Complexity VS. Continuous Process Improvement

Gad (Gadi) Dvir
Strategy Implementation LLC Managing Member

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Abstract: This paper describes complexity growth in different aspects of our lives. It demonstrates the speed of complexity growth in the electronics and semiconductor business and argues that traditional CPI is far too slow to address/fight the complexity growth. We describe an additional approach called High Velocity CPI (HVCPI) and why it is a better tool to fight the complexity growth.

INTRODUCTION

Complexity is growing in many products and services:

- Medicine: Explosion of disciplines, technologies, and medications
  - Depth and complexity of knowledge are driving an exploding number of disciplines and complex integration of diagnostics and treatments.
  - More disciplines drive more institutions and departments within the same hospital.
  - New tests and diagnosis capabilities including more types of test equipment e.g. imaging.
  - Medication and treatments become more specific and therefore complex with some types being personalized
- Cosmetics products and beauty services follow similar trends like the medicine and to a certain extent there is now overlap in such fields as plastic surgery.
- Airline industry: Planes and plane sizes fit to markets, airline industry deregulation and diversification increasing the number and size of airports, increasing the number of domestic and international routes driving heavier and more complicated air traffic.
- Photography: Media changes, Resolution + Ease of use + Cost reduction
  - Black and white on glass; black & white celluloid; movies; colored celluloid, digital, photo-shop editing.
- Banking and financial services:
  - From traditional savings and loans large portfolio of investments, financing and credit tools
  - From limited hours in one branch to online 24x7, as well as international banking.
  - From single currency deals to highly sophisticated multi-currency, 24X7 markets spread all over the globe.
  - More complicated tools to fund large investments.
- Content creation: Diversity grows fast – more creators can access delivery systems and generate content on a very low budget. On the other end - ever growing production efforts and costs generate a large concentration of movies or shows and large book publications get more expensive.
- Content delivery is distributed: Individual writers or creators can publish their creations on the World Wide Web, gain access to huge audiences and collect some return for their work. Conversely, large productions are being distributed by new and traditional concentrated content delivery channels.

There are many product segments and services that go through growing complexity in different aspects of their businesses.

What are the drivers of Complexity?

- Added value and meeting the market/customers' needs, desires and preferences. These are realized and measured by the willingness of the customers to pay. The markets force pushes complexity upstream to make products and services simpler to the consumer/end user.
- Scaling: The optimization of costs of systems by efforts to maximize utilization of the most expensive/rare subsystems or components.
- Globalization: Many systems operate in multiple languages. Connected systems must do it simultaneously and even be synchronized with other activities within the system. Many requiring 24X7 hours a day/365 day a year operation.
- Competition: It drives more features. Large actors in various sectors try to lock out competition by forcing standards for interfaces. Competition drives up the speed of innovation and complexity growth.

SPEED OF COMPLEXITY GROWTH:

Although we know that the systems that deliver these capabilities grow in complexity it is hard to assess how systems complexity grows in general. The iPhone is used in the rest of this article as an example of a very popular

product's capabilities and complexity growth over a 10-year period since the first iPhone introduction in 2007 until the iPhone XS MAX introduction in 2018. The iPhone is not unique. The first Samsung smartphone was introduced in

TABLE 1:
Change from the first iPhone (2007) to the iPhone X (2018)

Subsystem Category	**Component / Detail**	**2007**	**2018**	**Change**
Dimensions	H	4.5"	5.65"	-5% volume
	W	2.4"	2.79"	
	D	0.46"	0.30"	
Display	H	2.9"	5.31"	2.36X area
	W	1.9"	2.45"	
	Aspect/R	3.2	2.17	
	Color Bits	18	64	3.6X
	Pixels /"	163	458	2.8X
	Total Pixels	154K	3.334 M **	~18X
	Total Information/display			**~65X**
Storage	Max	16GB NAND	512GB NAND	**32X**
Processor computing power	Cores	4	6+8AI	3.5X
	Freq	412 MHz	2.49 GHz	6X
	Total			**21X**
BUS	Width	16Bits	64Bits	4X
	Frequency	103Mh	256Mh	2.5X
	Total			**10X**
On Processor Memory	DRAM cell size	0.29micro 2	.027micro 2	11X
	RAM	**128M**	**4GB**	**32X**
	Tech	45NM	7NM	
Connectivity	802.11***	b/g	a/b/g/n /ac	2.5X
	MIMO	N	Y	
	Blue Tooth	2.0+EDR	5.0	3X range, & DR=9X
Cellular (partial only) –	Bands	4	32	8x
	Modulation schemes T/R	2 (1 each T/R)	12 (T / R)	6X
	Antennas	1	3	3X
	Internal Modules	2	3	1.5X
	Total			**216X**
3D Touch		N	Y	
Face ID		N	Y	
Compass		N	Y	
GPS		N	Y	
Barometer		N	Y	
(Front Camera)		N	Y 8th gen.	
Rear Camera (iSight)	Configuration	Single	Dual, triple for XS Max	
	Lens Focus	F/2.8	F/1.8; F/2.4	
	Pixels	2 MP	12MP each	12X
	Video	N	Y	
	Auto Focus	N	Y	
Battery	Life (music)	24H	40H	1.67X*
	Capacity - W/h	5.18	12.08**	**2.6X**
Weight		135g	177-208g	
Component # level 1		23	60	**2.6X**
	W/h	5.18	12.08**	

*Other usage models show similar ratio
** XS Max model
*** Connectivity of the original model was available only through AT&T in the US. For international – iPhone used roaming with AT&T.

very limited geographies in 2010 and today challenges the capabilities of the iPhone, surpassing it in some features. Table 1 demonstrates the iPhone complexity growth, measured as a multiplication factor of the features of each subsystem.

The analysis shows that there are 20 subsystems in the X model compared to 10 in the original model. That is 2X over 10 years. We've marked in **BOLD** the factor that is carried forward for further steps in the analysis.

The 10 subsystems/functions that existed in the original model have been improved by factors varying from 10X to 216X. The frequency of upgrading each capability varies significantly.

Moreover, the overall complexity assessment depends a lot on the architecture of the overall system and interactions between the subsystems. On the lower end, we can assume the subsystems interact in pairs. In that case, the complexity growth of one subsystem impacts only one other system. As a more realistic case, the impact of additional functionality in one subsystem impacts an average of 3 or 4 other subsystems and needs to be accommodated by them as well. Some of this interaction may be "negative", ensuring that the subsystem in question DOES NOT interfere with another subsystem in a range of conditions. This put the ANNUAL rate of complexity growth at 3.33X, **6X** and 1X in respect of the subsystems interaction assumption of 2, **3**, and 4.

This is not the full story. The box volume available to pack in all this additional functionality and complexity shrank a bit (5%) and the number of Level 1 components

grew **2.16X**. The area allocated to the battery went from <60% to >75%. So, all level 1 component densities grew by factor of **4X,** which equates to an annual 15% packing density growth while accommodating all of complexity growth described above. This makes the challenge to support components to the newest phone each year to grow by factors of 3.8X, **6.9X** and 12.6X.

From my limited engagement with product development teams in one of the tier 2 suppliers, this is the level of complexity growth factors they are faced with. During the 6 years I was involved, the amount of combinations that needed to be tested for one tier two a subsystem of the transceiver (second level subsystem), grew by a factor of >100,000.

The challenges presented to the iPhone suppliers are also driven by factors beyond a single model. The number of models sold and supported in each year went form 1 in 2007 to 21 in 2018, an increase of ~1.35X per year. Even if a single supplier provides the same component to all models of a specific year, they must be tested with the whole build, to include different interactions. However, since that factor can't be simply applied, it will be ignored for the rest of the discussion.

iPhone volume sales grew from 1.39 M from 2007 (the year iPhone was introduced) to 231M in 2015 and stayed flat to down in the last 3 years. That means that the average volume growth factor per year is 1.89X until 2015.

The first item that is impacted by the complexity growth is quality of the physical product. The more complex the product is, the higher the risk and actual rate of failure. Without doing anything, a 3% failure rate will grow to 60% within five years. As we can see in Figure 1, the trend is opposite, Apple and its supply chain improved quality. The picture is much more concerning when we look at absolute numbers of failed units. 3% in 2007 was < 42,000, while in 2018 it would have been 7,170,000. It requires complex logistics and large technical support personnel to manage (it can be observed in Apple Stores- the percent of stores visitors for technical help is huge).

The traditional continuous processes (CPI) focus on reduction of variation of single component or level 2 subsystem. Most of the failures are coming from the interaction between subsystems and components. It is essential level – but is it enough? CPI has two levels:

- 6 Sigma which controls and reduces variation systematically.
- Major problem-solving methods that address the top one or two failure mechanisms and take a few months each to resolve. There are some known methods like 8D, Kepner-Tregoe and more. Most of the failures are due to software. Each OS used in the iPhones was an upgrade of the prior one and accommodates

Top 10 iOS Failure Rates by Model, Q1 2018

MODEL	FAILURE RATE %
iPhone 6	22%
iPhone 6S	16%
iPhone 6S Plus	9%
iPhone 6 Plus	8%
iPhone 7	8%
iPhone 7 Plus	7%
iPhone 5s	5%
iPad Air 2	4%
iPhone X	3%
iPhone 8 Plus	3%

Figure 1: Failure rate within two years of sale of the last 5 year's models. (for Model 8 and X – the current data is for period since introduction until publication).

the growing number of hardware components while providing more features. This demonstrates the software suffers from similar complexity growth as the hardware. The percent of HW failures is not known, but store observations shows that it is NOT negligible.

The cost of the iPhone went through significant change as well. While the original iPhone (largest memory) cost by the end of 2007 was $399, the introductory price of the leading 2008 phone was only $299. The price of XS Max model (largest memory) is $1,499, an average growth factor of 1.17X (17%) per year. Assuming the increase is spread equally through the supply chain, the impact on a tier 1 and 2 supplier who supply similar functionality year over year (from volume times price) is an additional 75%-125% revenue or 1.75-**2.25X**. This supplier has strong incentive to invest in additional manufacturing capabilities to support the growth in volume and complexity, so the manufacturing capability increases by the rate of potential revenue growth.
Assuming the efficiency of delivering new capabilities is growing, one can assume that the capability will grow **3X** YOY or **33%** above the investment rate. This is NOT enough to offset the complexity growth challenge they are facing. This is also not accounting for the RISK of new quality issues introduced by new capabilities, as demonstrated by the hike in failures with the Model 6 (and IOS 8). **Another factor of >2X of manufacturing capability improvement is needed.** This is the highest priority to successfully introduce the new/additional capabilities and address the quality challenges as described above. For that we add a third tier of CPI called High Velocity Continuous Process Improvement – HVCPI.

High Velocity Continuous Process Improvement (HVCPI):

The need for it and its basic principles were developed by Toyota and were first described by Steven Spear and H. Kent Bowen in their HBR paper "Decoding the Toyota DNA" [1]. Dr. Spear went on to further describe the method and some implementations in various enterprises in his book "The High Velocity Edge" [5]. Since then he continues to

Lecture at the MIT Sloan School of Management and at the Engineering Systems Division at MIT, while coaching organizations on implementation, with a major focus on the Health Care industry.

Figure 2 shows how the three different CPI activities are related to each other in an effort to address the challenges facing the industries described earlier.

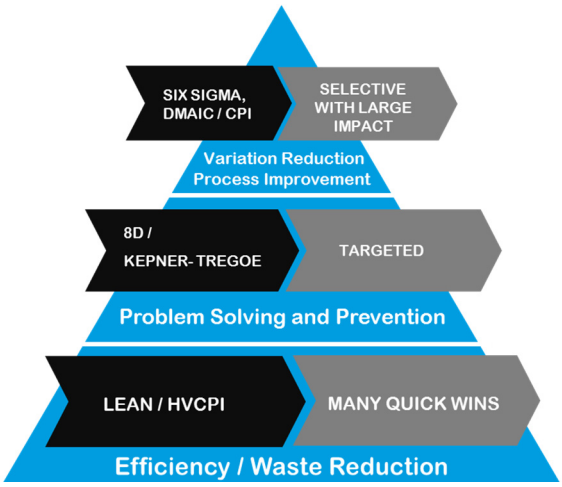

Figure 2: Hierarchy of different continuous improvement activities to address the different needs driven by fast growing complexity of products or services

The basic principle of the HVCPI is using the work of making a product or delivering a service to learn, on an ongoing basis and to rapidly improving the process of manufacturing or services. The faster the product or service flows through the enterprise, the faster the learning and improvement process is. There are a few efforts to make this happen:

- The decision to commit the organization to this method should be taken by the top level of the organization, who should also engage in the processes described below.
- Establish high level of understanding of the method at all management levels through personal training and experience.
- Establish integrative teams around each step of the process including first line employees, technicians, engineers, supervisors, and second level managers. The teams need to have participants from all organizations associated with the step, regardless the organizational structure including all shifts.
- The teams for each step should measure everything associated with each step and ask the upstream and downstream to measure the impact of the step on them and their performance. Make the measurements visual and visible by all employees of the step, close to where the work is done.

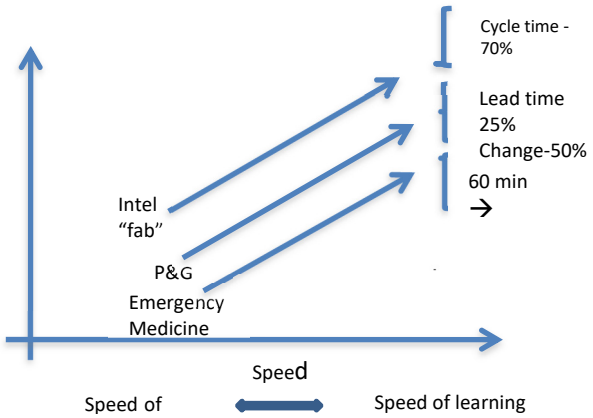

Figure 3: Demonstrates the impact of such an approach in three different examples described by Dr. Spear in his book "The High Velocity Edge" [5]

- GAMBA (Japanese) - All team members go to the place where the work is done and have direct observation of the work. Emphasis on indirect labor.
- Any defect or small problem you observe should be corrected. Usually, these defects have minimal impact on the overall product or service, but the cumulative impact will make a difference.
- Correction is a proposed change. Participant of each organization should validate that the change will not raise new defects or problems.
- All proposed changes should be validated by quick experiments performed as fast as possible to measure the impact and the risk to other parts of the process.
- Learning is captured and documented, **even in the case of failure.** Learning is the most critical outcome of this process.
- Use rewards and recognitions intensively to encourage team members to participate, contribute and openly raise concerns.
- Each team should meet at least twice weekly with work assignments to individuals or pairs to be performed between the meetings.

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