

# Factory Models for Manufacturing Systems Engineering

Stanley B. Gershwin

**Abstract**— We review MIT research in manufacturing systems engineering, and we describe current and possible future research activities in this area. This includes advances in decomposition techniques, optimization, token-based control systems analysis, multiple part types, inspection location, data collection and several other topics.

**Index Terms**— manufacturing system, performance, analytical model, finite buffer, real-time scheduling

## I. INTRODUCTION

### A. Goals of Research

A MAJOR goal of manufacturing systems engineering research is to develop mathematical models and analytical methods for factory performance prediction and for factory design. Such methods will lead to more efficient and better understood factories when the models are sufficiently accurate and comprehensive. Comprehensiveness refers to how many of the important phenomena in factory environments are described in the models, and increasing comprehensiveness is the primary challenge in this research activity.

Models have already been developed that predict, with good accuracy, production rate, average inventory, and average lead time in systems with unreliable machines; fixed or random operation times; random demand; finite buffers; tandem production systems, assembly/disassembly networks, and systems with loops; token-based control policies, including kanban, CONWIP, and others; and simple versions of scrapping. Efficient optimization methods have been developed for buffer sizes and production rate in tandem and tree-structured assembly/disassembly networks.

Current research is aimed at adding several additional phenomena, including multiple part types; reentrant flow; and more realistic models of imperfect yield and inspection. In addition, more comprehensive optimization methods will treat inventory; buffer placement; design of token-based policies; and inspection station placement.

In addition, we are always seeking opportunities to work with industry to verify the accuracy and practicality of these methods.

### B. Outline

We describe past research and current results in Section II. Current and anticipated future analytical research activities are outlined in Section III. Related work is summarized in Section IV and we conclude in Section V.

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 USA, gershwin@mit.edu, <http://web.mit.edu/manuf-sys/www>.

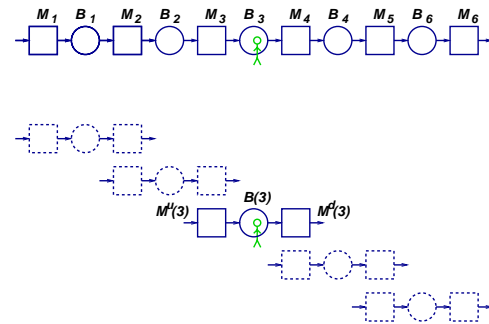


Fig. 1. Decomposition

## II. SUMMARY OF CURRENT MODELS AND METHODS

In this section, we review the literature of manufacturing systems engineering models. We focus on MIT work, and other closely related research is also mentioned. We make no attempt to survey the entire field, so we regretfully do not do full justice to our non-MIT colleagues.

An extensive survey of the literature up to 1991 appears in [14]. More recent surveys can be found in [20], [1], and [29].

### A. Decomposition of Lines

1) *Motivation*: Buzacott ([6], [7]) was one of the first authors to model and analyze production lines with finite buffers as Markov chains. (The *Buzacott model* has discrete material, unit operation times, and repair and failure times that are geometrically distributed.) He was only able to model two-machine lines successfully, however, because of the exponential growth in the size of the state space with the length of the line, and because there is no exact decomposition of the models as there is with Jackson or product-form networks [2] which have infinite buffers. The finite-buffer assumption is important in factory context because inventory and the space to hold it are major costs.

2) *Original decompositions*: Gershwin [18] analyzed finite-buffer production lines by developing an approximate decomposition method. (Also see [20].) Decomposition is illustrated in Figure 1. In this method, the system to be analyzed (often called the *original system* or *real system*) is approximated by a set of two-machine lines (or *building blocks*) in which there is one two-machine line for each buffer in the system. Building block  $i$ , which corresponds to buffer  $B_i$ , is composed of an upstream machine  $M^u(i)$ , a downstream machine  $M^d(i)$ , and a buffer  $B(i)$ . Buffer  $B(i)$  is the same size as  $B_i$ .  $M^u(i)$  and  $M^d(i)$  are often called *pseudo-machines*.

The pseudo-machines approximate the aggregate behavior of portions of the line up- and downstream of buffer  $B_i$ . The basic idea of the decomposition method is to find values for the failure and repair parameters of the pseudo-machines so that the material flow into and out of the buffer of each building block closely matches the flow of parts into and out of the corresponding buffer of the real system. In other words, consider an observer inside  $B_i$  who is able to see material entering and leaving the buffer but nothing else. We seek models of  $M^u(i)$  and  $M^d(i)$  such that he will believe us if we tell him that he is in  $B(i)$  of building block  $i$ .

The flow of parts into buffer  $B_i$  (when the buffer is not full) will stop when  $M_i$  fails and when  $M_i$  becomes starved (ie,  $B_{i-1}$  becomes empty) due to a failure of one of the upstream machines. The observer who believes he is in  $B(i)$  cannot make such a distinction; he thinks that all interruptions of flow into  $B(i)$  (when it is not full) are due to failures of  $M^u(i)$ .

Gershwin [18] developed a set of equations for the parameters of the two-machine lines for the decomposition of the Buzacott model of a  $k$ -machine line. Because two parameters are needed for each machine ( $p_i$ , the probability of failure, and  $r_i$ , the probability of repair) and because there are  $k-1$  buffers, there are  $4(k-1)$  parameters to be determined. That number of equations were derived. Dallery and his colleagues [16] developed an efficient algorithm for solving these equations, and it has been extended to all known extensions of the decomposition method.

An important limitation to the model of [18] is that all the machines were required to have the same operation times. Choong and Gershwin [11] overcame this limitation by extending the method to a line with discrete material and exponentially distributed operation, repair, and failure times. Burman [5], Hong and Glassey [27], and Le Bihan and Dallery [40] developed versions for a model with continuous material and exponentially distributed repair and failure times.

Di Mascolo, David and Dallery [48] and Gershwin [19] extended the Buzacott model decomposition to acyclic (tree-structured) assembly/disassembly networks. Jeong and Kim [36] extended it to a Choong and Gershwin [11] version of the the acyclic assembly/disassembly system and Gershwin and Burman [22] extended it to the continuous material model.

Other extensions, which allowed more general failure and repair behavior were contributed by Dallery ([15], [13], [40]), Tolio ([57], [56], [42], [43]), and others.

## B. Decomposition of Loops and Multiple-Loop Systems

1) *Practical needs:* A *loop* is a material flow system that consists of work centers or *machines* separated by storage areas (*buffers*) in which material travels from machine to buffer to machine in a fixed sequence and returns to the first machine. (Note that these loops are not the same as reentrant systems, which are discussed in Section III-B. Nor are they the same as rework loops, which are mentioned briefly in Section IV-D.) There are two reasons why we model production systems with loops:

a) *Material flow loops:* Some kinds of production systems require parts to be attached temporarily to pallets or

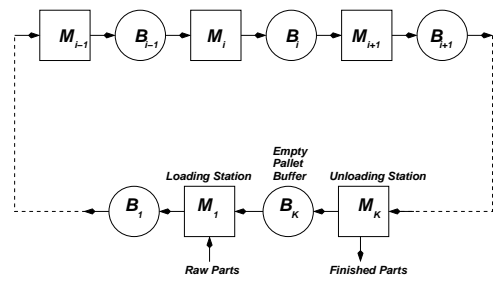


Fig. 2. Illustration of a closed production line

fixtures or carriers. The pallet serves as a mechanical interface between the part and the machines. In some cases, pallets are used to simplify material handling; in others, fixtures increase accuracy and the speed up the process by which parts are loaded precisely into the machines' work areas.

An example is a manufacturing system, illustrated in Figure 2, in which raw parts enter the system from outside and are loaded onto pallets or fixtures at a loading station (machine  $M_1$ ). The pallets and the associated parts then visit buffer  $B_1$ , machine  $M_2, \dots, M_{K-1}, B_{K-1}$ . Once all the operations have been performed, the part-pallet assembly goes to the unloading station ( $M_K$ ) where the part is unloaded from its pallet. The finished part leaves the system, while the empty pallet goes to the empty pallet buffer ( $B_K$ ) to wait for a new raw part.

The total number of pallets in the system — the *population* — is constant since pallets are not added or removed from the production line. For the pallets, the production line is closed. The production rate of parts is the same as the rate at which pallets travel through each workstation, and the distribution of parts in the system is the same as the distribution of pallets, except for the empty pallet buffer.

Closed loop production lines with pallets or fixtures can be observed in automotive fabrication, electronic component assembly, food packaging, and consumer manufacturing industries. Such loops are common where work pieces are loaded onto a support in order to ensure accuracy and stability during operations.

b) *Information loops:* In addition, loops occur in production systems controlled by CONWIP (constant work-in-process) [31], the production authorization card policy [9], the control point policy (CPP) [21], and other policies. There is a single loop like that of Figure 2 in a line controlled by CONWIP; in other cases, there are multiple loops. In systems controlled with such policies, *tokens* or *production authorization cards* behave similarly to the pallets as described above, and the number of tokens is constant either within the whole system or within a specific portion of the system.

2) *Decomposition Analysis of Closed-Loop Systems:* Closed loops differ from open networks because of the correlation that exists among the numbers of parts in each buffer of the closed system. When a part is in one buffer, it cannot be in another. The effects of this correlation increase when the number of machines decreases, or when the population is such that the buffers are all either almost empty or almost full.

Little work has been done on closed lines with unreliable machines and finite buffers. [17] proposed an analytical

method for the performance evaluation of closed lines that is a straightforward extension of the decomposition method developed for open lines. However, this method does not treat the correlation that exists among the numbers of parts in the buffers.

In a series of papers and theses that are still being written ([47], [58], [41], [46], [24], and [23]), researchers at MIT and the Politecnico di Milano are developing approximate decomposition techniques for very general systems: assembly/disassembly systems with multiple closed loops, finite buffers, and stochastic machines. In addition to any direct application to systems with multiple material flow loops, such methods will be essential for the analysis of control policies for factories. See Section III-A.

### C. Optimization

Optimization is helpful for system design and for the development of systems intuition. [52] and [26] describe gradient-based techniques for allocating buffer space in a production line. The extension to assembly/disassembly networks has been straightforward (and is not formally documented).

Meerkov and his colleagues ([34], [38], [39]) found optimality conditions for production lines and showed how to use these condition to improve the performance of a factory.

### D. Other Phenomena

a) *Yield*: Helber ([28], [29], [30]) extended the decomposition method to systems in which the flow of material was random. This made it possible to model scrapping (where parts are discarded at random) and multiple paths or processes. Dallery [12] took a different approach, in which multiple-route systems were transformed into equivalent single-route systems. Dallery's method is simpler, but more limited.

b) *Unreliable buffers*: Burman [5] developed a model for a production line with an unreliable buffer. This is of interest when the material flow system is mechanized and therefore subject to failure. He obtained an exact solution for a two-machine line, and proposed a simple extension to the decomposition method for longer lines.

c) *Repair interference*: Kuhn [37] extended these models and decomposition techniques to analyze production systems with a limited number of repair personnel. In earlier models, the repair process was simple: it did not depend on how many machines were down. In Kuhn's paper, a machine must wait to be repaired if too many other machines are already under repair.

## III. DESCRIPTION OF CURRENT AND FUTURE RESEARCH

### A. Token-based control

A major motivation for the algorithm development described in Section II-B is the analysis of control policies of manufacturing systems. [21] showed that many control policies can be represented as token-based, ie generalizations of kanban.

Such scheduling methods use kanbans or production authorization cards [8], [9] or other items that flow through the factory to prevent or allow production operations. A token is

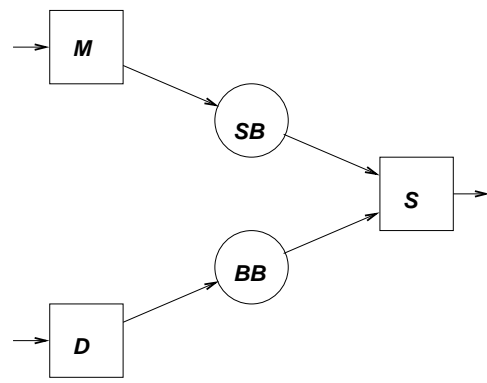


Fig. 3. Three-machine assembly system.



Fig. 4. Three-machine tandem line

issued by a machine when an operation is completed, or by the sales department when an order is received or when an item is shipped, or other factory entity. These tokens are required by a machine to do an operation, or by the raw material storage to release a part, etc. Thus the tokens carry information — they signal that some event has taken place that allows another event to occur elsewhere.

In [21], Gershwin uses an observation of Bonvik [4] to propose a relationship between surplus- and token-based policies. Bonvik observed that the behavior of the state (ie, the machine repair condition and the surplus/backlog) of the system analyzed by Bielecki and Kumar [3] is isomorphic to that of the assembly system in Figure 3 (except during the initial transient period, if the surplus in the Bielecki-Kumar formulation is greater than the hedging point).

In this figure, material is considered to be continuous.  $M$  is a machine which is identical to the machine in the Bielecki-Kumar formulation.  $D$  is a perfectly reliable machine which is generating tokens — also considered continuous — at the demand rate of the Bielecki-Kumar model.  $S$  is an infinitely fast, perfectly reliable assembly machine. Buffer  $SB$  has a finite size, the same as the hedging point in the Bielecki-Kumar formulation. Buffer  $BB$  is infinite.

We can consider  $BB$  to hold tokens and  $SB$  to hold material. When  $BB$  is empty and  $SB$  is non-empty, tokens enter  $BB$  at the demand rate, but are immediately matched up with items in  $SB$ . As a result,  $BB$  stays empty, but material is removed from  $SB$  at the demand rate. Because of their function in regulating  $M$  with tokens, we can refer to  $D$ ,  $S$ ,  $BB$  and  $SB$  as the *token flow control system* for  $M$ .

Because of this isomorphism for a single machine, [21] conjectured that attaching the same kind of token flow control subsystem to one or more machines in a more complex network would be a reasonable strategy. For example, to control the network in Figure 4, add the subsystems to create the larger network in Figure 5.

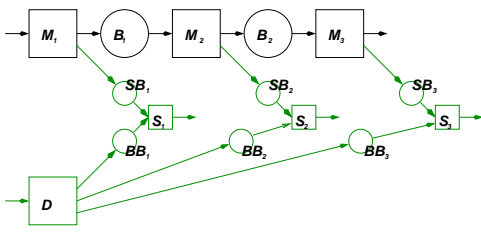


Fig. 5. Controlled three-machine tandem line

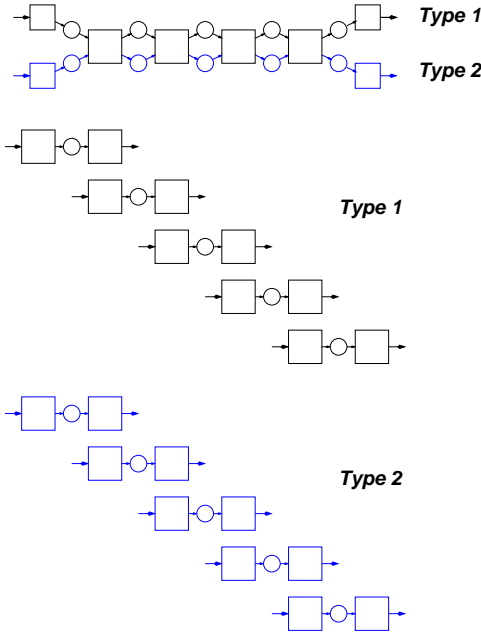


Fig. 6. Two-part-type line and a decomposition

### B. Multiple part types

The *control point policy*, which is proposed in [21], is a real-time scheduling policy for a production system with multiple part types. An important research goal is to extend the decomposition analysis to such systems. As a first step, we have analyzed the two-part-type tandem systems illustrated in Figure 6 in [50], [53], and [35]. The decomposition is indicated.

Reentrant flow is an example of multiple parts, not loops. Figure 7 illustrates how a two part-type system can be modified to create a reentrant system. The decomposition will be modified accordingly.

### C. Optimization

We are beginning to formulate and test a hypothesis: that the optimal distribution of buffer space in a line (the distribution of a fixed amount of space that maximizes the production

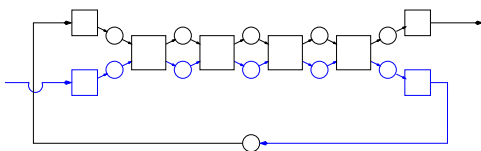


Fig. 7. A reentrant system

rate) is proportional to the variability of the inventory in each buffer. We will investigate several forms of this conjecture, but we expect that the best results will be obtained with standard deviation as the measure of variability.

If this hypothesis is true, it confirms the idea that the buffers are most effective when they are most variable. It also suggests an algorithm that may be faster and easier to implement than the gradient method of [26].

### D. Inspection Location

It is well known that inspection should ideally occur immediately after each operation in a factory. This prevents the production of unnecessary bad parts, and it prevents the waste of productive operations on parts that are destined to be scrapped. However, this is often not practical because of the expense of inspection. For example, capital expense and floor space may be saved by combining several measurements at one location.

We are investigating models that will predict the performance of systems with imperfect operations and inspection that cannot occur immediately after each operation. The goal is to help design inspection strategies using quantitative models of the consequence of each location decision.

## IV. OTHER ISSUES

### A. Other Performance Indices

Production rate and average inventory are not the only performance measures of a production system that are of interest. Others are important, but they are evidently harder to calculate.

Several authors ([49], [25], [55], [54], [44], [10]) explored the variance of production during a specified time interval  $(0, T)$ . (Some looked only at the limiting case in which  $T \rightarrow \infty$ .)

Related issues include the variance of the production lead time [51], and the delivery reliability [32], [45], [33],

### B. Data collection

The collection and management of information in factories is almost as important as the management of material. This information is used for many purposes, including:

- financial accounting
  - real-time and near-term decision-making about material flow, operations, set-up changes, etc.
  - long-term capacity planning. A great deal of care is devoted to the collection of financial data in every factory. However, the effort expended on the other items differs widely among factories. This is because financial performance is the ultimate performance measure of any business, and the other items have a less direct impact on the assessment or improvement of the firm's financial condition.
- Another use of factory data is
- for research, to further the understanding and predictability of factory behavior. But here the impact on a firm's

financial condition is even less direct, and data is rarely collected for this purpose.

In some high-technology factories (especially semiconductor fabrication facilities), a vast quantity of data is collected in the hope that it might eventually prove useful. However, this collection is often done without a clear, specific purpose, and as a result the data may never be used.

We hope to work with an industrial partner to develop a plan for data collection. The primary purpose of this collection will be for research, but we will work with company personnel to put it in a form that will be helpful in factory design and management.

Among the purposes for this data will be:

- **Model development.** We are considering beginning a variety of research efforts, such as the effect of process parameters on the frequency and duration of machine failures.
- **Model validation.** In our ongoing research, we have made several assumptions about the behavior of factory resources. For example, we have assumed that times to fail and times to repair are exponentially distributed. We would like to verify this; and if another probability distribution proves to be more appropriate, we will revisit our factory performance models.

We will make our data and research results available to our industrial partners. This may help them to redesign existing factories for greater efficiency, and it may be useful in the design of new factories.

### C. Instrumented simulation

Simulation is typically used to evaluate performance measures of economic interest, for example production rate, inventory, lead time, etc. These quantities are critical in the evaluation of factory design. Simulations constructed by systems researchers are used to evaluate such quantities either to verify the accuracy of an approximation method, or as part of an optimization method.

In the course of our work, we have observed another need that can only be satisfy by a simulation, but one which does not calculate quantities of obvious economic importance. These are simulations that verify the approximate assumptions we are making. For example, in Section II-A.2 we described an approach that depends crucially on whether we have approximated the flow behavior that an observer would see if he could only see the flow of material inside a buffer. Similar approximations are made in all the methods we develop, and we need a simple way of determining, for example, the distributions of up- and down-times that the observer sees.

Such behavior has no direct economic value, so simulations are not often written to investigate it. We will investigate general methods of *instrumenting* a simulation, ie, attaching virtual instruments to measure internal behavioral properties.

### D. Standard graphical notation

There is no widely used standard graphical notation for representing the flow of material in production systems. Such

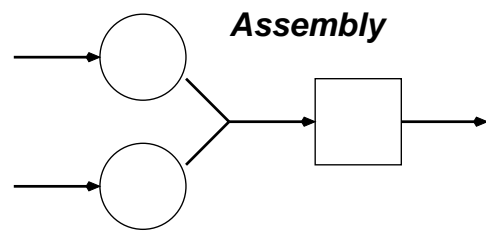


Fig. 8. Assembly

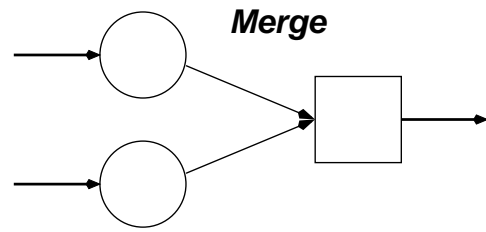


Fig. 9. Merge

a notation would be helpful in describing the phenomena mentioned in this paper and others, and it is essential for the eventual implementation of computer programs that analyze systems with many or all the phenomena. We propose some notation here.

Note that we are using squares for machines and circles for buffers. This is not essential for the standard, and other people have other preferences (circles for machines, squares or triangles for buffers, etc.). The more important issue to deal with material flow and its control.

Figure 8 shows assembly and Figure 9 shows merge. They are not the same: assembly occurs when two parts are brought together to form a single part; merge occurs when two streams of material come together to form a larger stream of material. In assembly, the machine cannot operate if *either* upstream buffer is empty; in a merge, the machine cannot operate only if *both* buffers are empty.

Additional graphical notation may be needed for merge if the two streams are treated differently, eg, if one has priority over the other. Figures 10–13 show various ways that merging material flow can be described in more detail. In Figures 10 and 11, the flow is controlled. This may refer to a flexible factory or to alternate sources of the same raw material. There are two sources in Figure 10 that take the same path after leaving the machine. The decision to be made is which source to use for the same product. In Figure 11, there are two kinds of material, and they take distinct paths after visiting the machine.

The flow splits randomly in Figures 12 and 13. As in Figures

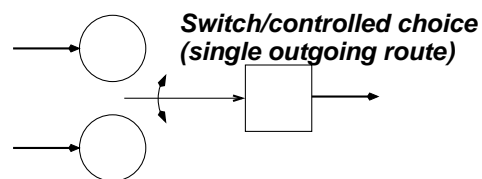


Fig. 10. Controlled choice of source — merge

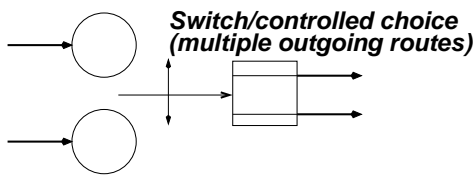


Fig. 11. Controlled choice of source — no merge

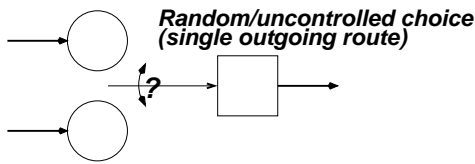


Fig. 12. Random choice of source — merge

10 and 11, there are two sources of the same material in Figure 12, and two sources of two different kinds of material in Figure 13.

Similar remarks apply to disassembly and splitting material flow. Splitting is important because it includes scrapping. Splitting and merging can appear in the same system when to form a rework loop.

It is worthwhile to represent the flow of information when it is in the form of tokens (kanbans, PACs, etc.). Although, in our models, token flow behaves the same as material flow, they have very different cost and revenue impacts. Figure 14 shows a simple way of distinguishing these flows.

## V. CONCLUSIONS

A considerable amount of work has been done on the analysis of stochastic models of manufacturing systems. These systems are difficult to evaluate because of their large state spaces and the absence of a closed form solution to the Markov chain transition equations. This paper includes a biased survey of this work, in which the bias is due to the emphasis on MIT efforts and other closely related research.

It also includes a description of several proposed or ongoing research directions. When many of these efforts are successful,

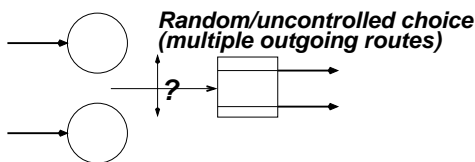


Fig. 13. Random choice of source — no merge

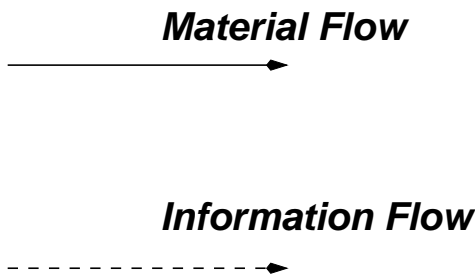


Fig. 14. Material and information flow indicators

and when software is written to make these results convenient for factory designers and operators, new factories will become more efficient and the intuition of the designers and operators will be improved.

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