DECODING VALUE AT THE SOURCE:

This article illustrates how lean production metrics function as part of a self-regulating cost management system.

THE ABCs OF LEAN PRODUCTION METRICS

TOM JACKSON

In August 1988, entrepreneur Norman Bodek and his company, Productivity Inc., featured the soon-to-be-famous lean consulting firm Shingijutsu at Danaher Corporation in a fabulous workshop known as "5 Days and 1 Night." This was the prototype for the now ubiquitous five-day *kaizen* workshop. Beginning on Monday, consultants from Shingijutsu and Productivity Inc. led an improvement team of Danaher managers, engineers, and guests from other companies in following Danaher's operators with stopwatches to gather data on the shop floor. The six lean metrics starred in Exhibit 1 were employed to analyze the data and redesign the flow of production. On one very long Wednesday night, contractors physically reorganized, rewired, replumbed, and reprogrammed the factory. On Thursday morning, Danaher employees used the same metrics to test and validate four functioning lean production cells. In the weeks that followed, Danaher supervisors and employees used the same metrics to manage daily production and highlight the need for further improvement. Practitioners of lean manufacturing and lean transactional processes — including health care — are intimately familiar with these metrics, which have appeared in many *kaizen* workshops during the last 29 years.[1]

My goal is to make sense of these metrics from a cost management perspective. In order to do so, I must add one more metric to the list, namely, takt time. Takt time (t), or takt for short, is the ratio between time available to produce and expected demand: t = time available to produce ÷ expected demand.

Everything in lean production happens just-in-time, as measured by takt; and, as

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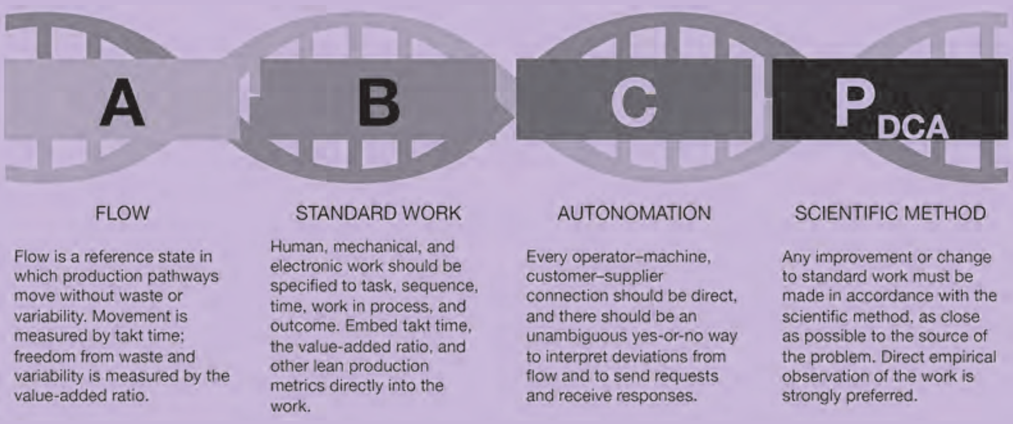
EXHIBIT 1 Lean Production Metrics

	METRIC	DEFINITION / EQUATION	PURPOSE IN RADICALLY DECENTRALIZED CONTROL SYSTEM
★	CT = cycle time of the cell	Measured empirically in seconds	Ensures adherence to target labor and material cost in production cells; ensures work balance.
	OCT = operator cycle time	Measured empirically in seconds	Measures actual work content of task sequences assigned to production operators.
	D = demand	Measured both historically and in real time	Ensures synchronization of production with both forecast and/or actual demand.
★	Floor space	Measured empirically in square ft.	Ensures adherence to targeted non-labor conversion cost; used to design, manage, and improve layout of production areas.
	K = # signal cards or kanban	$K = D \bullet (L + b) \div Q$	Where *D* = demand, *L* = lead time to replenishment, *b* = buffer stock, and *Q* = transfer batch size.
	L = transfer batch lead time	Measured empirically in seconds	Ensures that the right # of units are delivered to the right cell at the right time to keep production moving at takt.
★	*n* = operators needed	$n = \Sigma\, OCT \div t$	Ensures that takt time is met at target cost.
	Q = transfer batch size	Established internally and in negotiations with suppliers	Strictly controls the amount of inventory in each transfer batch or container.
	Scrap	Measured empirically in # units or lbs on *gemba*	Captures any material costs of poor quality in production cells that are not fully quantified by the loss of productive time.
★	*SWIP* = standard work in process	$SWIP = [f(n)]$	Ensures synchronization with takt time in production cells, and adherence to target material handling cost.
	t = takt time	$t = \frac{\text{net time available}}{D}$	Measures the just-in-time pace of market demand in seconds; used to synchronize all aspects of production with demand.
	Total lead time	Measured empirically in minutes or seconds	Measures the time parts spend being transformed in cells as well as time spent waiting in buffers.
★	Total part/input path	Measured empirically in linear ft.	Ensures adherence to target material management cost between production cells; used to reduce *L*, replenishment lead time.
★	*V* = value-added ratio	$V = \frac{\text{value-added time}}{\text{total lead time}}$	Ensures adherence to target labor cost in production cells; used to optimize n (operators needed) and other variables.
	Value-added time	Measured empirically in seconds	Measures how much time is spent “adding value” by changing the form, fit, and/or function of materials or information.

★ indicates original Shingijutsu/Productivity Inc. metrics

EXHIBIT 2 The DNA of Lean Cost Management



Benjamin Franklin once said, "Time is money."[2] Practically speaking, takt time is the average pace at which production must move to meet production targets within the time available — that is, without overtime. In each of Toyota's factories, an electronic production control board hangs above the factory floor. On this board, takt time is prominently displayed together with production targets and running totals of finished production. Many lean metrics are mathematical functions of takt. It is the context in which every lean metric must be understood.

During the design phase of the product life cycle, Toyota works with its suppliers to achieve a target cost of the project's components and materials. Target costing is a significant departure from the traditional practice of cost plus, in which producers simply add an acceptable margin to whatever their costs happen to be. In target costing, the objective is to price backward from a market price and then deduct a profit acceptable to investors. The result is the target cost. In a process known as value engineering, the manufacturer and its suppliers meticulously calibrate the form, fit, function, and weight of every component to achieve the target.[3]

The lean metrics in Exhibit 1 operationalize the target cost as the product enters the production phase of its life cycle. In production, the only problem that remains with respect to cost is to hit the target. All the information needed to control cost that is not already embedded in the product design, bill of materials, and new production equipment must be embedded in the production layout and workflow of every operator. This is the function of lean production metrics.

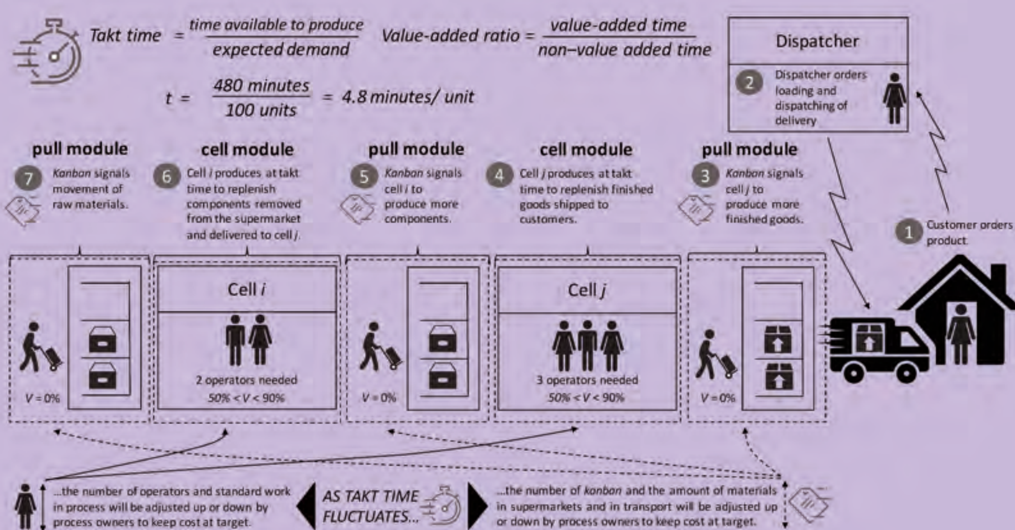
Of course, there is nothing new about target costing. Many American and European companies started adopting it decades ago. The only difference, according to Robin Cooper, between Japanese companies and the rest of the world is that Japanese companies like Toyota actually hit the target.[4]

Radical decentralization

It is generally agreed upon that the traditional standard costing model of the accounting profession does not provide the right information or provide it in a way that is timely enough to support advanced manufacturing methods such as lean production.[5] How do lean organizations get the right cost information when they need it? It's simple. Instead of relying on cost variance reports prepared a month or more after the fact, operators control cost in exactly the way they control quality: They reliably detect and correct deviations from standard or target cost and quality conditions as they occur on the shop floor.

Understanding how cost management moved from variance reporting to empowered employees requires a short history lesson.[6] Economists view the history of business organization as a study in decentralization. In the mid-1800s, the American railroads

EXHIBIT 3 Modular Cost Management: Cells and Pull Systems



and, later, big business adopted the command-and-control systems of the Prussian military establishment. Beginning with General Motors in 1919, however, businesses have progressively decentralized their decision-making, becoming increasingly adaptive and lean or, in the current lingo, agile. Decentralized decision-making in business organizations is comparable to parallel processing in computers: They both decrease latency or slowness in information processing.[7] In other words, parallelization gives us faster computers; decentralization gives us faster organizations. What makes Toyota's system unique is its radical decentralization. In effect, a lean organization is comparable to a massively parallel supercomputer. Toyota's decentralized model of cost management is independent of its centralized management and financial accounting systems. As H. Thomas Johnson advised, "To become lean, shed accounting."[8]

To understand how radically decentralized cost management works requires another reference. In a famous article in the *Harvard Business Review*, Steven Spear and H. Kent Bowen explained that the information about Toyota's decentralized management systems is like a DNA code consisting of four discrete letters. In Exhibit 2, I have reordered and restyled this code for purposes of our discussion of cost management.[9]

By decoding the first three letters of Toyota's DNA, we will see how the lean production metrics in Exhibit 1 are systematically embedded into frontline operations to keep cost under control without management intervention.

- A. *Flow* explores how process synchronization and value are measured in lean value streams. Flow provides reference conditions for target cost, standards of synchronicity, and value against which deviations can be measured "at the source" to trigger immediate corrective action.
- B. *Standardized work* explores how the metrics in Exhibit 1 are used to actualize the conditions of flow within production cells and the pull systems that connect them to form value streams.
- C. *Autonomation* explores how lean metrics are used by operators to maintain the state of flow in equilibrium by detecting and correcting defects that disrupt the flow. Most defects are addressed within takt time.

The article will conclude with a brief discussion of Plan, Do, Check, Act (PDCA) and the scientific method.

A. Flow. The first element of Toyota's code is flow. Flow is a reference state in which production pathways are free from waste and variability, as measured by the lean pro-

EXHIBIT 4 The Seven Wastes

WASTE		DEFINITION	MEASURED BY	TIME CONVERSION
1	Overproduction	Too many production units (more than the demand)	Time conversion	Non–value added time = # units × CT
2	Overprocessing	Too many process steps (or non–value added steps) to get the job done	Empirical time study	N/A
3	Waits/delays	People, information, machines waiting for value-added action	Empirical time study	N/A
4	Inventory	Work in process waiting for value-added action	Physical count or time conversion	Non–value added time = # units × CT
5	Transport	The physical distance the part or person must travel to get the final unit completed	Empirical time study	N/A
6	Motion	Bending, lifting, etc., to pick up or drop off assemblies and inventory	Empirical time study	N/A
7	Defects/rework	Poor product or service quality that generates testing + undoing mistakes + reworking to restore quality + scrap	Physical count, time conversion, time study	Non–value added time = # defects × CT

duction metrics. Of course, those pathways must be sufficiently free from waste and variability to ensure that the target cost set in the design phase of the product life cycle is met in the production phase. Lean practitioners normally describe flow pathways as value streams. See Exhibit 3.

Value streams have two components, cells and pull systems, which behave as discrete modules in a lean cost management system. A production cell is a highly compact arrangement of people, production equipment, materials or other inputs, and information designed to meet customer demand at target cost and target profit.[10] All production activities within cells are synchronized with demand by means of takt time. Production cells are connected by pull systems, which consist of stores of materials, known as supermarkets, and information or signals, known as *kanban*. *Kanban* are used to synchronize the movement of materials in standardized containers or transfer batches from supermarkets to production cells, where materials are integrated into the production flow. In section B on standard work, we will explore how these same two components are used to construct lean cost management systems.

Within production cells, operators and machines perform work that changes the physical form, fit, and/or function of materials and information into products or services that customers are willing to pay for.[11] Such activity is referred to as value-added. All other activity is referred to as waste, which is non–value added. Exhibit 4 sets forth a list of the seven classic non–value added wastes, all of which may be measured or interpreted as wastes of time. The ratio of value-added time to cycle time (CT) — the time a unit spends at rest or in process — is known as the value-added ratio (a starred element in Exhibit 1). Production cells are normally engineered to meet target cost at a value-added ratio (*V*) between 50 percent and 90 percent. Although there are exceptions, manual work involving critical thinking, such as the practice of medicine, will tend to have lower

EXHIBIT 5 Elements of Standard Work

ELEMENT	REQUIREMENT	PURPOSE
Standard task	Every discrete operation must be performed in exactly the same way.	Establishes conditions for measuring defects as deviations from standard task and sequence. Makes defects discoverable in space, not time.
Standard sequence	Every sequence of discrete operations must be performed in exactly the same order.	
Standard time	Every sequence of operations must be performed, on average, in the same amount of time *(OCT)*.	Treats elements of cost exactly like task and sequence, the elements of quality. Makes defects discoverable in time and space.
Standard work in process	Every sequence of operations must be supported by a constant level of work-in-process inventory *(SWIP)*.	
Standard documentation	Every sequence of operations must be tested and documented together with normal task times.	Supports systematic training and provides a baseline for improvement.

value-added content; work that can easily be standardized or automated, such as manufacturing assembly, will tend to have higher value-added content. All activities that occur between cells — the storage of inventory and the transportation of materials — are considered to be non–value added.

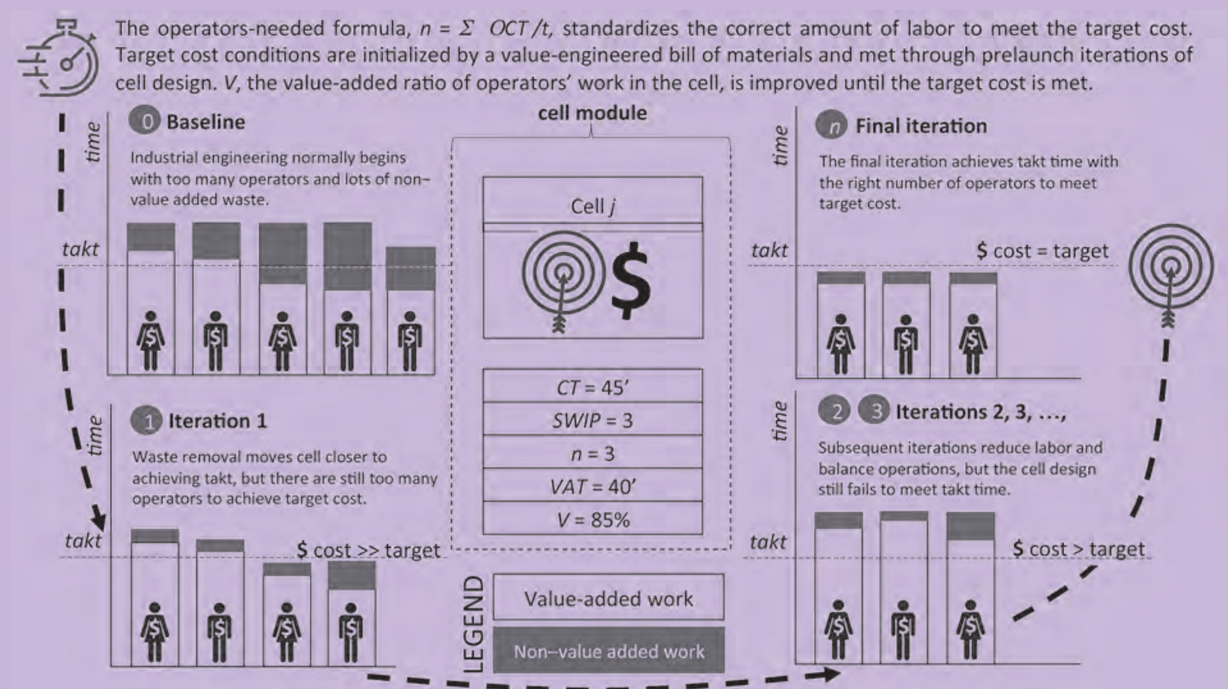
To summarize, the state of flow provides a reference state for lean cost management systems. Cells and pull systems are the basic building blocks of lean production systems as well as lean cost management systems. To achieve a state of flow, production must move at takt time with at least 50 percent value-added (with less than 50 percent waste) within production cells. Theoretically, the value-added ratio in a true state of flow is high enough to ensure that target cost conditions set in the design phase are satisfied. As we will see in section B, in the production engineering phase, iterations of improvement increase the actual value-added ratio until target cost is met.[12]

B. Standard work. Flow is defined by takt time and the value-added ratio — the metrics that underlie the cells and pull systems in a value stream. It is implemented through the industrial engineering of standard work. Standard work can be defined as the best way an organization knows how to perform a sequence of operations. Technically speaking, standard work incorporates the five elements in Exhibit 5. In the production engineering phase of the product life cycle, lean production metrics are used to control labor and materials management costs. Flow is established through the design and testing of standard work, which is specifically engineered to meet takt time with minimal waste or losses to non–value added activities.

Cell design. As illustrated in Exhibit 6, standard work for value-adding activities performed within production cells is tested, improved, and retested until the target cost is met at the correct levels of operator cycle time (OCT), operators needed (n), and standard work in process (SWIP). Any remaining problems with product quality are also addressed at this point.

The typical lean industrial engineering procedure conducts repeated time studies to discover and eliminate hidden waste. This may result in the elimination of non–value added time and subsequent reductions in OCT and n. Often, operators can be cross-trained so that once-specialized tasks can be performed by even fewer, more

EXHIBIT 6 Cost Management in Production Cells



capable operators. Reductions in *n* allow more compact arrangement of machines and inputs. Reductions in floor space of 50 percent or more are also common, permitting the construction of additional cells in the same area and reducing costs of space, heat, and light.[13]

Within lean production cells, materials are controlled by SWIP. The control of SWIP has three purposes. First, it helps to synchronize production with takt time by regulating how much work-in-process each operator physically controls at each step of the process. Second, the optimization of SWIP optimizes floor space used for storing work-in-process. Third, SWIP sets an upper limit on the CT of the cell. As a practical matter, SWIP is a function of operators needed (i.e., SWIP $f(n(t))$).

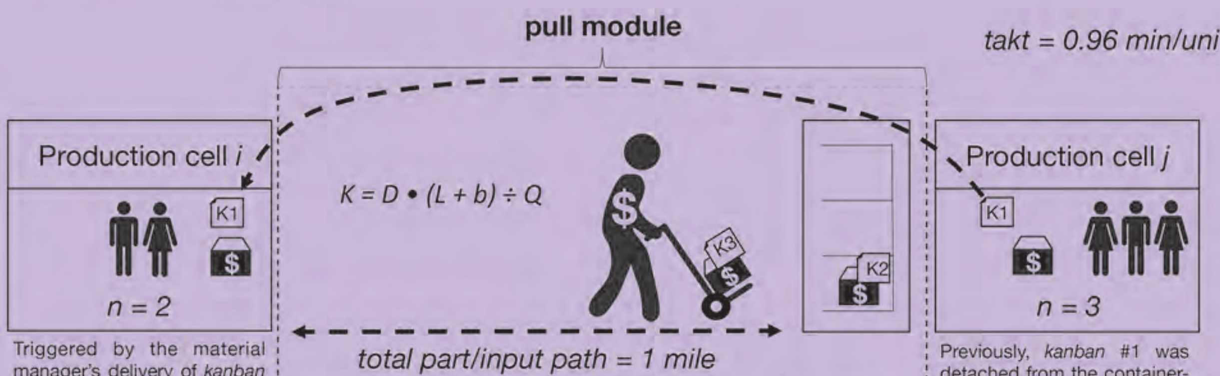
SWIP can be equal to *n,* where each operator operates one machine or workstation and no additional work-in-process is required to facilitate the movement of inputs from one machine to another or the loading or unloading of machines. SWIP may be greater or less than *n* depending on contextual factors such as the degree of automation, difficulty in loading and unloading machines, and the nature of teamwork within the cell.

Pull system design. Once production cells are capable of meeting takt and target cost, attention turns to the pull systems that connect them. Pull systems are designed to automatically ensure that materials or inputs are moved to production cells only when operators are ready to produce at takt. Pull systems are governed by the *kanban* equation: $K = D \times (L + b) \div Q$ (refer to Exhibit 1).

The *kanban* equation governs the number of signal cards or *kanban*, *K,* that circulate between two productions cells. As illustrated in Exhibit 7, *kanban* cards are used by production operators to communicate to materials managers the need to move parts from supermarkets to production cells for value-added processing.[14] The equation also standardizes the amount of inventory in supermarkets plus any containerized material in transit between supermarkets and cells. This number is simply the number of containers in circulation, given by *K*, times the maximum permissible amount in each container, given by *Q*. To audit the amount of material on the floor, operators

EXHIBIT 7 Cost Management in Pull Systems

The *kanban* equation plus standard work for material managers standardizes the amount of inventory in storage or transit between cells. The average time a unit spends between cells is also standardized because movement parts and inputs are synchronized by means of the takt time of cell *j*.



Time available to produce (8 hours/day)		0.33	days
D =	expected demand	500	units/day
Normal walk speed	@ 3 miles/hour • 8 hours/day	24	miles/day
TP/IP =	total part/input path	1	mile
L =	replenishment lead time	0.04	day
b =	buffer (20% of expected production)	0.20	day
Q =	transfer batch size	50	units/batch
K =	# *kanban* $K = D \cdot (L + b) \div Q$		
K =	500 units/day • (0.04 + 0.20 days ÷ 10 units/batch)	3	*kanban*

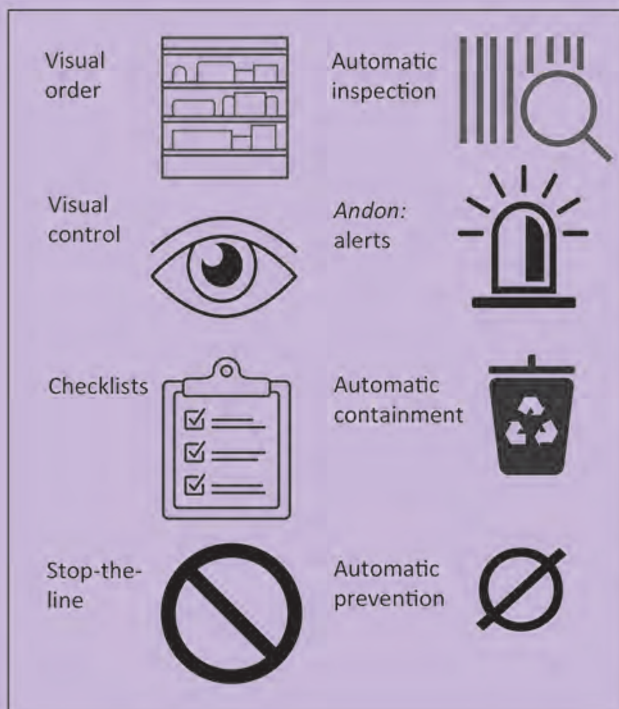
only have to count the number of *kanban* in circulation and multiply it by the container or transfer batch size.

Management's attention is more likely to fall on *L*, the replenishment lead time. *L* is a function of the total input path between the cells, another lean production metric starred in Exhibit 1.[15] If the total input path can be reduced by, say, 50 percent, so can the direct labor component of materials management. Like the work of direct production, the work of materials managers is organized into cells with their own takt times and defined by standard work and its metrics *n* and SWIP. *L* can often be measured by how long it takes materials managers to walk the distance of the part path. Thus, the total part/input path often becomes a target for improvement.

To summarize the logic of the lean metrics of standard work, the conditions for flow are established within cells during the production engineering phase of the product life cycle by regulating *V,* OCT, *n,* and SWIP. This ensures that all cells will meet takt time at target cost. The conditions for flow between cells (i.e., across the value stream) are established by optimizing the total input path. This regulates *L,* the number of units that circulate between cells, and the cost of materials management.

C. Autonomation. Once cells are capable of meeting target cost, how is the target cost equilibrium maintained? What are the "unambiguous yes-and-no ways" of sending and receiving signals that alert operators when deviations from the reference conditions of flow occur in actual operations? Operators maintain the equilibrium state of flow by responding to signals generated by deviations from flow. In this context, defects are defined as deviations from the reference state of flow, defined in terms of lean production metrics. Standard work and work-in-process are specifically designed to allow operators to perform this demanding intellectual work at the same time they make products or deliver services.

EXHIBIT 8 Methods of Autonomation



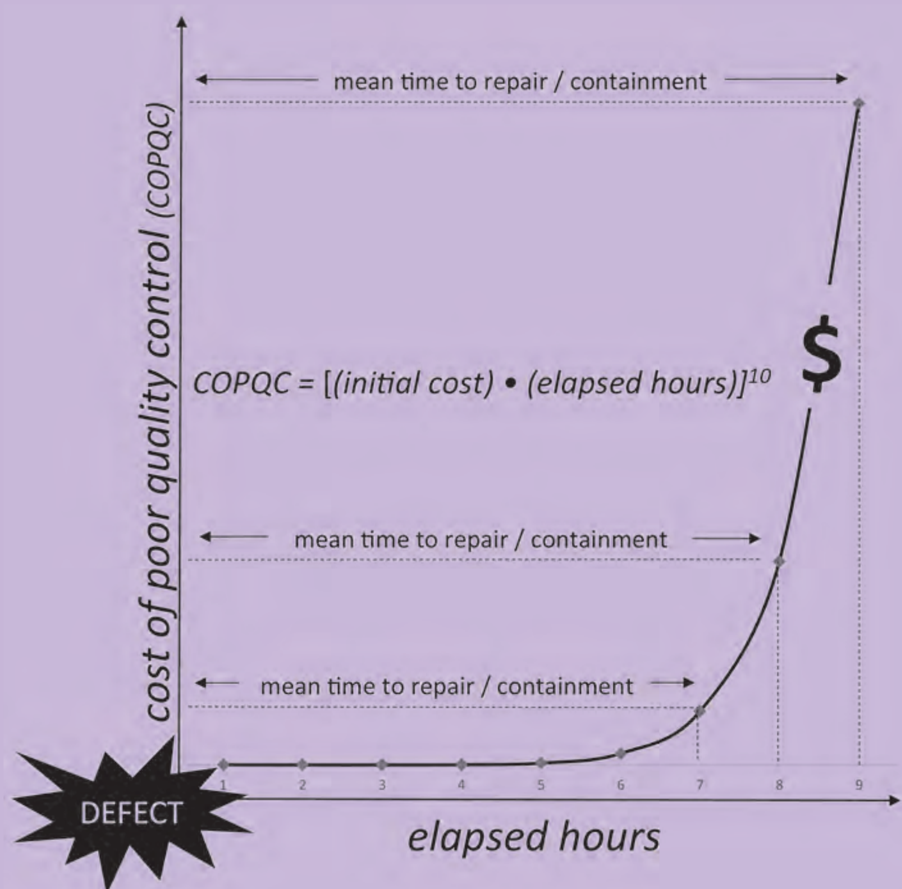
The bifurcation of duties into intellectual and physical components is known as autonomation.

Autonomation frees human operators to critically assess and adjust production activities at the same time they perform their value-added work. Informed by signals defined by lean metrics, autonomation is the motor of self-regulation. It operates at three levels: defect detection, containment, and prevention. Any or all of these three elements may be automated mechanically or electronically. In many cases, however, simple systems such as visual order or workplace organization, visual control, and simple checklists can achieve the required result with little capital investment (see Exhibit 8). Takt time and the lean production metrics of value-added, CT, *n*, SWIP, and total input path make it easy for operators themselves, as well as supervisors and managers, to discover deviations from flow as soon as they occur. As illustrated in Exhibit 9, the effect of autonomation is to detect, contain, and correct defects before the cost of poor quality control begins to rise.

The concept of autonomation can be illustrated by the practice of stop-the-line, with which most readers will be familiar. At Toyota, whenever an operator discovers a defect within a production cell, he or she pauses production momentarily to address it before allowing the workpiece to proceed to the next step in the process. Fellow workers and supervisors assist with difficult problems. Production is stopped completely only when the problem is too complex to be solved within the window of takt time.

Because the system is engineered to meet target cost at takt time, pausing the line to address routine production inefficiencies within takt ensures that Toyota can meet its cost targets. Because the reference state of flow and the standard work that articulates flow incorporate the elements of standard time and SWIP, the stop-the-line system ensures that cost, as well as quality, is kept under control. Operators pause the line not only when they discover physical defects, such as a dented fender or an incorrect dose of medicine, but also when they are unable

EXHIBIT 9 The Cost of Poor Quality Control



to complete their standard work within takt time or when actual work-in-process is inconsistent with SWIP.

The process of discovery and autocorrection is summarized in the window analysis in Exhibit 10. Square 1 of the window, upper left, signifies the state of equilibrium in which operators know and adhere to standard work, as measured by takt time and the lean production metrics. Squares 2–8 represent reciprocal situations in which there are deviations from the standard, because operators either do not follow or do not know the standard. In squares 2–8, the response is straightforward: Take steps to adhere to the standard and restore the conditions of flow. In most cases, simple deviations from known, effective standards can be discovered and autocorrected within takt.[16]

To summarize, the metrics of standard work and pull systems indicate, in real time, when production and materials management processes are either in control or out of control, giving rise not to management intervention but to self-regulation. With lean production metrics directly embedded into critical steps in the work, autonomation ensures that (a) deviations from a known and effective standard are discovered quickly, and (b) when they are discovered, they are normally corrected within takt time.

Conclusion

What happens when problems that cause deviations from flow are too complex to be discovered or solved within takt? For example, what happens in manufacturing when the problem is the product or equipment design? What happens in health care when a patient develops an unknown condition? These are situations that land

EXHIBIT 10 Window Analysis of Lean Cost Management

n_1 / n_2		EFFECTIVE STANDARD IS KNOWN; TAKT AND TARGET COST CAN BE MET		EFFECTIVE STANDARD IS NOT KNOWN
		Lean metrics indicate that standard is followed	Lean metrics indicate that n_1 is not following the standard	n_1 does not know the standard or what the metrics mean
EFFECTIVE STANDARD IS KNOWN; TAKT AND TARGET COST CAN BE MET	Lean metrics indicate that n_2 follows the standard	**1) TARGET STATE** n_1 and n_2 both follow a standard engineered to achieve flow; takt and target cost are met	2) n_2 helps n_1 to restore flow and meet takt and target cost	5) n_2 shows n_1 the standard; they both move to square 2
	Lean metrics indicate that n_2 is not following the standard	3) n_1 helps n_2 to restore flow and meet takt and target cost	4) n_1 and n_2 help each other to restore flow and meet takt and target cost	7) n_2 remembers the standard and demonstrates it to n_1; they both move to square 4
EFFECTIVE STANDARD IS NOT KNOWN	n_2 does not know the standard or what the metrics mean	6) n_1 shows n_2 the standard; they both move to square 3	8) n_1 remembers the standard and demonstrates it to n_2; they both move to square 4	9) The standard cannot be recalled or is ineffective; problem cannot be corrected within takt time

us in square 9 in Exhibit 10. The fourth letter of lean code, scientific method, speaks to Toyota's commitment to approach such problems systematically, not only with the statistical tools of modern scientific investigation, but also with the direct observation and creative thinking of frontline production operators. But this takes us far beyond the scope of this article, which has concentrated on why lean organizations don't land in square 9 when they can avoid it. Operators have all the information they need to intervene in real time to correct most problems.

Toyota's cost management system designs and maintains a flow of production that produces products and services at a target cost, without management intervention. An economist would say that lean systems are designed to maintain an equilibrium — that is, a self-regulating state of flow. The DNA of a lean production system keeps track of the plan — including targets and metrics — for the flow of production and, like biological DNA, stores a complete copy of that plan in every production cell. Autonomation, including the practice of stop-the-line — informed by lean production metrics deeply embedded in the work — virtually eliminates exponentially rising costs of poor quality by ensuring that the most obvious deviations from the standard are detected and autocorrected within takt time. Toyota's operators also have all the information they need to keep problems from spreading. Using the scientific method, they work to prevent problems from recurring in the future and even to anticipate problems with advanced predictive models. Lean metrics are designed to support both autonomation and science, both practiced by a community of engaged and empowered problem solvers. ■

NOTES

[1] The article focuses primarily on the six starred metrics. Other metrics in Exhibit 1 have been included to support this investigation, including takt time, *kanban*, and scrap. In fast-paced environments, lean metrics are often stratified into their statistical components to embed information more deeply into operations.

[2] Franklin, B., "Advice to a young tradesman," *Founders Online* (July 21, 1748). Available at: http://founders.archives.gov/documents/Franklin/01-03-02-0130.

[3] Cooper, R. and Slagmulder, R., *Target Costing and Value Engineering*. (Portland, OR: Productivity Press, 1997). See also: Cooper, R. and Slagmulder, R., *Supply Chain Development for the Lean Enterprise: Interorganizational Cost Management*. (Portland, OR: Productivity Press, 1999).

[4] Private conversation with Robin Cooper at Emory University in Atlanta, Georgia, 1999.

[5] See, for example, Maskell, B. and Baggaley, B., *Practical Lean Accounting: A Proven System for Measuring and Managing the Lean Enterprise*. (Portland, OR: Productivity Press, 2004): 134–136, 173–174.

[6] Accountants may be assured that there is nothing in so-called lean accounting that violates the principles of GAAP. See Cunningham, J. and Fiume, O., *Real Numbers: Management Accounting in a Lean Organization* (Managing Times Press, 2003): 29–36.

[7] Jackson, T.L., "The rise of the C-form organization," Rona Consulting (2006) (unpublished white paper).

[8] Johnson, H.T., Lean accounting: To become lean, shed accounting, *Cost Management* 20, no.1 (2006): 6–17.

[9] Spear, S. and Bowen, H.K., Decoding the DNA of the Toyota production system, *Harvard Business Review,* (Sept/Oct 1999): 97–106.

[10] In health-care processes, patients themselves become inputs, along with medicines and other supplies. The cost equations explored in this article are not changed.

[11] In health care, value-added work can be said to change the information, functionality, fitness, and feeling of the patient's well-being.

[12] When cells are connected by pull systems, the value-added ratio necessary to meet target cost drops below 50 percent, because of non–value added work-in-process stored in pull system supermarkets.

[13] Stubborn production bottlenecks and quality problems that prevent achieving target cost become the focus of an intensive team-based improvement intervention known as 3P (production preparation process).

[14] *Kanban* are also used to initiate the production of inputs by upstream processes for consumption (i.e., further processing, integration, or assembly) by downstream processes.

[15] The term *L* is often accompanied by additional terms that add extra time and inventory and that allow materials managers to respond to normal variation in demand and to more disruptions in production.

[16] For additional information about window analysis, see Fukuda, R., "Using window analysis for accurate fact finding and effective countermeasures," *Building Organizational Fitness: Management Methodology for Transformation and Strategic Advantage* (Portland, OR: Productivity Press, 1998).