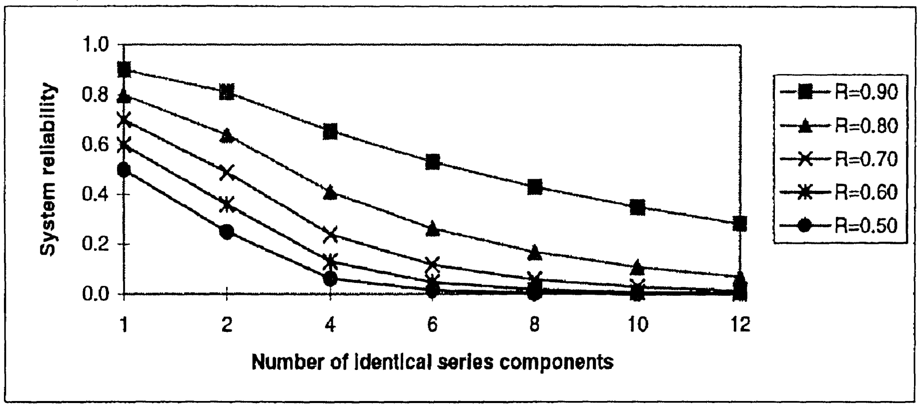


Figure 12. Effects of increasing the number of identical series components having reliability R.

3.2 Parallel System

Consider a system consisting of four independent stations A, B, C, and D connected in parallel (Figure 13). In this case, the system requirement is that only one station needs to be working for system success. In other words, this system can fail only if all its stations fail. The system reliability can be obtained by the following equation: $R_S = 1 - F_S = 1-(1-R_A)(1-R_B)(1-R_C)(1-R_D)$.

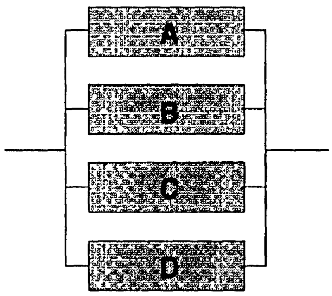


Figure 13. An example of a parallel configuration.

For comparison purposes, we also assume that $R_A= .85$, $R_B= .60$, $R_C= .75$, and $R_D= .80$. The reliability of the system is: $R_S = 1-(1-R_A)(1-R_B)(1-R_C)(1-R_D) = .997$ and $F_S = 1 - R_S = .003$.

Figure 14 demonstrates that as the number of stations in parallel increases and as the station reliability increases, the system reliability also increases. It shows that the reliability of a parallel system containing identical stations is a function of the number of parallel stations and the station reliability. This figure suggests that the system reliability rises sharply as the number of parallel stations increases, especially for a system in which the stations do not have very high individual reliability.

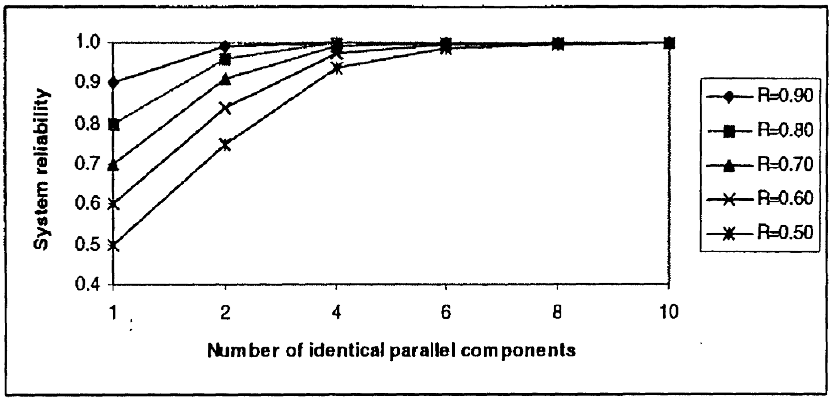


Figure 14. Effects of increasing the number of identical parallel components having reliability R.

The expected productivity from this particular parallel system is: $P_S = .25R_A + .25R_B + .25R_C + .25R_D = .75$. This example assumes that the workload per machine is balanced.

3.3 Hybrid Systems

Hybrid systems are combinations of serial and parallel systems. 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. A parallel-lines system consisting of four stations (two branches) is shown in Figure 15.

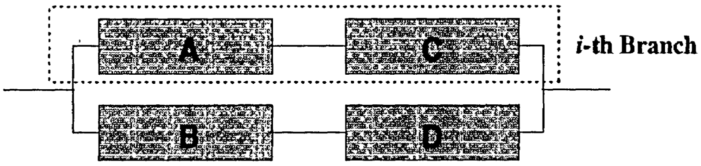


Figure 15. An example of a parallel-lines configuration.

For a parallel-lines configuration, the number of possible paths of material flow is equal to the number of branches in the system. The reliability of this system is: $P_S = .5R_AR_C + .25R_BR_D = .558$.

$$R_S = 1 - \prod_i \left(\text{Probability of } i\text{th branch failure}\right) = 1-(1-R_AR_C)(1-R_BR_D).$$

For comparison purposes, we also have that $R_A = .85$, $R_B = .60$, $R_C = .75$, and $R_D = .80$. The reliability of the system is: $R_S = 1-(1-R_AR_C)(1-R_BR_D) = 0.812$ and $F_S = 1 - R_S = .188$. The expected productivity from this particular parallel-lines configuration is: $P_S = .5R_AR_C + .5R_BR_D = .558$.

When a hybrid system is arranged so that there is more than one station group in the system, and each station group has several stations connected in parallel, then it is defined as a serial-groups system. A serial-groups system consisting of four stations (two station groups) is shown in Figure 16.

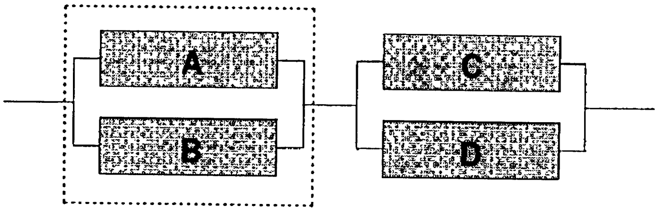


Figure 16. An example of a serial-groups configuration.

The reliability of this system is:

$$R_S = \prod_i (\text{Reliability of } i\text{th station group})$$

$$= [1-(1-R_A)(1-R_B)] * [1-(1-R_C)(1-R_D)].$$

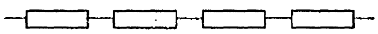
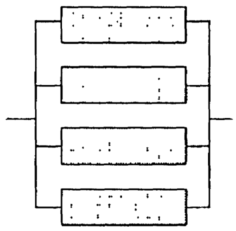
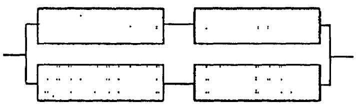
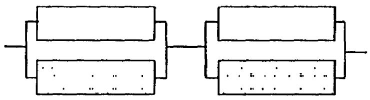
For comparison purposes, we have that $R_A = .85$, $R_B = .60$, $R_C = .75$, and $R_D = .80$. The reliability of the system is: $R_S = [1-(1-R_A)(1-R_B)] * [1-(1-R_C)(1-R_D)] = .893$ and $F_S = 1 - R_S = .107$. The expected productivity of this system is: $P_S = (.5R_A+.5R_B)(.5R_C+.5R_D) = .562$.

3.4 Comparison and Discussion

In Table 1, we summarize the results of system reliability analyses in Sections 3.1 - 3.3. From Table 1, we see that different system configurations have a strong impact on the reliability of the assembly systems. The system having four stations connected in a series has the lowest system reliability among these four systems. If we rearrange the stations and connect them in parallel, the system reliability becomes the highest. Hybrid systems have reliability between serial and parallel systems'. A serial-groups systems has a slightly higher reliability than a parallel-lines system has, but both of them are much more reliable than a serial system.

According to the comparison, we find that with constant machine reliability, the more possible paths of material flow that a system has, the more reliable it could be. A serial system has only one possible path of material flow, so system shutdown cannot be avoided if any of its stations fail. A parallel-lines system has more system redundancy than a serial system has, so there is a great

Table 1. Reliability 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		.812	.188	.558
Serial-groups		.893	.107	.562

improvement in system reliability. A serial-groups system has more possible paths of material flow than a parallel-lines system has, so its reliability becomes even higher. A parallel system has the highest reliability because it has the maximum system redundancy.

A parallel system has the highest expected productivity for the same reasons. Also, the serial-groups configuration has slightly higher expected productivity than a parallel-lines configuration.

Some operational implications of these observations are as follows. If we want to increase the reliability of some critical continuous processes, we can always purchase better machines having higher reliability to achieve this goal. But the costs may become too high. If we can combine several tasks and then duplicate the stations to form a parallel system, high system reliability can still be achieved even if the machines are not very "high-end".

4. VARIATION SIMULATION

Dimensional variation of an automobile body strongly affects the functionality, fitness, and customer satisfaction of the complete vehicle. The functionality of the vehicle includes door closing effort, wind noise, and water leakage. Fitness includes gap and flush.

Here we investigate the relationship between assembly quality and assembly system configuration. We design four different assembly system configurations to produce the same sheet metal product. With the same sources of variation (i.e., variation of incoming parts, variation in part positioning and clamping, and deformation due to welding), we simulate how the dimensional variation of assembled sheet metal parts is affected by the different system configurations.

There are several methods that can be used to predict or simulate assembly dimensional variation. The most commonly used variation simulation methods are worst case analysis, root sum square method, and Monte Carlo simulation. The individual parts of assemblies are considered as rigid bodies in these methods. However, for sheet metal assemblies, these methods cannot predict the variation of the assembly correctly because flexible sheet metal parts can deform during assembly.

A different approach, variation simulation using mechanistic models or "mechanistic variation simulation," is used here. The methodology was presented initially in Liu and Hu (1997). It combines engineering structural models with statistical techniques for better analyzing the variation stack-up of deformable sheet metal part assemblies.

A model shown in Figure 17 is used to demonstrate the basic concept of mechanistic variation simulation. v_i ($i = 1, 2,...,M$) and v_{tj} ($j = 1, 2,...,N$) are the deviations of the i-th part and the j-th tooling element from their nominal dimensions, respectively. v_a is the total deviation of the assembly. For one-dimensional (unidirectional) assemblies, the coefficients (S_i and S_{tj}) are usually taken as ± 1 in the traditional tolerance analysis model.

In mechanistic variation simulation, part deformations during assembly processes are no longer ignored. The coefficients (S_i and S_{tj}) are complicated functions of geometrical dimensions and material properties of the components, plus the work-holding fixturing (constraints), and joining (welding) schemes. The mechanistic variation simulation models can be formulated using the offset finite

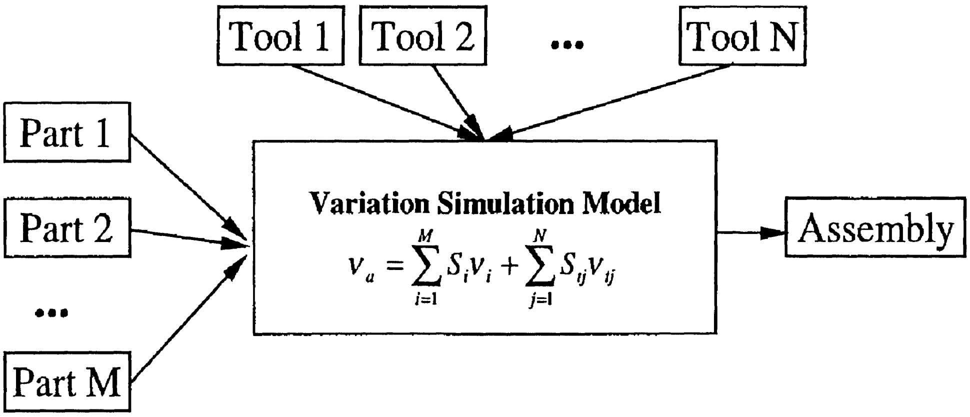


Figure 17. Variation simulation modeling (Liu and Hu, 1997).

element models proposed in Liu and Hu (1997). VarSimA, a computer program developed in the S.M. Wu Manufacturing Research Center at The University of Michigan, is used to perform this mechanistic variation simulation.

4.1 Simulation Set-up

For simulation purposes, we assume that three sheet metal parts are assembled into one long part using fixtures and welding. Each part has a length of 600 mm and a width of 400 mm. The thickness of each part is 1 mm. All sheet metal parts are steel. Because the parts are relatively "thin", a 4-2-1 locating scheme is used in this mechanistic variation simulation. Figure 18 shows the location of the 4 constraints on the individual sheet metal part. Figure 19 depicts the assembled parts in the simulation.

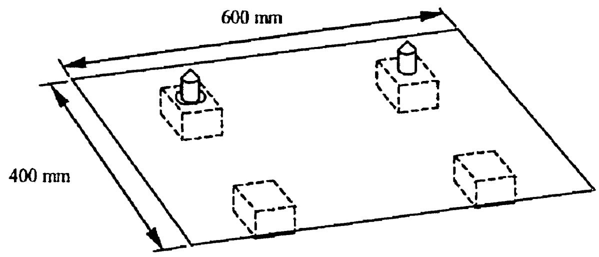


Figure 18. Four constraints (4-2-1 locating scheme) of an individual sheet metal part.

In Figure 19, the Xs show the location of welding points. Four triangles show the location of the 4-2-1 locating scheme during the final-stage measurement. A black dot at the rear-end-corner of the assembly shows the location of the audited point (up/down direction only).

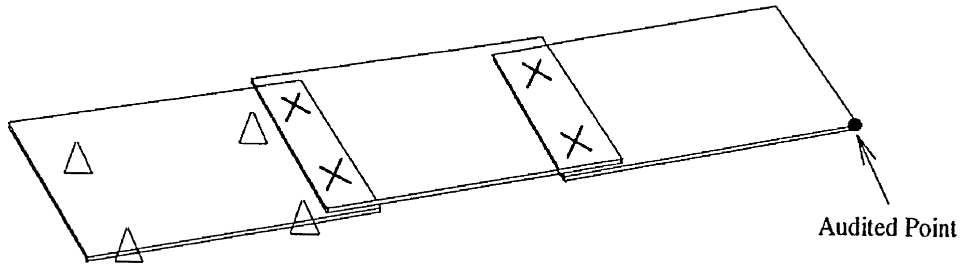


Figure 19. Final sheet metal assembly.

The computer program used here takes into account the dimensional variation of sheet metal parts and fixtures when simulating the variation stack-up of deformable sheet metal assemblies. Figure 22 illustrates a typical procedure in a sheet metal assembly process (Liu et al., 1996).

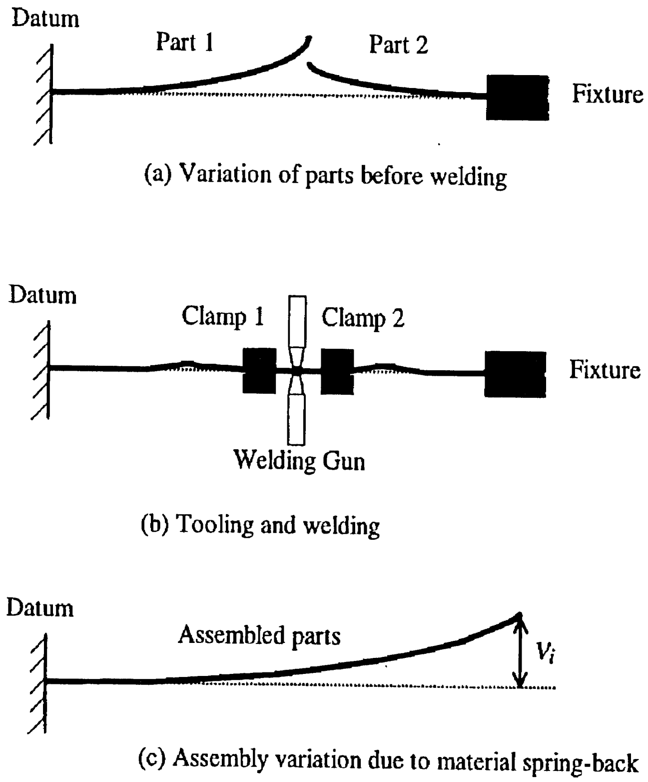


Figure 20. Variation stack-up in a sheet metal assembly process.

Throughout the simulation, we assume that each corner of the incoming sheet metal part has deformation before welding (Figure 20a). The magnitude of the deformation is normally distributed with a 6-sigma value of 1 mm in the Z direction. For up/down fixtures, their positions are also normally distributed with 6-sigma values of 1 mm. After releasing the clamps (Figure 20c), the mean deviation and 6-sigma values of the measurement points are calculated by the computer program. If this assembly needs to be assembled with another sheet metal part, then the calculated mean deviation and 6-sigma values will be used as the new "variation sources" for the next assembly process.

Four different assembly system configurations (serial, parallel, parallel-lines, and serial-groups) are designed to assemble parts. All system configurations share the same incoming parts (i.e., the same variation sources) and the same product design. The simulation details for each configuration are described in sections 4.2 – 4.5.

4.2 Serial System

In a serial assembly system, we weld sequentially one spot at a time, until all four spots have been welded as shown in Figure 21. Each station in the system performs one task (i.e., welding one spot). A total of four stations connected in series exist in the system.

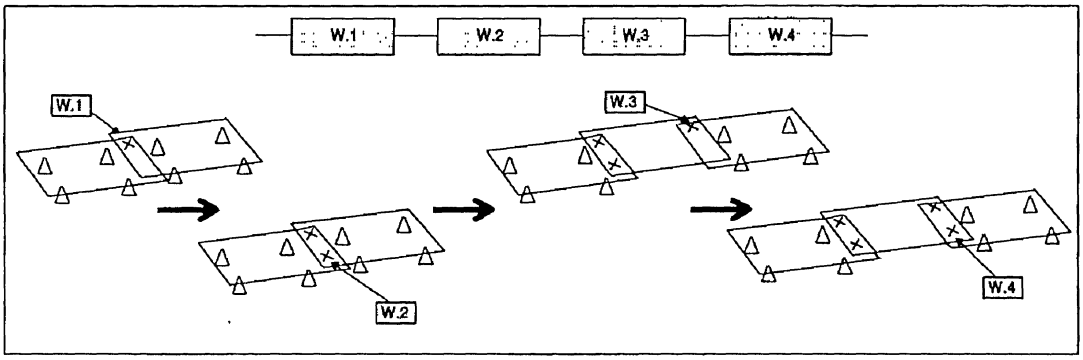


Figure 21. Simulation for a serial system configuration.

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

The production from this system is 1,200 assemblies per day. From the results of the variation simulation (i.e., mean deviation and 6-sigma values of the audited point), we plot the dimensions of the audited points of the 1,200 assemblies in a histogram in Figure 22. The histogram shows a normal distribution because only one material-flow path exists in a serial assembly system.

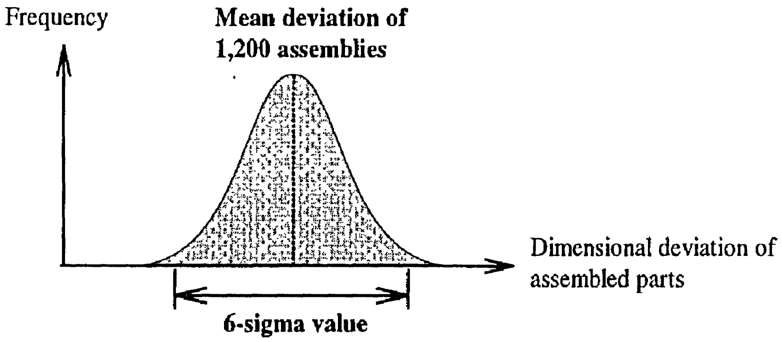


Figure 22. An example of a histogram of dimensional deviation for the serial system configuration.

4.3 Parallel System

In a parallel assembly system, four spots are welded simultaneously as shown in Figure 23. Each station in the system performs four tasks (i.e., welding 4 spots). In order to maintain the same throughput as the serial assembly system, four stations connected in parallel are in the system.

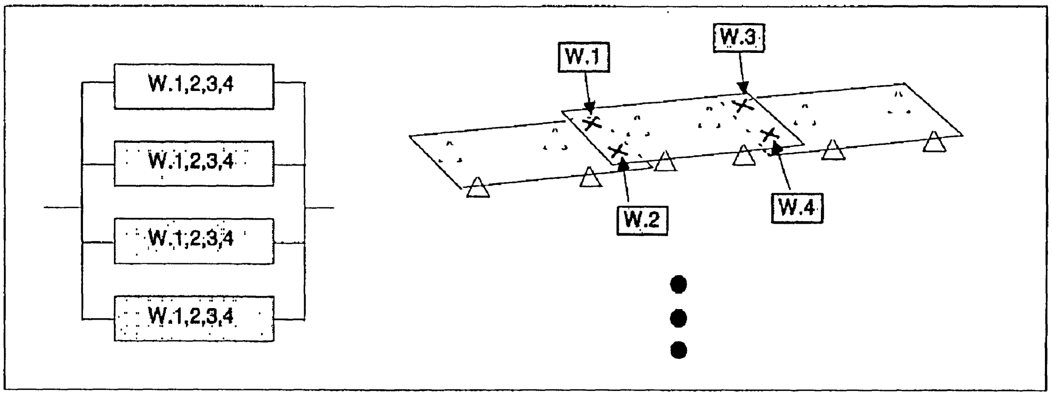


Figure 23. Simulation for the parallel system configuration.

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. In order to simulate this situation, we assign different levels of mis-alignment to the up/down datums of these four stations. The magnitude of each mis-alignment is a random number between -1 mm to 1 mm.

1,200 assemblies are produced evenly by these four stations each day (i.e., 300 assemblies each station). An example of a histogram of the dimension of these 1,200 assemblies is shown in Figure 24.

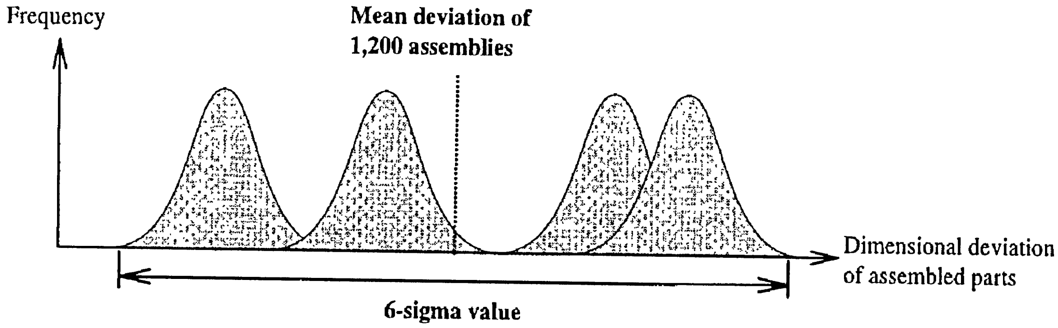


Figure 24. An example of a histogram of dimensional deviation for a parallel system configuration.

4.4 Parallel-lines System

In a parallel-lines assembly system, two spots are welded at a time, until all four spots have been welded as shown in Figure 25. Each station in the system performs two tasks (i.e., welding two spots). Two stations connected in series exist in one branch, and we duplicate the branch in order to maintain the same throughput as the serial assembly system.

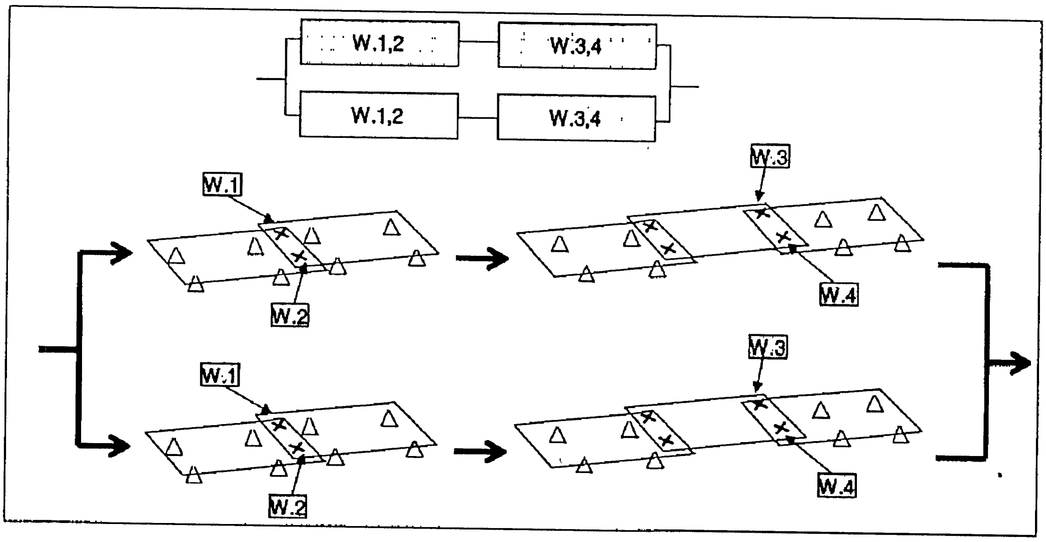


Figure 25. Simulation for the parallel-lines system configuration.

Again 1,200 assemblies are produced evenly by these two branches each day (i.e., 600 assemblies for each branch). Because we also assign different levels of mis-alignment to the up/down datums (random numbers between -1 mm to 1 mm), the products passing through these two different assembly paths may have different dimensional distributions. An example of a histogram of the dimensions of these 1,200 assemblies is shown in Figure 26.

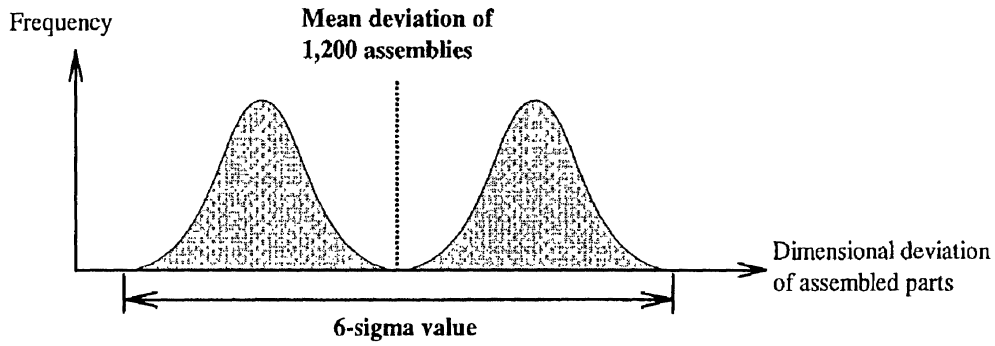


Figure 26. An example of a histogram of dimensional deviation for the parallel-lines system configuration.

4.5 Serial-groups System

In a serial-groups assembly system, two spots are welded at a time, until all four spots have been welded as shown in Figure 27. Each station in the system performs two tasks (i.e., welding two spots). 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 throughput as that of a parallel-lines assembly system.

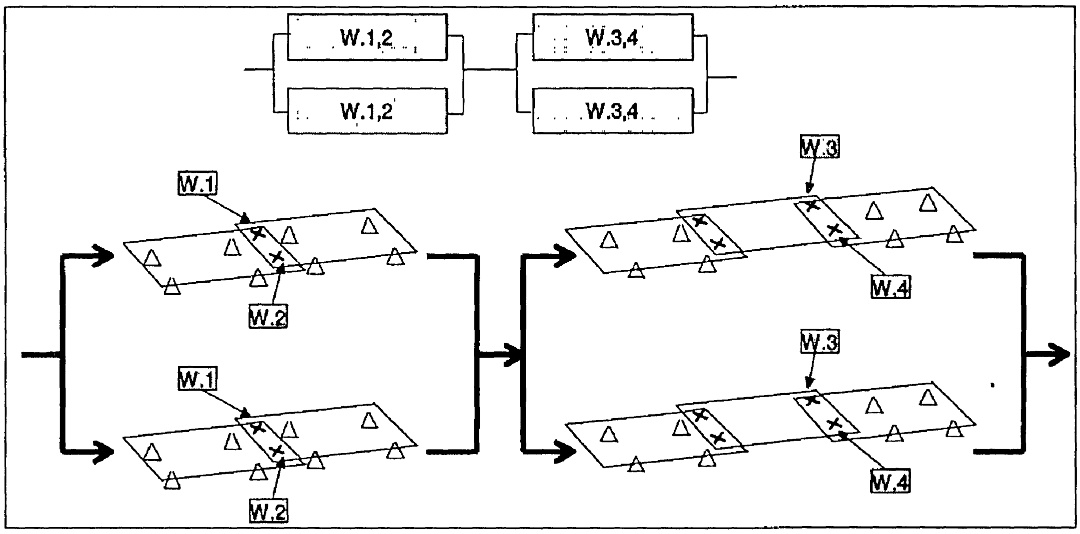


Figure 27. Simulation for the serial-groups system configuration.

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 different levels of mis-alignment are assigned to up/down datums (random numbers between -1 mm to 1 mm), the products passing through these four different assembly paths may have four different dimensional distributions. An example of a histogram of the dimensions of these 1,200 assemblies is shown in Figure 28.

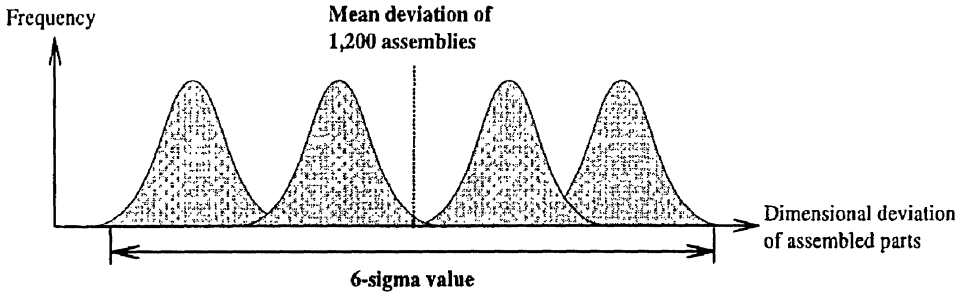


Figure 28. An example of a histogram of dimensional deviation for a serial-groups system configuration.

4.6 Simulation Results

For each station in the serial assembly system, we show an example of the contour of mean deviation and 6-sigma values of the parts on finite element models for this serial system after all four operations have been performed in Figures 29 and 30. The histogram of the simulated 1,200 parts is shown in Figure 31. Overall mean deviation is 17.45 mm and the 6-sigma value is 65.80 mm.

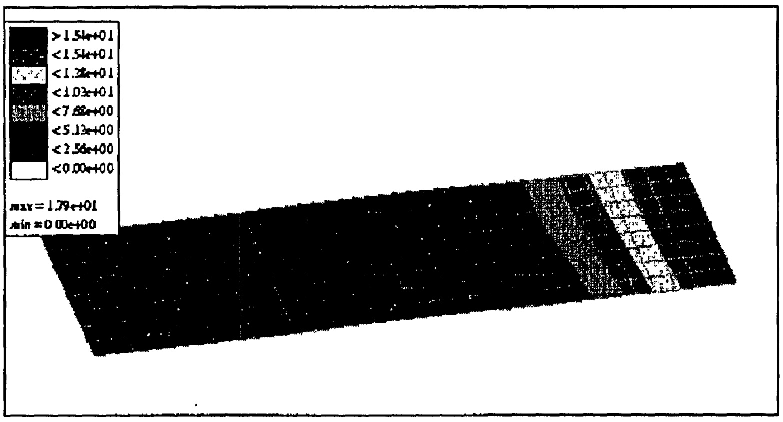


Figure 29. The contour of mean deviation after the fourth operation in the serial assembly system.

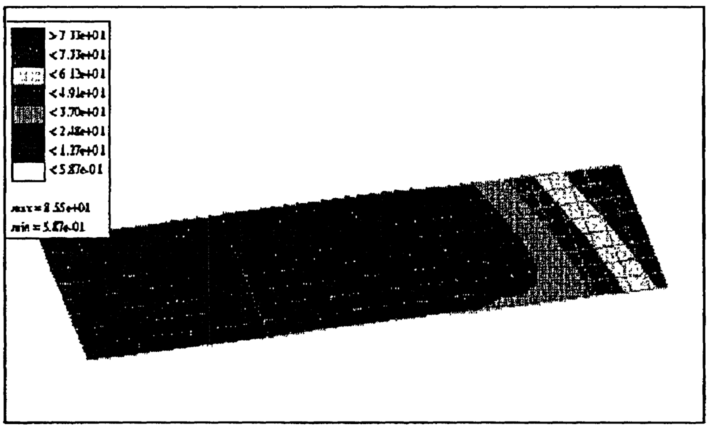


Figure 30. The contour of 6-sigma after all four operations in the serial assembly system.

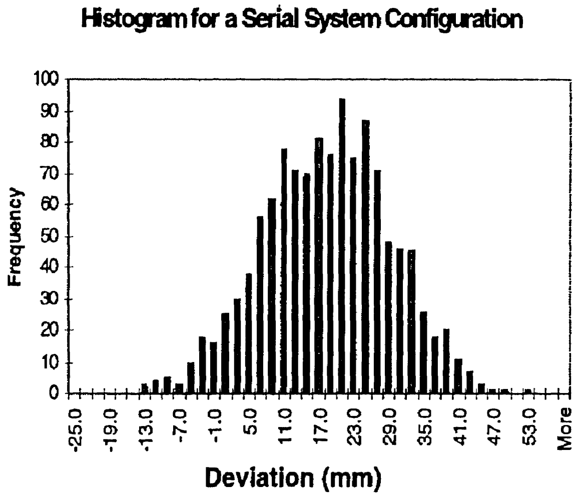


Figure 31. Histogram for the serial system configuration (X-bar = 17.5mm, 6σ = 65.8mm).

For the parallel assembly system, the histogram of the simulated 1,200 parts is shown in Figure 32. Overall mean deviation is 2.01 mm and 6-sigma value is 101.18 mm.

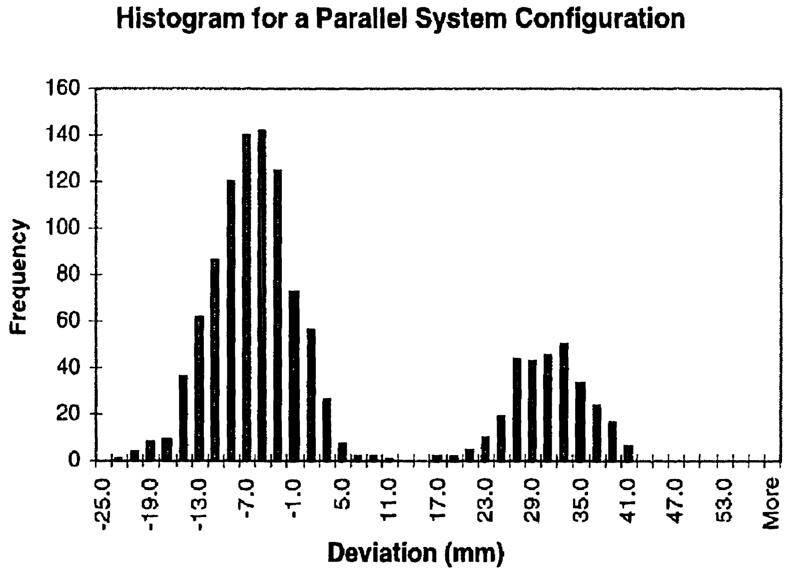


Figure 32. Histogram for the parallel system configuration (X-bar = 2.0mm, 6σ = 101.2mm).

For the parallel-lines assembly system, the histogram of the simulated 1,200 parts is shown in Figure 33. Overall mean deviation is 4.46 mm and 6-sigma value is 23.25 mm.

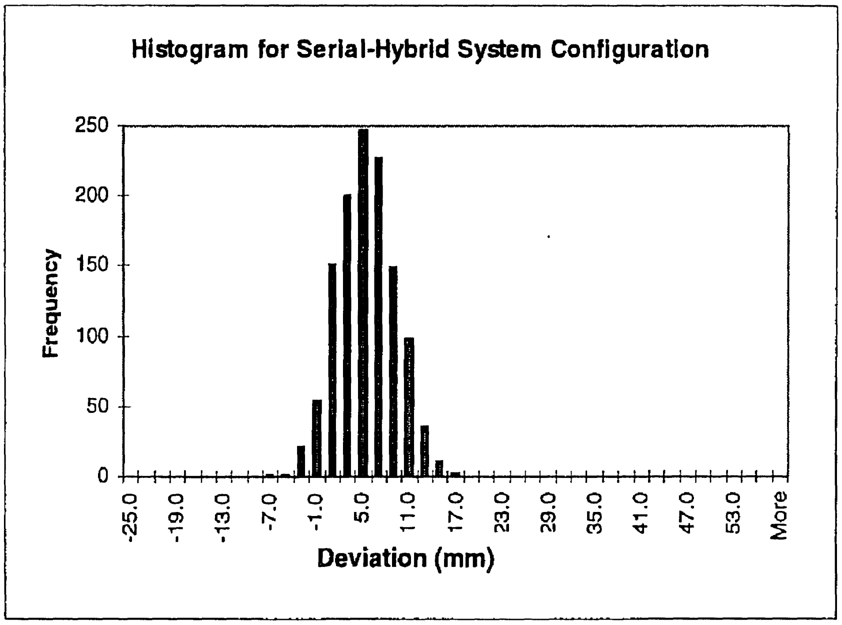


Figure 33. Histogram for the parallel-lines system configuration (X-bar = 4.5mm, 6σ = 23.3mm)

For the serial-groups assembly system, the histogram of the simulated 1,200 parts is shown in Figure 34. Overall mean deviation is 4.39 mm and 6-sigma value is 56.57 mm.

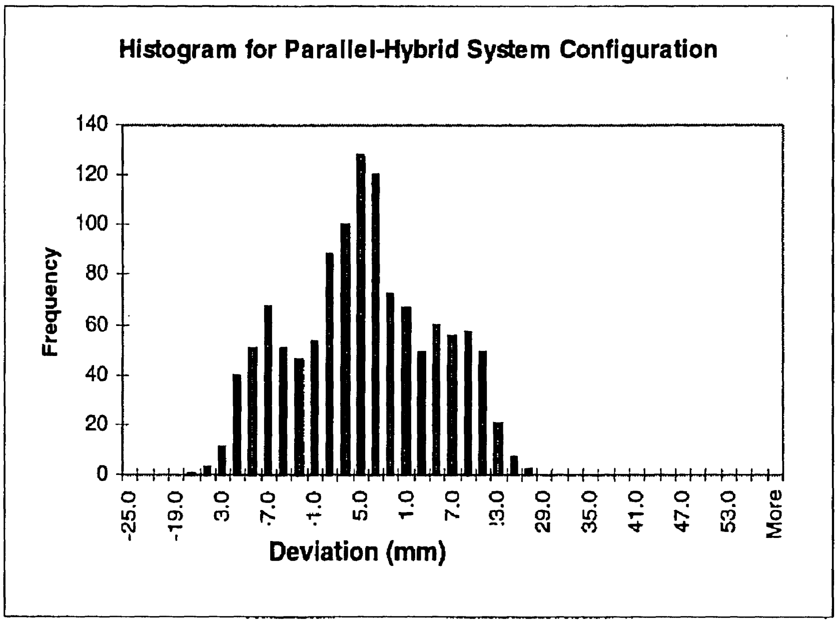


Figure 34. Histogram for serial-groups system configuration (X-bar = 4.4mm, 6σ = 56.6mm)

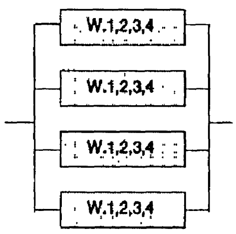
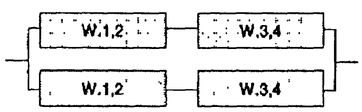
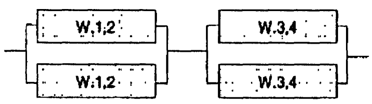
4.7 Comparison and Discussion

Table 2 lists the results of the mechanistic variation simulations for serial, parallel, parallel-lines, and serial-groups system configurations. In a serial assembly system, parts are processed through the maximum number of fixtures in a series. The more fixtures the parts pass through, the higher variation stack-up the parts can have. As a result, parts produced by a serial system configuration have the highest mean deviation.

A parallel system configuration has the maximum number of material-flow paths. Each flow path has a different set-up condition. Thus the quality variation of parts produced by the parallel system configuration has the widest distribution. As a result, a parallel system produces the highest 6-sigma value.

A parallel-lines system configuration has 2 material-flow paths, and there are only 2 stations in each path. Because the number of material-flow paths is smaller than the number that a parallel system configuration has, the distribution of quality variation is small. In each path, 2 stations do not cause serious variation stack-up. As a result, mean-deviation and 6-sigma values of the parts produced by a parallel-lines system configuration are the smallest among the four different system configurations.

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

A serial-groups system configuration also has 2 stations in each material-flow path. The mean deviation of its products is similar to the mean-deviation of the products from the parallel-lines system. But the number of possible material-flow paths are larger than the number that a parallel-lines system configuration has. Therefore, the 6-sigma value is larger.

5. CONCLUSIONS AND FUTURE WORK

We investigated the performance characteristics of various automotive body assembly system configurations. The assembly system configurations include serial, parallel, parallel-lines, and serial-groups configurations. These configurations have significant influences on system performance in terms of reliability and quality variation. In §2, we first illustrate the definition of various types of system configurations in great detail. By applying the precise definitions of various system configurations to existing body assembly lines, we present benchmarked body assembly system configurations. We find that serial system configurations still dominate in various automotive assembly plants. But in recent years, more parallel-lines system configurations are adopted by car makers. Since other than serial system configurations are increasingly being adopted, new problems associated with the characteristics of different system configurations may occur. Additional research needs to be done in the field of system configurations so that we can prevent or solve these problems.

In §3, we study the system reliability and productivity of four different body assembly system configurations. After examining a serial configuration, we find that as the number of stations increases or as the station reliability decreases, the system reliability decreases. We show that the system reliability can drop sharply as the number of serial stations increases, especially for a system in which the stations do not have a high individual reliability. For a parallel configuration, we find that as the number of parallel stations increases or as the individual station reliability increases, the system reliability also increases. This suggests that the system reliability can rise sharply as the number of parallel stations increases, especially for a system in which the stations do not have high individual reliability. When studying hybrid system configurations, we find that both the number of possible flow paths and the number of serial stations/groups can strongly affect the system reliability and producivity. By comparing the results of the studies, we conclude that with constant station reliability, an assembly system could become more reliable and productive if it has more possible paths of material flow. For example, the parallel system configuration has the maximum possible paths of material flow (i.e., having the maximum system redundancy), and its reliability and productivity is highest among the four different system configurations. This suggests that if we want to increase the reliability of a critical serial process using not-so-expensive reliable machines, we can combine several tasks and then duplicate stations to form a parallel system.

In §4, we investigate the relationships between quality output and the various assembly system configurations. We design four different assembly system configurations to produce the same sheet metal product. With the same sources of variation (i.e., variation of incoming parts, variation in part positioning and clamping, and deformation due to welding), we simulate how the dimensional variation of assembled sheet metal parts is affected by different system configurations. Mechanistic variation simulation is used to analyze the variation of deformable part assemblies. The results of the simulations can be summarized as follows.

1) In a serial assembly system, parts are processed through the maximum number of fixtures in series. The more serial fixtures the parts pass through, the higher variation stack-up (in both mean deviation and 6-sigma value) the parts have. As a result, parts produced by a serial system configuration have the highest mean deviation. The 6-sigma value of the audited point ranks second among the four different system configurations.
2) In a parallel assembly system, parts are only processed through one fixture in each branch. Although the quality variation (6-sigma) of the parts produced by each branch is small, the mean deviation of the output of each branch is quite different (4 different mean deviation values) because of different set-up conditions. As a result, the parallel system produces the highest 6-sigma value.
3) In hybrid (parallel-lines and serial-groups) systems, the number of processing paths and the number of stations in each path can both affect the quality output. Because a parallel-lines system has fewer possible processing paths than a serial-groups system has, its quality variation of parts (6-sigma) is

smaller. Also, both hybrid systems have fewer stations in each processing path than a serial system has. Thus their 6-sigma values are smaller than a serial system's.

By considering both reliability 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 reliability and quality output. By providing more system redundancy, a parallel-lines system can improve the reliability of the system using not-so-reliable stations. Also, the quality output 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 quality output may start to deteriorate with too many possible processing paths (e.g. parallel systems).

From this basic understanding about how different system configurations affect system reliability 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 an appropriate body assembly system configuration which has a shorter changeover time is vital for this competitive automobile industry.

Furthermore, the combined effect and trade-offs between all system performance measures should be studied. Here we addressed system performance measures individually. However, in automotive body assembly, variation, reliability, change-over 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.

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