CENTER FOR QUALITY OF MANAGEMENT JOURNAL

Reprint No. RP09500

Vol. 7, No. 2 WINTER 1998

ISSN: 1072-5296

Using Integrated Management Systems to Design a Lean Factory

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Introduction

This paper will explore aspects of the work of a Chrysler Corporation team that set out to design a new-vehicle assembly plant for a lean production system. From May until December of 1996 I was working at Chrysler in Detroit, Michigan as an intern under MIT's Leaders for Manufacturing program; and I had the opportunity to be part of this design effort. The paper will illustrate the development of an integrated management system, and I will extract from the case generic lessons for organizations to consider when designing other integrated management systems.

Integrated management systems combine methods that work well together to address specific circumstances.[1] There are more management methods, engineering tools and theories available to choose from than any manager could possibly absorb. No methodology will be the single "right" tool, but many of them have their uses. Integrated management systems provide the manager with a way to use a variety of tools in combination based on an understanding of peoples' situational needs, resources and skills; and of course of the tools themselves. Managers have always used multiple managerial tools, but have often not thought so deliberately and rigorously about how they fit together.

Lean Manufacturing

By way of background I will start by briefly describing lean manufacturing. This means in effect, describing the Toyota Production System (TPS), the world benchmark in automotive manufacturing — and probably in manufacturing in general.

The philosophy of TPS is that you should look at manufacturing as a system and optimize the system as opposed to the parts. TPS is very robust, responding adaptively and effectively both to internal factors such as bad raw material or high product variability and to external factors such as demand fluctuations. TPS is also self-improving. Every action at Toyota serves two purposes: (1) to deal with the situation at hand, and (2) to build capacity and skill to deal with

[1] See "Using Integrated Management Systems to Design a Lean Factory" by Thomas H. Lee and David Walden, Center for Quality of Management, 1996.

future problems. To monitor this robust, continually improving system requires balanced measures and goals, although there is some hierarchical ranking in importance among the goals of safety, quality, delivery, and cost. The systems emphasis in TPS is crucial. When adding to an existing system, we should be concerned with the fit with the enhancement of that system. For that reason, factory designers must thoroughly understand the production system they are building a factory for. Many observers of Toyota walk away with a piecemeal understanding of the system, and they fail when endeavoring to implement a piece of the system taken out of context. But Chrysler Corporation, in trying to develop their own production system, studied Toyota extensively; the Chrysler Operating System (COS) is based on TPS. COS consists of four subsystems:

1. Robust, capable, and in-control processes. Process capability is so embedded in Toyota's system that many Toyota employees are not even aware they are better at it than other manufacturers. In-control processes are processes that are predictable and stable, and capable processes are those that meet the needs of the customers. This subsystem is supported by tools such as SPC and the andon system, which I will describe below.
2. Leveled and balanced schedules. The scheduling and logistics systems are designed to maintain in-control processes in the factory and to meet customer demand with what customers want, when they want it. This is where Toyota creates a robust supply chain from suppliers to customers. Just-in-time is one tool that supports this subsystem.
3. Value-added activities. Every action at Toyota must add value for the customer. Furthermore, the elimination of waste is everyone's job and is done constantly. Some of the tools of this subsystem are standardized work, kaizen[2] workshops, and the PDCA cycle (described below).
4. Human infrastructure. Human infrastructure is an often under appreciated subsystem of TPS. Every individual in the system must understand his or her role within the system and must continually develop the skills demanded by that role.

Factory Design

Most of the popular literature surrounding the implementation of lean manufacturing focuses on existing operations and on the tools and skill set those operations require. While I don't think this is a wrong approach for most firms, it misses a critical component: the design of factories themselves. Whether a firm is designing new factories or retrofitting old ones, decisions made during the factory design process will have a major impact on the firm's ability to move toward the goals of lean manufacturing.

To demonstrate the importance of factory design, we can look to history. In the past century, perhaps the most significant single factor in the rise in America's productivity was the electrification of manufacturing processes. Manufacturing literature on the period around the turn of the century often stresses the impact of Taylorism or Ford's innovations in enhancing productivity, but factory design played an equally important role.

The technology to electrify manufacturing processes existed as early as the 1880s, but it was not significantly implemented until the 1920s. The primary factor in the delay was the physical design of both new and retrofitted factories. The older factories were often built several stories high to facilitate distribution of mechanical or water-power through a system of gears and belt drives. Factory electrification allowed for one-story, low-infrastructure factories with improved material flow and a much safer environment for workers. But even in new factories, it was decades before firms began building one-story plants. The delay in implementation occurred because (1) no one individual understood all the technologies or subsystems that needed to come together into one factory system; and (2) managers were concerned with the investment tied up in the existing plant and equipment. I argue that factory design today, for much the same reason, is one barrier preventing firms from realizing the productivity gains they could achieve by implementing lean manufacturing.

Using an Integrated Management System

If one of the barriers to the optimal design of new plants is the fact that the necessary knowledge is distributed

[2] Kaizen is defined as 'activities designed for continuing improvement involving management and workers.' For more information please refer to *Kaizen: The Key to Japan's Competitive Success* by Masaaki Imai, McGraw-Hill, July 1989.

throughout the functional organization, the management system must bring together those functions in new and integrated ways and explore how to redesign the interfaces among the various subsystems. In this section I will review some of the tools and management practices Chrysler utilized to manage this integration. I will focus on three tools: axiomatic design, queueing theory, and systems dynamics.

Table 1:

Customer Attribute	Functional Requirement	Design Parameter
Human infrastructure: Role/responsibility clarity	Factory systems that enhance role/responsibililty clarity.	Factory systems that enhance role/responsibiltiy clarity.
	Factory systems that provide clear communication channels.	Area that displays day-to-day plant activities, performance metrics, and responsibilities.
	Clear definition of the physical extent of responsibilities.	Physical boundaries.
	Definitions of physical extent of responsibilities.	Buffers defining bounded segments that align with management structure.
	Definition of physical extent of line worker responsibility.	Clearly marked workstations that bound the line workers' responsibility.

Axiomatic Design

Axiomatic design is a design tool innovation put forth by Professor Nam Suh, head of MIT's Mechanical Engineering Department.[3] It attempts to decompose the design of any product (including "products" ranging in scale from a water faucet to a national economy.) Nam Suh's design tools attempt to manage in accordance with two important axioms:

1. *The Independence Axiom: Maintain* the independence of functional requirements.
2. *The Information Axiom: Minimize* the information content.

The essence of axiomatic design is that it enables designers to decompose the functional requirements of the product and thus to map the architecture of the product directly onto the functional requirements. Table 1 shows an example of application of the axioms in factory design.

In this example, the factory management is the customer and the factory is the product. The table attempts to demonstrate how one customer attribute, role/responsibility clarity in human infrastructure, can be decomposed into more tangible parameters. These parameters, in turn, facilitate system design.

At this point it is worthwhile to bring up the integral nature of a factory system. There are design features even in this small example that have other functions and benefits, such as buffers or the communication center. A system as integral as a factory cannot be completely decomposed, so relying too heavily upon something like axiomatic design will lead to frustration and poor designs.

This brings me, however, to the first significant benefit our Chrysler team realized with axiomatic design. Even with architecture mapping less developed than in the example above, this breakdown of parameters was much more explicit than any factory architecture the design group had seen before. Traditionally, the existing management structures and communication paths would manage the architecture as a stream of inputs and outputs from various very tacit knowledge groups. In this case, however, the knowledge groups representing production, building construction, conveyor systems, material flows, and so on all had to work much more explicitly. The axiomatic design process helped the team create centralized explicit knowledge from distributed tacit knowledge. As a result, conversations went much deeper into the relationships among the various functions and into the architecture of the factory.

Queueing Theory

Queueing theory helps us mathematically model some of the interrelationships within the factory operation to gain insight into how they work. Systems analysts often use simulation today to provide answers to mathematical design questions, mostly because the cost of computing is relatively low. Simulation is a great tool for working out the bugs and tweaking the design variables, but it is not as useful if you are trying to explore the relationships between different design parameters and the performance criteria. Queueing theory provided the Chrysler team with an analytical model for analyzing systems of queues and processes.[4]

It may be best to describe queueing theory in the context of our example from table 1. The model of a queue includes the arrival rate, the size of the queue, and the service rate. In the case of an assembly line, those can be translated directly into an upstream process, a buffer, and a downstream process (figure 1).

[3] Axiomatic design can be explored more fully in *The Principles of Design* by Nam P. Suh, Oxford University Press, 1990.

[4] The queueing theory model for this project was developed with help from MIT Professor Steven Graves and MIT Ph.D. candidate Sean Willems.

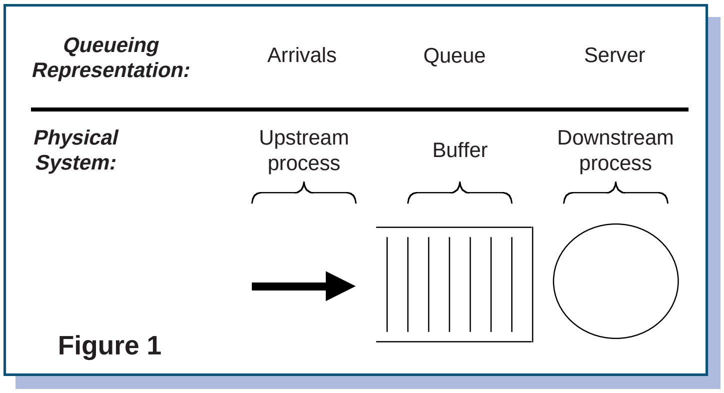

Figure 1

Several of these are considered in series, with each downstream process acting as the upstream process for the next queue system. Our model included as inputs the probability of failure for a workstation, the number of workstations in a line segment, the probability of the upstream segment's being starved, the buffer size, and the speed of the conveyor system. The output measure is the probability of the downstream segment's being starved, which is representative of the lost production due to variation and problems in manufacturing.

This model, contained within a spreadsheet, could give very quick iterations and trials to let us determine relationships and experiment with extremes. This speed and flexibility are very valuable when you are dealing with a new paradigm in factory design. Several insights came out of this work. First, several factors could improve throughput, such as reducing line segment size, increasing buffer size, and decreasing the probability of failure. But each of these variables helped only up to a point; then the incremental value of changing that variable was diminished. From this we learned that factory designers should look to balance the way they use throughput-improving design parameters, because one has its limits. The second major insight was that while most of these design parameters cost significant investment dollars, the variation reduction—that is, reducing the probability of failure—cost nothing but the expense of training and minor continuous improvement dollars. This is why at Toyota, while the use all of the throughput improvement techniques, they focus most of their efforts on variation reduction.

We used the queueing model as a learning tool, and it was especially valuable when we were faced with trying to understand new relationships. But while some relationships are physical, as in this example, some are not and require different tools, as in the next example.

Systems Dynamics

The launch of this new factory for Chrysler will involve thousands, maybe millions of variables, all connected in some way. Modeling the dynamics of the whole launch period would be a daunting task. But by looking at pieces of the problem and using systems dynamics to capture the dynamic forces at play, we can understand what the failure modes may be and gain some insight into high-leverage solutions.

The systems dynamics model shown here (figure 2) tells part of the story of what is involved in implementing lean manufacturing in a new factory. The *andon* system is one piece of the Toyota Production System. In the *andon* process a line worker can signal his or her team leader when there is a quality problem. The team leader responds and decides whether or not to solve the problem within the workstation, possibly stopping the conveyor to do so. Either way, two things happen. First, the short-term effect is that throughput goes down when the line is stopped to allow workers to fix problems. Second, however, the problem-solving process gets started much closer to the problem itself. If the problem-solving approach is maintained, it will reduce the need for rework and improve the quality and throughput of the factory.

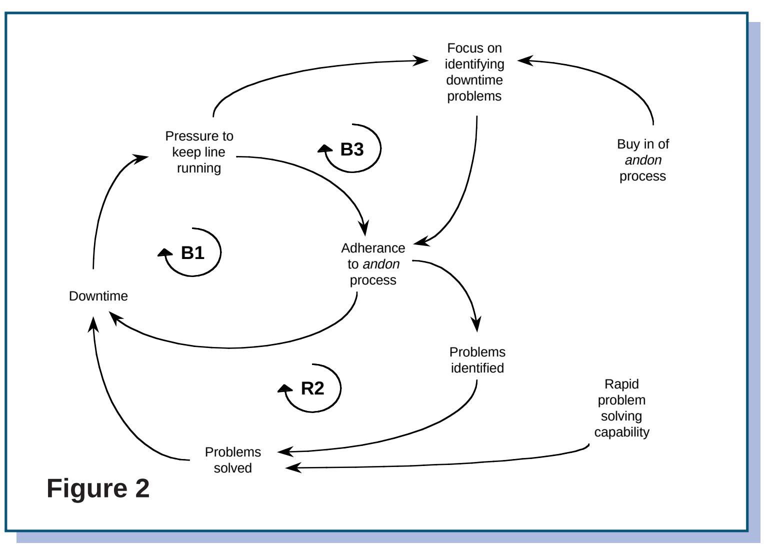

Figure 2

As shown in figure 2, there are three dynamic loops that describe this transition into an *andon* system. The first loop, B1, is a balancing loop that represents the pressure to keep the line running and intolerance for deviation from the standard continuously running rate. The second loop, R2, is a reinforcing loop that helps solve problems at their root; it depends on workers' ability to identify the problems as they happen and the production team's problem-solving capacity. The third loop, B3, is what maintains the systems at the new, lower level of problems. The factory management is focused on the long-term throughput, and therefore problem solving instead of management pressure is the tool of choice to keep up throughput.

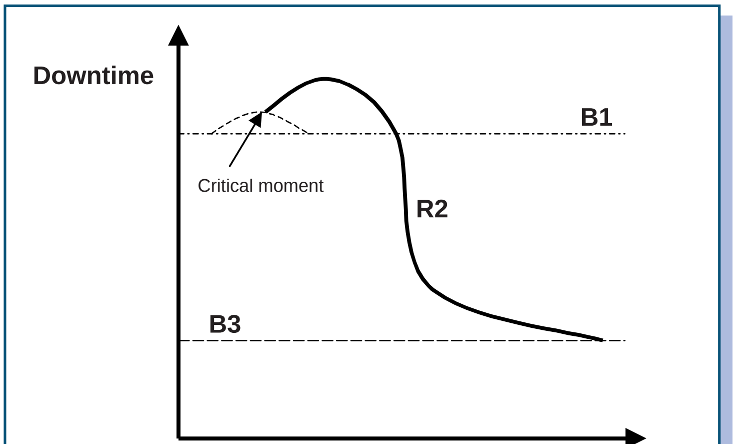

Figure 3

Figure 3 diagrams these dynamics. In this behavior-over-time graph, there are several high-leverage points that will make or break the transition to an *andon* system. First, the management must shift their thinking about how to achieve throughput to a long-term, problem-solving focus. This change will weaken balancing loop B1 and strengthen balancing loop B3. The other high-leverage move is to build significant problem-solving capacity within the production teams and support staff of the factory. This is the critical component that lends weight to reinforcing loop R2.

Understanding the dynamic forces in the example of implementing the *andon* system can help us identify the failure modes and high-leverage solutions for a multitude of problems. We use systems dynamics in this example not just to explore and solve a specific problem but also to build our own capacity to identify and solve other problems. This is one of the reasons that we do not have to model all of the dynamics involved in implementing the lean factory system; as a component of integrated management systems, systems dynamics serves primarily as a tool that complements axiomatic design and queueing theory.

Thinking in Terms of PDCA

Reviewing these examples, you can see that each one can be mapped onto the Plan-Do-Check-Act (PDCA) cycle. Each piece of the integrated management system must act to enhance both action and learning and continue the learning cycle. The importance of each piece of PDCA is due to the length of the overall project's PDCA cycle. Table 2 summarizes how these activities—including the lengthy process of designing and building a new factory, map onto the PDCA cycle.

Integrated Management Systems Under Discontinuity

I want to step out of the case example to explore the general concept of integrated management systems under discontinuity. The Chrysler example discussed in this paper highlights an integrated management system under a discontinuity in the structures, mental models, and theories that underlie the company's day-to-day processes; that is, at a time of instability in the organization. At times of instability the individuals involved must pay close attention to systems as they relate to the new understandings. Creating an integrated management system is not more or less important under discontinuity than it is under a stable system, but it is important.

Discontinuity: A Matter of Degree

An organization will face various levels and types of instability over time, as shown in this behavior-over-time graph (figure 4). The organization could face changes in its entire business model that would generate a high level of company-wide instability as in the first peak on the graph. Or the organization could face a discontinuity in just a piece of its business, such as the factory design example in the Chrysler case. This would result

Table 2:

PDCA Cycle	Axiomatic design cycle	Queueing model cycle	Systems dynamics cycle	Factory design and build cycle
PLAN	Set up the structure for the mapping and the team's conversation that will guide the factory design.	Develop the model, assumptions, and plans for capturing the learning.	Determine the problem area and collect information to being piecing together the model.	Design the factory and plan for implementation.
DO	Capture the team's brainstorming and design conversations through mapping functional requirements to design parameters.	Experiment with the model to understand the relationships between features.	Build the model, the relationships, and the implications.	Build the factory and launch the new processes.
CHECK	Begin turning the design parameters into factory blueprints and capture conflicts or gaps in design.	Compare the new lessons learned to the blueprints and current understanding.	Test the implications with those who will be affected.	Monitor the progress of the launch and the performance of production against the plan.
ACT	Resolve the conflicts in the blueprints and capture the new lessons learned in the mapping.	Make changes to the factory design and integrate the learning into existing structures and design tools.	Implement the lessons learned and capture the lessons from the model for the rest of the organization.	Add, subtract, or re-deploy resources to correct the deviations and capture and standardize the learning.
Time length	Weeks to months	Weeks to months	Days to months	Over several years

in a lower level of instability for the organization as a whole; but a great deal of change for some individuals within the firm. In either case, the organization must take the learnings obtained during its period of change and slowly integrate them into operational practices, incentive structures, and reporting structures.

At all levels of stability or instability, it is important to examine the organization as an integrated management system. At the highest levels of discontinuity managers should engage tools designed for exploration and learning, such as tools for systemic analysis, tools for exploring mental models, and dialogue tools. The methodologies used in our factory design case study would fall into this category. As the organization returns to relative stability, its managers must consider how to create an integrated management system that encompasses the learnings from the discontinuous period. Process owners, incentives and motivation, reporting structures, and standard operating procedures can help effect such integration. I believe that this distinction between organizational needs at different points on the stability — discontinuity spectrum is under-appreciated by managers today. To demonstrate how important it is, table 3 examines the tasks associated with building a factory and how the tools will differ at each end of the spectrum.

The Interpersonal Domain

Each of the activities involved in the Chrysler design project was a mix of the technical and interpersonal domains. We have been talking mostly in the technical

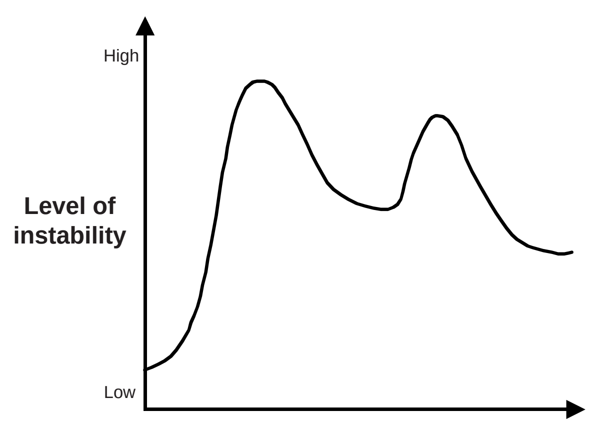

Figure 4

domain, so I would like to highlight an example of the interpersonal elements involved in this integrated management system.

Axiomatic design drew together the tacit knowledge and varied skills of a wide-ranging set of people to capture explicitly the relationships between design parameters and functional requirements. Drawing out and integrating tacit knowledge is not a trivial interpersonal task. One of the skills required by the team is a strong sense of dialogue. Dialogue requires open-ended, building conversation that is filled with a spirit of inquiry and a sense of trust. I won't go into how to build trust, because there is a lot of work in this area already (although none of it is comprehensive enough for managers to work with). I can, however, present the benefits to the project once trust is built up.

Building trust made this effort work on several levels. First, the team members were able to work together in an environment surrounded with uncertainty without being shackled by anxiety and fear. Second, the team members could put down in writing their expectations and concerns without feeling they would be condemned if their ideas were not proven accurate. Finally, thanks to the high level of trust, team members did not feel they had to worry about confirming or validating each other's intuitions and ideas; they were set free to create much more efficiently.

Conclusions

In conclusion, a few reflections on the Chrysler plant design project and on integrated management systems in general.

Why an Integrated Management System Made This Project Better

The Chrysler design project required a great deal of exploration, experimentation, and learning. In addition, the potential consequences of failure were huge. Between the people, processes, and functional departments, so much needed to be pulled together that there was no way one tool would have been comprehensive enough to run the program. Only by pulling together a collection of the right tools in an integrated management system could the team have completed this ambitious project.

Each of the tools played a role. If the organization had been focused exclusively on systems thinking, they might not have started with the rather linear but fundamental understanding of the factory architecture that axiomatic design provided. If the group had been dominated by the Theory of Constraints, they would have spent so much time on the schedule that they wouldn't have stopped to ask if the elements and bottlenecks would be different, as systems dynamics allowed. I am not suggesting that systems thinking and the Theory of Constraints are invalid. In fact, the integrated management system enhances their value to the organization, because the insights and outputs of such tools can become inputs into other tools, and as the tools are assembled into an integrated management system they have synergistic value.

Table 3:

TASK	High level of discontinuity in tasks or processes	Stable operating conditions
1. Understanding relationships between operating conditions and factory design features.	Understanding requires explicit knowledge of operating conditions, factory elements, and interrelationships (axiomatic design/architecture design).	Understanding is embedded in the tacit knowledge of factory designers, some of it from rotation of managers back and forth between production and factory design. Relationships embedded in the information flows and reporting structures.
2. Understanding mathematical relationships in conveyor systems so as to design features such as line speed.	An analytical model can help managers explore the mathematical relationships between design parameters and performance characteristics (queueing theory).	Prepacked simulation takes old data with new design parameters to predict performance characteristics.
3. Lining up resources and implementation plan so as to launch factory and product rapidly.	Team needs to recognize that with a new factory there are different/new modes of failures and different points of leverage (systems dynamics explore that).	Team assembles and converges on factory coordinated by launch manager. Standard metrics and processes in place.

Designing Your Own Integrated Management Systems

There are two points I would like to make about designing your own integrated management system, the first about what tools to select and the second about how to assemble them.

What tools should you select? In the Chrysler project, my own earlier exposure to the tools of axiomatic design, queueing theory, and systems dynamics allowed me to see that they could be used together. I had learned about axiomatic design from a discussion by Dr. Nam

Suh, the tool designer. Queueing theory I had learned about from Professor Steven Graves's classes in the Leaders for Manufacturing program at MIT. Although I had worked with systems dynamics in many ways, I was introduced to it by MIT Ph.D. and learning organization trainer Daniel Kim.

What if I hadn't been introduced to these tools and had had to pick different tools? They wouldn't necessarily have been the wrong tools; integrated management systems are not binary right/wrong sets of tools. But some tools are better than others for a given application, and I believe that some exposure to a multitude of tools will help the designer select better tools. I suggest that getting enough exposure to know the value of a variety of tools is more important than knowing all the subtle ins and outs of each tool. In the Chrysler case there were probably several violations of pure theory in the use of the tools, but that did not make them invalid or useless.

This brings me to my second point: No matter how good or bad the selection of tools, they still need to be assembled into a system. The use of the word *system* in the phrase "integrated management system" is not faddish or meaningless, because just as important as what tools are selected is how the designer manages the interfaces, the inputs and outputs, as these tools become a system. The System Designer must spend a great deal of time making sure each tool or exercise is not used in isolation, because otherwise it has no value to the overall project. In the case example, it was just as important to think about how to capture the learning from axiomatic design and how to use and distribute the factory architecture as it was to choose axiomatic design as a design tool.

Questions for Further Research

There are two questions that I believe need much more work. First, as I have already suggested, our selection of tools at Chrysler was somewhat arbitrary and was based on previous exposure to the tools. Is there a better way to select tools? Can there be an optimal integrated management system in a given case? And if so, is it different for each firm, project, and situation? More understanding of these questions will help further the work of integrated management systems.

The second question is how to integrate the technical and interpersonal domains. Much of management literature deals with these issues independently. There are theories of leadership, organizational learning and culture, and motivations and incentives. On the technical side, there are theories such as queueing theory. How to integrate the interpersonal and technical domains is the ultimate question for integrated management systems theory.

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