Reconsider Machine Layout to OPTIMIZE PRODUCTION
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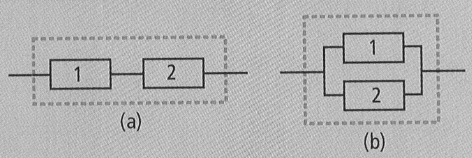
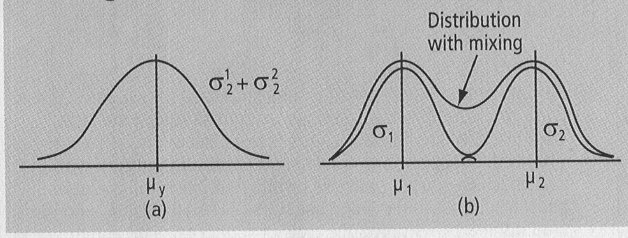
System Configuration

Reconsider Machine Layout *to* OPTIMIZE PRODUCTION

These configurations illustrate serial (left) and parallel machine arrangements.



Dimensional variation of parts from (a) serial configuration, and (b) parallel configuration.



Manufacturing system configuration can heavily influence performance, capacity, and reliability

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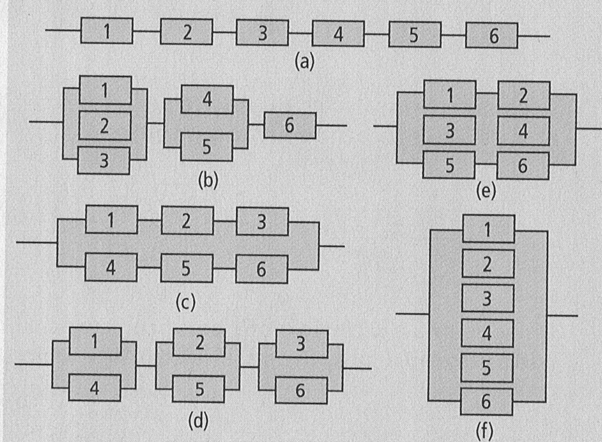
Traditional manufacturing systems for medium and high-volume production are designed as serial lines. Each machine performs some of the operations needed to complete the part, and there is only one flow path. Though this type of system is cost-effective for medium or high-volume production, it isn't suitable for the new era of global competitiveness, which features large fluctuations in product demand and increasing product variety.

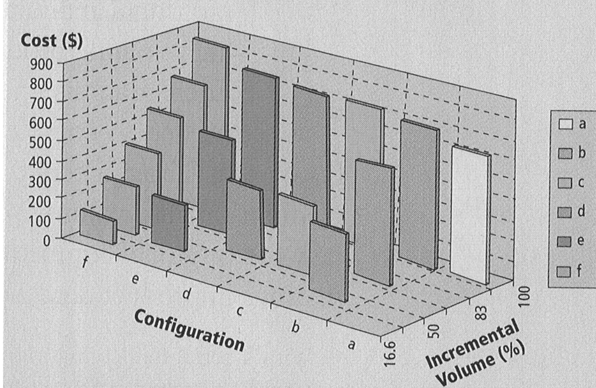
With a serial-line configuration, increasing the volume of production usually requires construction of an entire new line. There is no guarantee, however, that the manufacturer will be able to double sales. If sales don't increase in step with production capacity, the extra capacity will not be fully utilized. Furthermore, the structure of the serial line fits the manufacture of one product type, and can't efficiently handle product variety. A serial line also has relatively low reliability; when one machine fails, the entire system fails. There is a need to use new manufacturing system configurations that can respond better to the changing market demands of this new era of global competitiveness.

Manufacturing systems can be designed in many configurations; for example serial, parallel, or hybrid. A parallel configuration has multiple identical part flow

System Configurations



Six configurations are shown with six machines in each. To compare these configurations, cost assumptions summarized in the table were made, where the base costs of the machines are all the same: $100,000. But because of the different operations required with each machine, tooling costs will be different. The result of the comparison is shown in the graph below. Its *X*-axis shows the six configurations, the *Y*-axis shows the scale of adding capacity, and the *Z*-axis shows the corresponding cost for each step in the scale.



System Scalability, Both Resolution and Cost.

paths, while a hybrid configuration is a mix of serial and parallel configurations. Different configurations have profound impacts not only on adaptability to market demands, but also on reliability, productivity, product quality, and cost. It's important to understand this impact to properly select the optimal configuration.

Given a certain number of machines, the number of possible configurations is very high. With four machines, for example, there are 10 possible configurations; with five machines, 24 configurations. Each configuration affects productivity and part quality, and requires a different investment cost as well as a different expansion cost to allow incremental increases in production volume.

Until now, there has been no method available to allow manufacturing engineers to systematically analyze the impact of different configurations. Usually, quality and productivity are evaluated separately. But a set of new methodologies we've developed at the university"s Engineering Research Center for Reconfigurable Manufacturing Systems enables manufacturers to select manufacturing configurations from a total system perspective.

When selecting a manufacturing system and its configurations, we are concerned with the following performance measures:

- System initial cost,
- Quality,
- Reliability and throughput,
- Scaleability—cost of adding capacity to adapt to market demand,
- Number of product types that the system can produce, and
- System conversion time between products.

Analytical or computational tools are necessary to evaluate these performance measures. To develop these tools, we begin with the basic models of performance for a serial and a parallel system with two machines. Then we use six selected configurations with six machines to illustrate the analysis for more-complex manufacturing system configurations.

Quality has many meanings. We are mainly concerned with the dimensional quality of machined or assembled products. We define quality as the deviation of a dimension from design intent. The closer a dimension is to the design intent, the better the quality. With volume production, the quality of the process can be measured by the mean deviation from the design intent $\bar{y}$, and the standard deviation σ_y from the mean. The second moment from the design intent, $\bar{y}^2 + \sigma_y^2$, can be used as a single measure of the total variation by combining the mean deviation and standard deviation. In physical units, the square root $\sqrt{\bar{y}^2 + \sigma_y^2}$ is used. Assume that the capability for each machine is given as (μ_i, σ_i^2). For a serial configuration with two machines, if the operation in Machine 2 is dependent on that of Machine 1, then the resulting quality will be given as: $\sigma_y^2 = \sigma_1^2 + \sigma_2^2$.

For a system with two machines in parallel, each machine will perform all the operations in a single setup. As a result, the variation for the parts from each machine will be smaller compared to that from a serial configuration. Because of the two part-flow paths, however, statistical mixing exists. As a result, total part variation generated by the parallel configuration could be larger, depending on the differences in the process means of the two parallel machines.

For configurations of six machines, Monte Carlo simulation is used to estimate the dimensional variation from each configuration. Assume that each machine has a capability of setting the mean to within ±10 µm, and has a repeatability of 10 µm (one standard deviation). In this case, the configuration with the greatest number of flow paths has the largest quality variation. Because there is only one part flow path and no mixing exists, the serial line has the best quality (lowest dimensional variation).

The classical definition of reliability was developed for aerospace and electronic systems, and measures the probability of system failure. Similar definitions have been developed for manufacturing machines and equipment. Machinery/equipment reliability can be defined as the probability that the machinery or equipment can perform continuously, without failure, for a specified interval of time when operating under stated conditions.

This definition cannot be directly applied to manufacturing systems because, in a parallel configuration, when one of the machines fails, the system can still deliver 50% of system productivity—assuming that the two machines perform identical functions in the same cycle time. Therefore, we introduce the term expected productivity, which accounts for the probability of failure and the corresponding productivity associated with each failure mode.

For a system with two machines, there are three modes of failure: no machine fails, one machine fails, and both machines fail. Where R_1 and R_2 are the reliability of machine 1 and 2 respectively, the expected productivity is the sum of the productivities weighted by the probabilities of the corresponding failure modes. For a serial system, the expected productivity E[P] is:

$$E[P]=1\times R_1R_2+0\times R_1(1-R_2)+0\times R_2(1-R_1)+0\times(1-R_1)(1-R_2)=R_1R_2$$

which is the same as the reliability of the system.

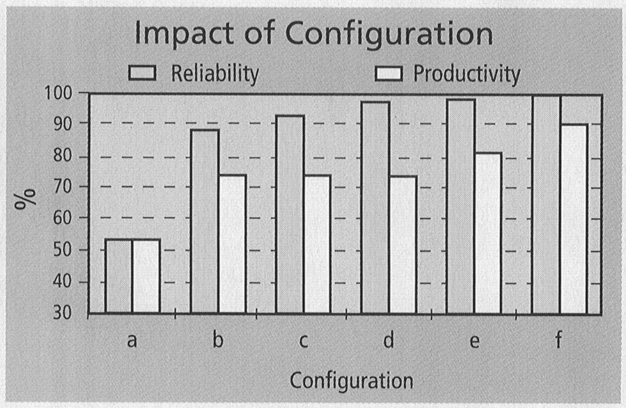
For a parallel system, the expected productivity is

$$E[P]=1\times R_1R_2+0.5\times R_1(1-R_2)+0.5\times R_2(1-R_1)+0\times(1-R_1)(1-R_2)= 0.5R_1 0.5R_2$$

which is a weighted sum of the reliabilities of the two machines.

Similar models can be developed for system configurations with three or more machines. The basic models with two machines provide the basis for analyzing more complex system configurations. For the six machine configurations mentioned previously, reliability and expected productivity again vary according to the complexity of part flow.

Capacity scalability is the ability to adjust the production capacity of a system in steps or stages. To adapt to fluctuations in product demand, capacity must be adjusted quickly and cost-effectively. Initial system configuration has a profound effect on system adjustment step-size and its cost. For



Reliability and expected productivity for the six machine configurations discussed.

example, if a six-machine serial line was originally built, and an increase in production volume is needed to satisfy market demand, an entire new line must be added, which will double the production capacity of the system.

The smallest adjustment steps can be employed when the original system is pure parallel, but the initial cost of a parallel system is the highest. In a parallel configuration, each machine must perform all operations on the product, and therefore each machine must have all the necessary tools available and be able to perform all the required functions. As a result, cost per additional unit of volume is highest with parallel configurations.

Compromise is possible. For example, if a product requires machining on both the upper and side surfaces, in a six-machine configuration three machines might be three-axis vertical milling machines, and the others might be three-axis horizontal milling machines. In a parallel system, all six machines must be five-axis milling machines—a system that is much more expensive.

The tradeoff is system cost versus capacity scaleability. For a six-machine system consisting of three machines of each of two types, scaleability would be performed in steps of 33.3% rather than steps of 16.6%, as with the parallel configuration. The steps involved in adding capacity with other configurations vary according to system configuration.

Of course, in each configuration, theoretically, the manufacturer can add one machine in parallel to any existing system, which makes the addition for all configurations equal. This is not recommended in practice, however, because integrating a different, complex machine into a system that does not include such machines increases integration and maintenance costs, and may cause part-quality problems.

In selecting a production system, a manufacturer must take several considerations into account:

- Initial system cost,
- Quality—ability of the system to produce parts with small variation,
- Expected productivity that accounts for the reliability and productivity,
- Scalability—cost of adding capacity to adapt to market demand,

- Number of product variations that the system can produce, and
- System conversion time between products.

A serial system is ranked the lowest when considering these points—it can only produce one product at a time efficiently, and it requires longer conversion time. The more a system moves from serial toward parallel configuration the better it ranks on these two last points. As a system moves toward parallel configurations, however, it becomes more expensive.

A pure serial system has low reliability and, in turn, low expected productivity. It's not recommended. A pure parallel system is very expensive in terms of both initial cost and the cost for adding capacity.

If the system must produce only one or two parts of the same family, we recommend that you select configuration "c" (see *System Configurations* illustration). If the number of parts is three or larger, we recommend selecting configuration "e".

System configuration has a profound effect on performance. Although the examples we've discussed are from the machining domain, the scope of our methodology is quite general, and it can be applied to other manufacturing domains. ■

WANT MORE INFORMATION?

This article is based on a technical paper in the Annals of the CIRP. Copies of the complete paper can be obtained from S. Jack Hu at jackhu@umich.edu.

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