$WIP = T_l \times R_t$

Figuring to Improve

Mark R. Hamel Michael O'Connor

 $D_p \times D_p$



LEAN MATH

LEAN MATH Figuring to Improve

Mark R. Hamel Michael O'Connor



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Also by Mark R. Hamel Kaizen Event Fieldbook: Foundation, Framework, and Standard Work for Effective Events, SME 2010 To my first teachers and former professional educators, my late father, James Hamel, and my mother, Pauline.

And, in sincere gratitude to my ever-patient wife, Mary Ellen, my children, Jack, Kate, and Molly, who periodically questioned whether this book would ever come to fruition, my many math teachers who undoubtedly would prefer to remain anonymous, and Michael Arcangelo.

—Mark R. Hamel

To light, light in the morning, light in the evening. The light of truth, the light of beauty, the light of love.

And many thanks to all the loved ones who supported me throughout this effort, especially Jesse, Mia, and Coco for all their understanding the many times I said: "It's almost done."

—Michael O'Connor, Ph.D.

REVIEWER COMMENTS

"A practical math book may sound like an oxymoron, but *Lean Math* is both pragmatic and accessible. Hamel and O'Connor do an excellent job keeping the math as simple as possible, while bringing lean principles to the forefront of the discussion. The use of insurance and healthcare industry examples especially helps simplify the translation for lean practitioners in non-manufacturing industries. Readers will be able to use the numerous tables and figures to clearly illustrate and teach lean concepts to others. *Lean Math* is a reference book that every lean practitioner or Black Belt should have in their library!"

-Peter Barnett, MBB, Liberty Management System Architect, Liberty Mutual Insurance

"Lean Math is a comprehensive reference book within which the lean practitioner can quickly find straightforward examples illustrating how to perform almost any lean calculation. Equally useful, it imparts the importance of the relevant lean principal(s). While coaching some recent transformation efforts, I put *Lean Math* to the test by asking several novice practitioners to reference it during their work. They were promptly rewarded with deeper insight and effectiveness—a reflection of this book's utility and value to the lean practitioner."

—Greg Lane, international lean transformation coach, speaker, and author of three books including, "Made-to-Order Lean: Excelling in a High-Mix, Low-Volume Environment"

"While the technical, social, and management sciences behind lean must be learned by doing, their conceptual bases are absolutely validated by the math. This validation is particularly crucial to overcoming common blind spots ingrained by traditional practice. Hamel and O'Connor's text is a comprehensive and readable resource for lean implementers at all levels who are seeking a deeper understanding of lean tools and systems. Clear diagrams and real-world examples create a bridge for readers between theory and practice—theory proven by practice. If math is the language of science, then *Lean Math* is indeed the language of lean science."

—Bruce Hamilton, President, Greater Boston Manufacturing Partnership, Director Emeritus for the Shingo Institute

"Hamel and O'Connor provide both the novice and experienced lean practitioner a comprehensive, common-sense reference for lean math. For example, I know that our Lean Support Office team would have gladly used dozens of *Lean Math* entries during a recent lean management system pilot. The concepts, context, and examples would have certainly helped our execution and provided greater clarity during our training activities. Lean Math is a must have book for Lean Support Office people!"

—Dave Pienta, Director, Lean Support Office, Moog, Inc. Aircraft Group

"Mark and Michael have done a tremendous service for the lean community by tackling this daunting subject. There are so many ways to quantify value, display improvement, and define complex problems that choosing the right methods and measures becomes an obstacle to progress. *Lean Math* helps remove that obstacle. Almost daily, operations leaders in every industry need the practical math and lean guidance in these pages. Now, finally, we have it in one place. Thank you."

-Zane Ferry, Executive Director, National Operations, QMS Continuous Improvement, Quest Diagnostics

"Too many lean books dwell on principles, but offer little to address critical how-to questions, such as, 'How do I use these concepts to solve my specific problem?' With plain English explanations, simple illustrations, and examples across industries, *Lean Math* bridges a long-standing gap. Hamel and O'Connor's *Lean Math* is sure to become a must-have reference for every lean practitioner working to improve performance in any modern workplace."

—Jeff Fuchs, Executive Director, Maryland World Class Consortia, Past Chairman, Lean Certification Oversight Committee

"Lean Math fills a huge gap in the continuous improvement library, helping practitioners to translate data, activities, and ideas into meaningful information for effective experimentation and intelligent decisions. This reference comes at a critical time for the healthcare industry as we struggle to improve quality, while controlling costs. Though we don't make widgets, our people, processes, and patients will benefit from the tools provided in this reference. The numerous examples, as well as the Gemba Tales scattered throughout the book, bring life to the principles and formulas. *Lean Math* is impressive in both scope and presentation of content."

—Tim Pettry, Senior Process Improvement Specialist, Cleveland Clinic

"Lean Math is a great book for those times when only the correct answer will do. The math, along with the Gemba Tales, are helpful for those in the midst of the technical aspects of a transformation, as well as those of us who once knew much of this but haven't used it in a while."

—Beau Keyte, organization transformation and performance improvement coach, author of two Shingo-Award winning books: "The Complete Lean Enterprise" and "Perfecting Patient Journeys"

"Math and numbers aren't exclusively the domain of six sigma! Toyota leaders describe lean as an organizational culture, a managerial approach, and a philosophy. They also maintain that the last piece of lean is technical methods, which includes the math we need for properly sizing inventory levels, validating hypotheses, gauging improvement, and more. *Lean Math* is a useful book that compiles important mathematical and quantitative methods that complement the people side of lean. Hamel and O'Connor are extremely qualified to deftly explain these methods. Lest you think it's a dry math text, there are Gemba Tales and examples from multiple industries, including healthcare, which illustrate these approaches in very relatable ways."

—Mark Graban, Shingo-Award winning author, speaker, consultant, and blogger

"When you begin a lean journey, it's like starting an exercise regimen—the most important thing is to start. But as you mature, and as you achieve higher levels of excellence, rigor becomes increasingly important. Lean Math provides easy, elegant access to the necessary rigor required for effective measurement and analysis and does so in practical terms with excellent examples."

--Misael Cabrera, PE, Director, Arizona Department Environmental Quality

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Partner and COO at The Murli Group, Mark R. Hamel is an award-winning author, blogger, and speaker. He has played a transformative role in lean implementations across a broad range of industries including aerospace and defense, automotive, building products, business services, chemical, durable goods, electronics, insurance, healthcare, electric

power, and transportation services. Mark has successfully coached lean leaders and associates at both the strategic and tactical levels.

In his 19-year pre-consulting career, Mark held executive and senior positions within operations, strategic planning, business development, and finance. His lean education and experience began in the early 1990s when he conceptualized and helped launch what resulted in a Shingo-Prize-winning effort at the Ensign-Bickford Company.

Mark holds a B.S. in mathematics from Trinity College in Hartford, Conn., M.S. in professional accounting from the University of Hartford where he graduated with honors, and a M.A. in theology from Holy Apostles College and Seminary, summa cum laude. He is a CPA in the state of Connecticut and is dual APICS certified in production and inventory management (CPIM) and integrated resource management (CIRM). Mark was a national Shingo Prize examiner for eight years, has helped develop exam questions for the ASQ/AME/SME/Shingo Lean Certification, and is Juran certified as a Six Sigma Black Belt.

A gifted author, educator, and communicator, Mark wrote the SME published and 2010 Shingo Research and Professional Publication Award-winning book, *Kaizen Event Fieldbook: Foundation, Framework, and Standard Work for Effective Events.* He is the founder and primary contributor of the lean blog, Gemba Tales (www.gembatales.com), co-founder of the Lean Math blog (www.leanmath.com), and was a regular columnist for Quality Digest. Mark is also a faculty member of the Lean Enterprise Institute.

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MICHAEL O'CONNOR, PH.D.



Michael O'Connor, Ph.D. is a lean six sigma implementation consultant. He has led or co-led a number of lean six sigma launches that have produced hundreds of millions of hard dollar benefits. In recognition of this achievement and his transformative work, Dr. O'Connor was awarded the Master Black Belt

of the Year award by the International Quality and Productivity Center.

Michael is a passionate educator and communicator. His interests span a broad spectrum and he has given workshops on topics ranging from Dirac's Large Number Hypothesis to the integration of lean and six sigma at the National Health Service. Given this scope, it is not surprising that Dr. O'Connor has worked with leading organizations in check processing, healthcare, insurance, IT services, semiconductor manufacturing, server manufacturing, telecommunications, and the Federal Government.

Michael is a life-long learner and holds B.S. degrees in electrical engineering and physics, and a M.S. and a Ph.D. in physics. He is a certified Master Black Belt and a Shingo Prize Examiner.

Michael can be contacted at DrMike@LeanMath. com.

ACKNOWLEDGMENTS

The lean community is decidedly magnanimous when it comes to sharing lessons learned and teaching willing students. We believe that this spirit is rooted in the lean principles of humility, respect for the individual, and a rabid passion for improvement of self, organization, and community.

While every technical book requires an author(s), he or she cannot reasonably produce an effective work in a vacuum. It is prudent and edifying to access the wisdom of others. We certainly did that for Lean Math and we think it helped make it a better resource for the lean practitioner.

Accordingly, we would like to acknowledge a number of folks who helped us through our literary plando-check-act phases. They graciously read through (think of this as "check") at least one Lean Math draft, in part or in whole, and provided constructive criticism on which we often "acted." Some of these same people also contributed "Gemba Tales," or short, real-life, stories to help provide readers with further insight into particular math entries.

Who are these generous people to whom we are indebted?

- Richard Crowe,
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- · Jerry Foster,
- John Rizzo,
- · Brian Swayne, and
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Finally, we would also like to recognize Rosemary Csizmadia, SME Senior Production Editor, who exhibited the patience of Job and a singular dry wit, all while making prose, formulas, figures, and texts in *Lean Math* somehow work.

INTRODUCTION

"If people do not believe that mathematics is simple, it is only because they do not realize how complicated life is." —John von Neumann

WHY A LEAN MATH BOOK?

Most people do not purchase a "math book" unless compelled by some sort of onerous academic requirement. Even the definition of "mathematics" can be mind-numbing: "The science of numbers and their operations, interrelations, combinations, generalization, and abstractions, and of space configurations and their structure, measurement, transformations, and generalizations" (Merriam Webster OnLine 2015). What?!?

So, why on Earth would anyone actually need a lean math book?

At the risk of sounding like Dr. Seuss, my bookshelves are full of books, my desk is full of books, and I have books in the basement and books in boxes. My books are on business, business management theory, decision making, lean, six sigma, mathematics, physics, et al. What do all these books have in common? I purchased them with the intention of learning a better way-a better way to think about problems, a better way to solve problems, a better way to make value flow-in short, a better way to improve. However, among my many books, there is no unique and central reference for lean math. This condition creates a lot of waste, specifically the waste of motion as I search for some math insight secreted away within my personal library or files or online. And then there is the waste of defects (nothing like applying really bad kanban sizing!) or over-processing as I unnecessarily "re-invent" or overcomplicate some formula. I trust that readers may have also suffered through these same types of waste.

Frankly, lean transformations are challenging enough without math that is inconsistent with lean principles, misapplied, or just plain wrong. But while lean math is a tool and a construct for thinking, it is not a panacea. It must be subordinate to lean principles and common sense.

Virtually all of the math contained within this book has been subjected to rigorous plan-do-check-act (PDCA) cycles—the ultimate guide and teacher (see Figure 0-1). It has been "planned" on flip charts, white boards, and notepads at the gemba, on the occasional spreadsheet, or even in statistics software. Then it has been implemented and evaluated, often first within the safe confines of multiple simulation rounds.

Ultimately, the math must be adapted for the specific problem that the lean practitioner is trying to solve. To that end, this book should provide a sure foundation and starting point for thinking and experimentation. Math should help provide the lean thinker with:

- necessary understanding and insight into the reality of the current condition,
- the elemental and systems logic of a leaner target condition, and
- quantified and characterized gaps between the current and target condition and a measured perspective on how to close them.



Figure 0-1. Lean math in context.

Of course, the acknowledgement of the opportunity and the application of the appropriate action or countermeasure is up to the practitioner.

Clearly, *Lean Math* is not a book that the lean practitioner should read completely in one sitting (and definitely not before operating heavy machinery!). It is instead a reference from which the reader should pull what he or she wants and needs, when it is needed (think just-in-time). In return, the book will often prompt the reader to think more deeply... and more leanly.

The vision for *Lean Math* is that it will pragmatically teach, reinforce, and refresh mathematical tools and principles that can help practitioners more effectively implement lean within their organizations. The authors have stayed away (for the most part) from esoteric mathematical concepts, keeping the focus on what lean practitioners will need on their journeys.

The formulas reflected herein may not necessarily be the only or even always the best ones to achieve the lean mathematical purpose. We have tried to share what we understand to be "the" or at least, "a" generally accepted formula. On occasion, several formulas may be contained within an entry; however, this does not necessarily mean that all possible formulas have been covered.

Lean math is a vast and not too simple territory. Frankly, creating this reference has been arduous. With so many formulas, numbers, examples, figures, and tables, there is sure to be an occasional error, for which we beg the reader's forgiveness. If it seems that there is something lacking (a certainty, we eventually had to stop writing) or not quite right, feel free to contact the authors (Mark@leanmath. com or DrMike@leanmath.com). We are committed to continuous improvement and want to make *Lean Math* as good as it can be. Readers are invited to view fresh content and interact with the *Lean Math* community at www.leanmath.com.

CONTENT AND FORMAT

Lean Math contains over 160 unique entries, spanning 10 chapters. Some entries are brief and simple and others relatively involved. The intent is not to confer a doctorate in lean math, but to provide the lean thinker with a basic, if not firm, understanding of each concept, its lean relevancy (why should I care?), related formula(s), figures, tables, tips, caution areas, and realistic examples, as well as the occasional "gemba tale" to relate an illuminating real-world story.

Lean is a holistic business strategy. Without that understanding there is a danger of relegating lean math to a sterile bunch of entries or tools—essentially skipping the "know why" and jumping to the "know how."

Categorized within each chapter, the entries reflect a certain affinity to one another without getting too fancy or too splintered. Is it possible that some entries could be reasonably grouped into different or multiple categories? Absolutely! But we feel that they are captured in the one best category—reflecting solid lean reason.

Each of the chapters contains a brief introduction that frames the math category and provides context at two levels:

- How the "family" of entries relate to each other, and
- How and why the category should be meaningful to the lean practitioner.

Here is a brief summary of each chapter:

- 1. Systems-oriented Math. This chapter captures six entries that reflect systems thinking and a number of interdependencies. The entries include Value Stream Analysis Math Overview, Little's Law, and Process Mapping Math Overview.
- 2. *Time*. Try stringing together a few sentences about lean without using the word "time." Challenging isn't it? Time and space is where value is added or squandered. Numerous entries include Takt Time, Cycle Time, Processing Time, Queue Time, Lead Time, and everything in between.
- 3. *The "Ilities.*" This is certainly a goofy title, but this chapter delves into certain quantitative descriptors of a workstation, process, or value stream. The "ilities" extend to availability, reliability, stability, capability, and quality. Entries include Operational Availability, Mean Time Between Failure, Overall Equipment Effectiveness, Run Charts, and Process Capability.
- 4. Work. This chapter characterizes the work for, and within, a given system, and provides insight into how effectively resources process that work. This extends to the subjects of Capacity, Throughput, Utilization, Productivity, and Efficiency. In addition to entries that bear these very names, others include Optimal Staffing, Work Content Variation, Bottleneck Rate, and Process Cycle Efficiency.
- 5. *Inventory*. One measure of leanness is inventory, its velocity through the value stream, and the strategic use of it within pull systems. This meaty

chapter contains 19 pull-system math entries, as well as ones around intervals, inventory, and inventory management.

- 6. Performance Metrics. The basic True North metric categories are quality improvement, delivery/lead time/flow improvement, cost/productivity improvement, and human resource development. The chapter's introduction provides a pertinent discussion about lean performance metrics including their purpose, anatomy, context, and interpretation. A representative sample of lean operational and financial metrics is explored in this chapter.
- 7. Basic Math and Hypothesis Testing. This chapter covers the bread-and-butter techniques for describing and comparing data sets. Entries include simple concepts such as Average and Median, as well as the more advanced like Standard Deviation, Hypothesis Testing, T-tests, and Linear Regression. While Chapters 7, 8, and 9 endeavor to keep these traditional six-sigma-type entries at the "green-belt" level, some of them can get a bit involved. In any event, they should be more than sufficient for the serious lean practitioner.
- 8. *Measurement*. Lean can be summarized, perhaps over-simplistically, as measure-improve-measure. Clearly, it is critical to have data that faithfully reflects the current condition. The lean practitioner must ensure that he or she has selected suitable measures and that the measurement system is sufficient. Entries in this chapter are centered predominately around measurement system validation.
- 9. Experimentation. Once valid measurement systems are in place, the practitioner can begin experimentation. This chapter explores the math around identifying and quantifying the sources of variation, investigating how outputs respond to changes in inputs, or how they vary by group and, finally, how the output and its variation respond to changes in input variables.
- 10. Other Miscellaneous Stuff. This chapter, as the name implies, serves as a catchall for a handful of entries that did not readily fit in the other chapters. They include Multi-voting and PICK Chart Math.

While *Lean Math* is a rather large reference book. entries have not been proliferated by solving for each variable. Readers can pursue this as needed by following sound mathematics. See Figure O-2 for an example.



where:

WIP = average work-in-process inventory, in units

- T_{i} = average lead time, typically in seconds, minutes, hours, or days
- R_{\star} = average throughput rate, number of output units per the unit of time used in T_{μ}

Figure 0-2. Solving for variables.

GRAPHICAL ICONS

Lean Math uses three common icons throughout this book. They are as follows.

Tips. Brief insights are captured, which 1. may help the lean practitioner tailor or better leverage the math for a particular situation. For example, it may be useful when defining the productivity metric to include all direct and indirect hours (inputs), thereby providing more holistic insight into the productivity of a given team, value stream, etc.



Caution. This identifies possible traps in the calculation or application of the entry's math. For example, the concept of every part every interval (EPEI) can serve as an extremely powerful driver

of batch and related setup reduction to improve customer-satisfying flexibility and agility and reduce inventory investment. However, in a strict sense, it is specific to a fixed repeating schedule. In other words, not all parts are equal relative to demand, risk, etc. As such, changeover distribution (and there is an entry for that!) may not be reflective of EPEI.





Gemba Tales. Supplements to the math entries, Gemba Tales relate real-life stories to share insights and

sometimes humor. An example Gemba Tale appears next.



Guts and intuition will only get you so far. A West Coast check processing operation routinely experienced significant demand

variation night to night and hour to hour. Due to the nature of the business, level loading was not an option. Instead, staffing needed to be somewhat dynamic, but the requirements had to be based upon something beyond rough guesses. And, it needed to happen within the context of standard work.

Leaders, many with over a decade of experience, had a grasp of the factors that drove demand variation. However, as we began to develop a much needed staffing model, it became evident that the understanding was incomplete at best. That, and standard work was a new concept to the folks.

The number of staff required to perform the operation(s) depended on the work content, operator balance, and the available time. Using direct observation, the team measured the check processing work content for each item. While the available time was known, we also needed to know the quantity and timing of the nightly check arrivals. Using this information, we could calculate the total work content (cycle time × quantity) and divide by the available time, thereby identifying the staffing needs throughout the shift.

We took leaderships' brainstormed list of factors that drove demand, built a multi-variate regression model (don't worry if you don't know what this is now, it's in the book), and were able to only explain about 50% of the variation. Clearly, this wasn't going to be good enough. So, together we went back to our laptops. We tested over a 100 other input factors and ended up with a model that explained over 90% of the observed variation. This relatively accurate model was a big step forward. It helped drive big results in the areas of productivity and stability.

The check processing leader never modeled her demand, never calculated takt time, and never created an operator balance chart. She had an undeveloped sense of what needed to be done. She knew demand varied quite a bit, and knew the average number of items that would be processed, and that her managers kept telling her that her team was understaffed. By applying lean math within the broader context of lean, we were able to accurately predict the demand, hour by hour on any given night...and we were able to show that she was overstaffed by 60 people (out of 240)! This was an organization that had become bloated because they were using guess work instead of letting data and analysis help inform their decisions.

Sometimes, math is cool!

EXAMPLES/CASE STUDIES

Lean Math makes use of examples within virtually all entries, attempting to maintain a balance across industries through the use of three mostly non-threaded case-study subjects. Here, the term "non-threaded" means that the examples do not necessarily build upon (thread) themselves throughout the book, although they occasionally do. In any event, it is hoped that a certain "familiarity" with the case study subjects will help the reader from a contextual standpoint.

Please note that the examples are purely fictional and for the purpose of illustration. In other words, we made that stuff up. So, don't get too excited if, for example, the cycle time for a process in an example seems too long or short. Also of note, the examples rarely mimic those within other lean books where the values and answers always tend to be neat and round and perhaps unrealistic—60-second takt time, 20-minute pitch, etc.

Occasionally, some vocabulary may appear more industrial in nature. For example, the term "product" is typically associated with a manufacturing value stream. However, "product" can also refer to a service offering. The point here is that lean principles should trump all. In some ways, it would be best to have totally industry-neutral entries and examples. Unfortunately, that is not practical.

Following is a brief characterization of the fictional (usually) non-threaded case study subjects. They are experiencing many of the same victories and struggles that so many other real-life organizations experience within their lean journeys.

1. *Mathtronix Industries* is multi-national electronics manufacturer that produces a broad range of devices and systems for both industrial and residential use. Its numerous product families span both high-volume/low-mix and low-volume/high-mix offerings. The processes within the various value streams typically include the population of printed circuit boards manually and/or in an automated manner through the use of surface mount technology machines. Other processes include soldering, testing, assembly, and pack-out. Due to the company's vast size, geographic dispersion, product mix, and technologies, the lean transformation at Mathtronix has its challenges. Some areas have excellent footholds and others still live within the batch-and-queue world. The rest are in between. Overall, Mathtronix is getting better each day.

- 2. *Mathema Insurance Company* is a North American property and casualty insurer serving personal, agency, and commercial markets. Mathema's major value streams include sales, underwriting, and claims. There are deep functional and business-line silos within Mathema. However, several pioneering leaders have taken their parts of the organization to unprecedented performance levels through comprehensive lean implementation. Others have felt little impetus to change. Eventually, the hope is that senior executive leadership will learn, see, do, and lead.
- 3. Sigma Health Systems (SHS) is a regional network of clinics, hospitals and other healthcare facilities. SHS serves 32 communities across three northeastern states. SHS launched its lean transformation 24 months ago with a pilot in one of its primary care practices. It later expanded through a successful initial deployment phase to a number of other practices. Currently, SHS is in full-scale deployment throughout all of its clinics and is now piloting lean in its flagship hospital within the emergency department. The organization is "feeling" the change and there are other pockets of meaningful lean activity. The biggest challenge for SHS may be to not go too fast.

"READING MATH"

The "math" contained within this book ranges from the purely mathematical formula (e.g., average, takt time) to metrics (e.g., inventory turns, on-time delivery), to pseudo-mathematical (e.g., change management, waste elimination effectiveness), to concept introduction (e.g., hypothesis tests), to data and math integrity considerations (e.g., gage repeatability and reproducibility, measurement system validation). No matter the entry, the reader is bound to run into formulas, symbols, and mathematical definitions. It is worthwhile to briefly review the relevant symbols outlined in Table 0-1.

But, before you panic, know that the vast majority of the math within this book is limited to addition, subtraction, multiplication, division, and some common sense rounding. In fact, if you can regularly figure out how much to tip the wait staff at the conclusion of dinner, then 85% (consider that a scientific guess) of the *Lean Math* content will be a breeze. The rest of the math may require a spreadsheet (for example, who really wants or needs to calculate standard deviation by hand without the assistance of a scientific calculator?!) or some statistical software. This is when you may want to find a buddy who has Minitab[®] on his laptop...and knows how to use it.

The entries herein take a humane and common sense approach to notation. Mathematicians have developed wonderfully efficient notation and conventions. Unfortunately, the notation can be hard to understand because a fair bit of it is in Roman, Greek, or Extra Terrestrial (we are guessing here, but how else is the use of \forall , \exists , and \therefore to be explained?). And to further complicate matters, mathematical conventions are not always strictly followed. For example, in statistics, the convention is to use Greek letters when referring to a population and Roman letters when referring to a sample. So the average of a population is written as μ , whereas the average of a sample is written as \overline{x} . But unfortunately this convention breaks down when discussing standard deviations, where it is common to use the symbol σ even when referring to the standard deviation of a sample. All of this just adds to the richness and complexity of the language of mathematics. Like with thinking in and interpreting other languages, the best approach is to keep an open mind.

LEAN MATH NOTATION

Math formulas instill a certain expectation of precision. Often that is appropriate. But, at the same time, as lean practitioners we need to live in a gemba-based world that requires experimentation, reflection, and adjustment. So, we should not get too wrapped up in precision...but rather accuracy. Nevertheless, there is some basic *Lean Math* notation that needs explanation.

In Table 0-1 certain variables are referenced, for example, x, a, b, A, and B. Most Lean Math entries have at least one formula with multiple variables. These variables, virtually always independent in that they are inputs into a system, represent a value that may change within the scope of the problem or operation. For example, work content (W_c) and takt time (T_i) within the optimal staffing model (see Chapter 4) are independent variables.

Typically variables have single-symbol names, with constants from the beginning of the alphabet (e.g., a, b, and c) and variables from the end (e.g., t, x, y, and z). You can thank the 17th French philosopher and mathematician, Rene Descartes, for that. The single-symbol names are usually italicized and often lower case. Upper-case variables are traditionally used for random variables within probability and statistics. All that we can say is that we tried our best

Math Field	Symbol	Description	Definition	Example		
	e	Euler's number	Base of natural logarithms	$e \simeq 2.7182818$		
Constants	π	pi	$\pi = \frac{C}{d}$ where: C = circumference of a circle d = diameter of a circle	$\pi \simeq 3.14159265$		
	=	Equals sign	Equality	7 = 4 + 3		
-	~	Approximately equals	Near equality	1.9999999999999999 ~ 2		
-	>	Strict inequality	Greater than	7 > 6		
-	<	Strict inequality	Less than	7 < 8		
	\geq	Inequality	Greater than or equal to	7 ≥ 6		
-	≤	Inequality	Less than or equal to	7 ≤ 8		
Basic math	()	Parentheses	Calculate expression inside first	$3 \times (4 + 1) = 15$		
busic mum	[]	Brackets	Calculate expression inside first	$[(3+2) \times (2+5)] + 2 = 37$		
	+	Plus sign	Addition	3 + 2 = 5		
	_	Minus sign	Subtraction	5 – 2 = 3		
-	×	Times sign	Multiplication	3 × 5 = 15		
	/	Division slash	Division	8/2 = 4		
	—	Horizontal line	Division/fraction	$\frac{8}{2} = 4$		
Power	a ^b also a ** b	Power	$a^b = \overbrace{\alpha \times \ldots \times \alpha}^{b \text{ times}}$	3 ² = 9		
	\sqrt{a}	Square root	$\sqrt{a} \times \sqrt{a} = a$	$\sqrt{9} = \pm 3$		
Factorial	n!	Factorial	$n! = n \times (n-1) \times (n-2) \times \times 1$	$4! = 4 \times 3 \times 2 \times 1 = 24$		
	x	Overbar or bar	Sample average	$\overline{x} = (3+2+5+4)/4 = 3.5$		
	x	Single vertical bar	Absolute value	-3 = 3		
-		Floor brackets	Rounds number to lower integer	[2.7] = 2		
	$\begin{bmatrix} x \end{bmatrix}$	Ceiling brackets	Rounds number to upper integer	[2.7] = 3		
Algebra	[x+0.5]	Nearest integer	Rounds positive number to nearest integer	[2.7 + 0.5] = 3 [2.2 + 0.5] = 2		
	\sum	Sigma	Summation—sum of all values in a range or series	$\sum_{i=1}^{3} 2^{i} = 2^{1} + 2^{2} + 2^{3} = 14$		
	П	Pi	Product of all values in a series	$\prod_{i=1}^{3} 2^{i} = 2^{1} \times 2^{2} \times 2^{3} = 64$		
	e ^x	Exponentiation	Exponentiation of the number x	$e^0 = 1$		
Common functions	ln (x)	Natural logarithm	Natural logarithm of the number x (where $x > 0$)	In (1) = 0		
	erf (x)	Error function	Error function evaluated at x (the error function is the integral of the normal distribution)	erf(0) = 0		

Table 0-1. Mathematical symbols.

Math Field	Symbol	Description	Definition	Example		
	P (A)	Probability function	Probability of A occurring	P(A) = 0.7		
	$P(\overline{A})$	Probability	Probability of not A occurring	$P(\overline{A}) = 0.3$		
Probability and statistics	P(A ∩ B) and P (AB)	Probability of events intersection	Probability of events A and B	$P(A \cap B) = 0.7$		
	P(A∪B) and P (A or B)	Probability of events union	Probability of events A or B	$P(A \cup B) = 0.7$		
	P(A B)	Conditional probability	Probability of event A given event B occurred	P(A B) = 0.5		
Calculus	$\int_{a}^{b} f(x) dx$	Definite integral	One of several things you thought you would never use again after calculus class	$\overline{y} = \frac{1}{b-\alpha} \int_{a}^{b} f(x) dx$ where: y = f(x)		
	$\frac{\partial}{\partial x_1} f(x_1, x_2, \ldots)$	Partial derivative	Rate of change of function $f(x_1, x_2,)$ in the x_1 direction while keeping all the other x_n variables constant	$\frac{\partial}{\partial x_1} \left(x_1^2 + x_2^2 \right) = 2x_1$		
Linear algebra	$ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \times \begin{pmatrix} e & f \\ g & h \end{pmatrix} $	Matrix multiplication	Note: if the two matrices are identical, then this is equivalent to squaring a matrix	$ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \times \begin{pmatrix} e & f \\ g & h \end{pmatrix} = \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix} $		

Table 0-1. Mathematic	ıl symbols (continued).
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to follow these conventions, but we are pretty sure that we broke more than a few rules. The easiest notation many times is no notation. For example:

Productivity = good output for period in units or dollars inputs for period in units or dollars

Who can't understand that?! The problem is that more complicated formulas end up being way too long for the printed page.

Most variables have been kept to one letter with a subscript to further identify it—like the "T" for time and "t" for takt. Of course, this convention is not always possible and not always prudent. For example, everyone knows "WIP" as work-in-process inventory. We have no desire to needlessly invent brand new variables. Another, occasional departure from convention is the double subscript, for example, I_{cc} , inventory carrying cost. (Our apologies if we have offended any math purists.) There is absolutely no need to memorize variables. Each entry defines the relevant variable(s) immediately after the formula is introduced.

BEFORE YOU BEGIN

Readers may be thinking, "Enough already! This is a reference book. Let me pick and choose what I need (and really ignore what I do not need)." But first, there are several suggestions that should help make *Lean Math* more value-added.

Test math that is new. No doubt some of these mathematical tools will be unfamiliar. When approaching a new mathematical tool, it is helpful to start by putting in a simple set of data (ideally one where the answer is already known) to see if the tool does what is expected (for example, it is known that the average of 4, 5, and 6 is 5, so this could be useful for proving the formula to calculate an average). After testing, explore how the tool responds to special cases. Then use the tool on the actual data.

Get your hands dirty. Some of the Lean Math entries can be intimidating. It would be easy to just do nothing—the old analysis paralysis. But lean is largely about learning by doing. This is where, depending upon the implementation risk, trystorming and simulation are critical strategies for moving forward. So, for example, if a mixed-model production kanban is to

be implemented, it probably makes sense to do some tabletop simulations. Proxy kanban cards can be run through several weeks of actual historical demand... in detail, as the supermarket levels, stock-outs, emergency kanbans, impacts of changeovers, unplanned downtime, etc., are tested. This will reveal when and where the system breaks down. Then adjustments are made and the simulation is run again and again.

When the implementation risk is less significant, like developing a new performance metric, the trystorming or simulation may be close to zero. Simply put it out there and apply PDCA in real time.

"Use" the math. As fellow lean practitioners, we are all looking to effect continuous improvement. A 5% or 10% improvement today is better than an 80% improvement at some unspecified time in the future.

Make use of the Appendices. The subject matter therein is important and relevant to the understanding and application of lean math. Here is a brief overview of each one:

- A. "Standard Work for Analyzing Data." Math uses data as inputs and generates data as outputs. But data has no real utility if the user can not make sense of the numbers and derive the insight necessary for effective decision making and problem solving. A four-step process to help better analyze the data is explained. The standard work is called PGA-T—Practical analysis, Graphical analysis, Analytic analysis, and...it must all Tell a story. An overview of PGA-T is given with the help of an example.
- B. "Understanding and Dealing with Variation." In the real world, variation happens. Organizations routinely experience demand variation, process stability issues, supplier performance challenges, and the like. The sources of variation are endless. And, variation may be normal or abnormal. There is a need to understand the variation and its implications to the flow of value. In trying to reduce variation, the systems and, therefore, the lean math, must rationally anticipate it. This is where concepts, such as the coefficients of variation and factors of safety, are applied.

We hope that you find *Lean Math* value added. Consider this reference a tool to help facilitate the effective deployment of lean. Unlike school, there are no final exams, just the perpetual application of PDCA.

Keep learning! Keep improving!

Lean math phobias and other related disorders. Sometimes lean math prompts less than optimal responses from folks. Four of the more non-value-adding reactions are characterized as follows.

- Apoplectic. This is essentially a math anxiety induced stroke. Some people would be more than happy living in a math-free world. The mere mention of numbers and formulas can lead to hyper-ventilation, lack of focus, and non-productive hand-wringing.
- Catatonic. As in eyes-glazed-over stupor. This stupor can be induced by either boredom (math is not that exciting) or as a coping mechanism that convincingly signals to co-workers that they better take over because the afflicted one's brain has seized up. Often the catatonic state is preceded or followed by apoplexy.
- Obsessive. Some people get into the math so much that they lose any notion of balance between theory and reality. Lean-oriented math is a vehicle for improvement. It is not the end game...and the best application of "belts" is to hold up one's pants.
- Contentious. And then there are those who would like to argue over every aspect of math, often not because it matters, but because it is a venue to establish and showcase intellectual superiority. During these arguments (often really during the contentious one's monologue) the other people tend to look around for possible escape routes.

REFERENCE

Merriam Webster OnLine. http://www.merriam-webster. com/dictionary/mathematics. (Retrieved March 19, 2015)

SAMPLE ENTRIES

CYCLE TIME

Cycle time (T_c) , also known as drop-off rate and average cycle time, represents the average time, or average interval of time, it takes for a specific process to produce a part or product, complete an operation, or provide a service. It is therefore a time-based measure of process output. Cycle time is the time per unit, in contrast to the rate, which is the number of units per measure of time.

 T_c encompasses the start of the process and the operator's and/or machine's return to the ready position for the next cycle. It is applicable for both flow and batch processing. T_c should be confirmed through direct observation of multiple cycles. Lean practitioners need to identify and understand significant T_c variation and address it appropriately.

Cycle time must be considered in the context of takt time. At the risk of oversimplifying, T_c must be consistently less than or equal to the takt time to satisfy customer demand. This synchronization is the nucleus for balancing work content among operators, designing work areas and material and information flow, specifying machines, sizing first-in-first-out (FIFO) inventory lanes, etc. Most importantly, the T_c versus takt time "tension" drives continuous improvement.

In the event that T_c is substantially faster than takt time, there is a risk of overproduction and the use of extra operators and/or machines. In such situations, the lean practitioner should consider strategies to manage that risk: reduce staffing and/or machine speeds, employ continuous flow, institute supermarket pull and/or sequential pull, etc.

The generic use of cycle time is mathematically presented as:

$$(F2-6)$$

$$T_c = \frac{T_o}{O}$$

where:

 T_c = cycle time, in seconds or minutes per unit

 T_o = time duration of observation, in the same unit of measure as T_c

O = output, in units completed during T_{o}

See Figure 2-6 for examples of T_c calculations for continuous series production, batch production, and parallel processing.

If cycle time is dictated by the operator(s), meaning the machine time is internal to the operator's time (the operator is actively managing, monitoring, or waiting for the cycle to complete), then:

- For one operator, T_c equals the processing time of that operator.
- For multiple operators, T_c equals the processing time of the operator with the longest processing time.
- For a machine-intensive process that requires little or no human intervention, T_c may equal machine cycle time or, as appropriate, effective machine cycle time.

Out-of-cycle or non-cyclical work represents operations that are not performed during each cycle. Examples include changeovers, periodic quality checks, pallet moves, reporting, etc. Depending upon the frequency of this work and the time to complete it, out-of-cycle work may be amortized and included within the cycle or netted against the available time.



Figure 2-2. Cycle time overview.

Of note, there are a number of important T_c variants (see Figure 2-2), which are presented in the following entries in this chapter:

- Effective Machine Cycle Time,
- Machine Cycle Time,
- Operator Cycle Time,
- · Planned Cycle Time, and
- Weighted Average Cycle Time.



First thing first. The relatively new lean practitioner proudly explained to his sensei how he and his team

were going to implement a kanban system for a family of manufactured parts. This ostensibly was a very lean way to improve the value stream. Yet the sensei did not seem quite as enamored with the plan. Rather, in his Japanese accent, he softly said one word, "Setup," which sounded unnervingly like, "Shut-up."

The student did not immediately recognize what the sensei was inferring, until he repeated the word to himself. The kanban sizes would be too large and unwieldy until setup could be sufficiently reduced. (Also see Available Time and Rationalized Available Time, Processing Time, Takt Time, and Time Observation Form Math in this chapter; and Service Rate and Service Time in Chapter 4.)

MEAN TIME TO REPAIR

Mean time to repair (MTTR) is the expected time between failures for a repairable system (see Figure 3-11). Having a low and consistent MTTR is often critical for achieving predictable flow through a value stream.

Maintenance is commonly classified as either being predictive, preventive, or corrective. *MTTR* quantifies the average time to repair corrective issues. The repair time clock starts when the machine goes down and stops when the machine is put back in, or is at least completely available for, service. Thus the repair time includes not only the time required to actively repair the system but also the time waiting for resources, parts, and management decisions (should they be needed).

(F3-7)

$$MTTR = \frac{\sum_{i=1}^{n} TTR_i}{n}$$



Figure 2-6. Example T_c calculations.



Figure 3-11. Illustration of the term used in the formula to calculate MTTR.

where:

MTTR = mean time to repair

TTR = time to repair

n = number of failure events

Example. Mathema Insurance Company has been tracking the time to repair its legacy claim processing software. The data and the resulting *MTTR* are shown in Table 3-4.

Some lean practitioners use MTBF as a proxy for uptime, and combine it with MTTR as a proxy for downtime to measure availability (see Figure 3-12). That is,

(F3-8)

$$A = \frac{\text{Uptime}}{\text{Total Time}} \times 100\%$$
$$= \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} \times 100\%$$
$$= \frac{MTBF}{MTBF + MTTR} \times 100\%$$

Table	3-4. Time to repair data for the le	gacy
	claims processing software	
	at Mathema Insurance Company.	

	1 /
No.	TTR, Minutes
1	35.7
2	49.2
3	34.2
4	48.4
5	44.5
6	35.6
7	47.7
8	45.5
9	35.1
10	43.4
11	41.4
12	34.4
13	47.4
14	42.7
15	38.0
Average	41.5



Figure 3-12. Illustration of Formula 3-8. The average time between failures (*MTBF*) is used to estimate uptime and the average time to repair (*MTTR*) is used to estimate downtime.

When reporting availability, the impact of planned downtime should be considered. Some organizations exclude planned downtime. For systems that frequently undergo maintenance, this can have the unfortunate effect of reporting high availability numbers when in fact the system is almost never available. Clearly, reporting misleading information is not consistent with lean principles. To avoid this confusion, it is recommended to consider using an availability measure that includes planned downtime as part of downtime. For example, achieved availability uses the mean time between maintenance events (not just failures).

(F3-9)

$$A_a = rac{MTBME}{MTBME + MMT} imes 100\%$$

where:

 A_a = achieved availability

MTBME = mean time between maintenance eventsMMT = mean maintenance time (does not include logistic delays or delays waiting
for approvals or paperwork) in the same
unit of measure as MTBME

If repairs are relatively routine, such as the changeover of worn dies or the replacement of modular units, single-minute exchange of die (SMED) techniques can be highly effective as a means of reducing repair time.

Operational availability (see later entry in this chapter) is also an excellent alternative measure. Like achieved availability, it uses mean time between maintenance events. But instead of using mean maintenance time, it uses mean down time. So this metric reflects the customer experience. That is, it gives the percent of time that the equipment is available to the user/operator. (F3-10)

$$A_o = rac{MTBME}{MTBME + MDT} imes 100\%$$

where:

 A_{o} = operational availability

MTBME = mean time between maintenance events MDT = mean downtime in the same unit of measure as MTBME

Obviously, the simplest way to reduce the MTTR for a system is for the system to never break, in which case the MTTR is 0. Achieving this goal often requires a careful analysis in the design phase of the system's potential failure modes (commonly using tools like fault tree analysis and design failure modes and effects analysis). If repairs are not completely eliminated by the original design, then the system can be later redesigned based on the observed failure modes. Additionally, the total repair times for a system often can be reduced through initiatives such as total productive maintenance.

(Also see Changeover Time in Chapter 2; and **Mean Time Between Failure**, **Overall Equipment Effectiveness**, and **Operational Availability** in this chapter.)

DEMAND SEGMENTATION

Demand segmentation is a technique for categorizing different demand types into groups that share similar characteristics. Demand is differentiated largely by sales or consumption volume and demand variation. Strategies for planning, scheduling, purchasing, selecting the best replenishment system, and (kanban) sizing should follow suit.

A common technique for analyzing demand is an ABC production or sales analysis. This approach stratifies the stock-keeping units (SKUs) or part numbers based upon demand volume into three categories: A items (high runners), B items (medium runners), and C items (low runners). However, while this analysis provides valuable insight, it fails to incorporate the important element of demand variation.

In general, pull system design applies a factor of safety to cover both normal demand variation (buffer stock) as well as internal and/or external process stability issues (safety stock). More importantly, demand

variation should be a key determinant of the flow versus pull and related resource management strategy.

A coefficient of variation (C_v) is a straightforward means of measuring demand variation. It describes the variation within a particular data set. (See Chapter 7, Basic Math and Hypothesis Testing.) A lean practitioner can graph both volume and C_v (as *Y* and *X* axis, respectively) within a scatter plot to visually help in the segmentation exercise. Sometimes it is helpful to graph volume not only in terms of units, but dollars as well.

The demand segmentation examples in Figure 5-12 and Figure 5-13 reflect possible treatments for production items (finished goods, subassemblies, etc.) and purchased items, respectively. Segmentation categories are not based upon an exact science. And, category assignment is *not* merely a digital exercise. In other words, a high volume and low C_v is not the final arbiter.

The lean practitioner must take into account things like strategic market imperatives, targeted service levels, projected future demand (often historical demand data is used to determine demand variation, but it is prudent to look at both historical and projected demand to understand volume), inventory "investment," etc. See Figure 5-14 and Figure 5-15 for insight into production and purchased material segmentation options, respectively.

As mentioned previously, the lean practitioner should be mindful of inventory investment levels. Segmentation and decisions around fulfillment/ replenishment strategy(ies) should consider current state and desired future state inventory levels. It is useful to consider the days of inventory on hand (I_d) as well as inventory dollars (see Figure 5-16).

(Also see **Average Period Demand** in this chapter and Coefficient of Variation in Chapter 7.)

													[A]	[B]	[B]/[A]
	Mathtr	onix (fi	nished	goods)							Annual	Average Weekly	Standard Deviation	Coefficient
				Н	istorical v	veekly	demand	, units				Historical	Demand	Weekly	of Variation
SKU	1	2	3	4	5		48	49	50	51	52	Demana	Domana	Demand	(~,)
UL490	10,012	13,747	13,389	15,431	13,948		14,741	10,125	11,041	12,146	15,499	676,411	13,008	2,070	0.2
XP100	3,967	5,032	10,756	12,721	9,967		16,112	4,259	4,314	2,115	5,076	386,459	7,432	4,621	0.6
ZT250	386	168	1,003	417	12		12,370	294	56	27	386	78,619	1,512	3,826	2.5





													[A]	[B]	[B]/[A]
Mathtronix (purchased materials)									Annual Historical	Annual Average Historical Weekly	Standard Deviation Weekly	Coefficient of Variation			
SKU	1	2	3	4	5		48	49	50	51	52	Demand	Demand	Demand	(C _v)
81-412M	19,427	18,203	19,261	20,134	18,311		15,732	17,980	17,217	15,648	12,519	907,046	17,443	2,274	0.1
33-003M	4,119	5,278	9,856	12,071	10,769		15,030	5,101	3,314	6,744	3,212	392,569	7,549	4,115	0.5
64-159C	42	851	5,079	175	4		1,960	0	3,773	0	12	61,859	1,190	1,840	1.5
59-213K	0	0	0	160	0		0	0	2,295	0	0	12,766	246	722	2.9
Demand Seamentation															



Figure 5-13. Segmentation example for purchased items.

Demand segmentation can provide valuable insight for production work area design strategy. For example, high-volume/low C_v products, sometimes called "runners," are often best produced on dedicated lines. Moderate demand/moderate C_v products, sometimes referred to as "repeaters," may be grouped together to gain consolidated volume and run on one or more shared work cells. Similarly, the low-volume/high C_v products, also known as "strangers," can be run to order on one or more flexible work cells. Lean practitioners will also keep in mind the design implications of product families and work content variation.

Introduction



*Defer to next level down as attributes dictate





*Defer to next level down as attributes dictate



Figure 5-16. Segmentation, fulfillment/replenishment strategy, and inventory.

KANBAN SIZING: TRIANGLE KANBAN

Triangle kanbans (Figure 1-23) are one of three types of signal kanbans. They are unique from a sizing perspective in that there is only a single kanban per part number or stock-keeping unit (see Figure 5-29). Accordingly, kanban sizing math has nothing to do with determining the number of kanbans—it is obviously fixed at one. Instead, the math for this variable interval, fixed quantity kanban is around determining the total manufacturing lot size, which is the total kanban size, and the appropriate reorder point.

There are two basic methods of sizing triangle kanbans.

- 1. A product-specific lot size applies a universal every part every interval (EPEI) for all parts made by the supplying operation. This yields lot sizes that are unique to each part because they are based upon their own unique demand. This method better matches production with demand and thus minimizes inventory levels, although it is a bit harder to manage.
- 2. A universal lot size applies EOQ-type thinking and/or a more simplistic one-size-fits-all approach to determine a universal lot size for all parts. For example, management may determine that the supplying operation will produce every part number



Figure 5-29. Triangle kanban.

in 500-piece lots, no matter what each part number's specific average demand level may be. This method, while easier to manage (same lot size for every part), will generally require more inventory.

Method 1 uses the following formula to determine product-specific lot size. The result is rounded to the nearest practical container quantity.

(F5-38)

$$S_{k}=rac{ar{D}_{p} imes T_{r} imes F_{s}}{C_{c}}$$

where:

- S_k = size of the triangle kanban (a.k.a. manufacturing lot size) in containers
- D_p = average period demand, typically in units per day, week, or month
- T_r = replenishment lead time, essentially the production interval, for the same period that \overline{D}_p is calculated
- F_s = factor of safety
- C_c = container capacity, in the same unit of measure as \bar{D}_p

Example. Mathtronix is establishing a triangle kanban system for an array of stamped parts produced by a 120-ton press. T_r , based upon the EPEI for the press, is 2.2 days. The demand period used to calculate \overline{D}_p and F_s is weekly, so T_r , for the purposes of this calculation, is 0.44 (the 2.2 day interval divided by a 5-day week). Calculating S_k for part A, which has a weekly \overline{D}_p of 2,730, F_s of 1.15, and a C_c of 300 parts, yields the following:

$$\begin{split} S_k = & \frac{2,730 \text{ units/week} \times 0.44 \text{ weeks} \times 1.15}{300 \text{ units/container}} \\ = & 4.6 \text{ containers, rounded to 5 containers} \end{split}$$

Method 2 applies a universal lot size, which really yields more of a "floor." The minimum universal lot size to be applied to all parts manufactured by a given work center can be determined as follows. Because C_c can be different per part, it may be prudent to calculate the universal S_k solely at the unit level and then convert to the container count specific to each different part.

(F5-39)

$$S_k \geq rac{{{ar D}_p} imes F_s}{O_\Delta}$$

where:

- D_p = average period demand, typically in units per day, week, or month for the total of all products produced by the supplying resource
- F_s = factor of safety, as best determined for all parts considered
- $O_{\rm A} = {\rm the \ supplying \ resource's \ changeover \ opportunities for the same period used within \ \bar{D}_{\rm p}$

Example. Mathtronix is establishing a triangle kanban system for an array of stamped parts produced by a 120-ton press. Management has decided that, at least for now, a universal lot size should be used. \bar{D}_p for all 5 part numbers is 19,105 per week. The approximate F_s for all five products using weekly demand data as well as unplanned press downtime

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data is 1.25. O_{Δ} is 11.5 per week (2.3 per day, as reflected in the O_{Δ} entry example × 5 days). Therefore, the minimum universal lot size is as follows:

$$\begin{split} S_k \geq & \frac{19,105 \text{ units/week} \times 1.25}{11.5 \text{ changeovers/week}} \\ &= 2,076 \text{ units/changeover} \end{split}$$

If there is a standard C_c of 300 parts/container across the entire family of parts, a reasonable universal lot size, S_k , is 2,100 (7 containers of 300 parts).

(Also see Pull System Math Overview in Chapter 1; and Average Period Demand, Changeover Opportunities per Period, Every Part Every Interval, Factor of Safety, Replenishment Lead Time, and Reorder Point in this chapter.)

- "...If math is the language of science, then *Lean Math* is indeed the language of lean science."
- Bruce Hamilton, President, Greater Boston Manufacturing Partnership, Director Emeritus for the Shingo Institute
- "...Lean Math is a must have book for Lean Support Office people!" — Dave Pienta, Director, Lean Support Office, Moog, Inc., Aircraft Group
- "...There are so many ways to quantify value, display improvement, and define complex problems that choosing the right methods and measures becomes an obstacle to progress. *Lean Math* helps remove that obstacle..."
- Zane Ferry, Executive Director, National Operations, QMS Continuous Improvement, Quest Diagnostics

About the book

Lean transformations are decidedly more challenging when the math is inconsistent with lean principles, misapplied, or just plain wrong. Math should never get in the way of a lean transformation, but instead should facilitate it. *Lean Math* is the indispensable reference for this very purpose. A single, comprehensive source, the book presents standard and specialized approaches to tackling the math required of lean and six sigma practitioners across all industries—seasoned and newly minted practitioners alike. *Lean Math* features more than 160 thoughtfully organized entries. Ten chapters cover system-oriented math, time, the "-ilities" (availability, repeatability, stability, etc.), work, inventory, performance metrics, basic math and hypothesis testing, measurement, experimentation, and more. Two appendices cover standard work for analyzing data and understanding and dealing with variation.

Practitioners will quickly locate the precise entry(ies) that is relevant to the problem or continuous improvement opportunity at hand. Each entry not only provides background on the related lean principles, formulas, examples, figures, and tables, but also tips, cautions, cross-references to other associated entries, and the occasional "Gemba Tale" that shares real-world experiences. The book consistently encourages the practitioner to engage in math-assisted plan-do-check-act (PDCA) cycles. *Lean Math* truly transcends the "numbers" by reinforcing and refreshing lean thinking for the very purpose of Figuring to Improve.

"...This reference comes at a critical time for the healthcare industry as we struggle to improve quality, while controlling costs. Though we don't make widgets, our people, processes, and patients will benefit from the tools provided in this reference..."

—Tim Pettry, Senior Process Improvement Specialist, Cleveland Clinic

"When you begin a lean journey, it's like starting an exercise regimen...as you achieve higher levels of excellence, rigor becomes increasingly important. *Lean Math* provides easy, elegant access to the necessary rigor...and does so in practical terms with excellent examples."

— Misael Cabrera, PE, Director, Arizona Department of Environmental Quality



