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Case

ABCtronics: Manufacturing, Quality Control, and Client Interfaces

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1. Introduction

"Today is going to be long," the thought came to Phil McDermott, as he casually checked the time on his watch while negotiating a busy crowd in the high-speed rail station. After arriving at the station, he started for his office. As an intern at ABCtronics, he never anticipated he would be asked to attend today's meeting. But Jim was adamant; last evening he had said, "Look at this as a good learning opportunity." After that, Phil was left with little or no option.

The steel and glass-structured gigantic office building was already in sight. The location houses the manufacturing facility of eight-inch fabrication of ABCtronics, along with other departments, such as the quality and reliability team (QRT), the sales and marketing team (SMT), and the customer interface team (CIT). Phil directly reported to Jim Morris, the chief operating officer. Today, all important vertical heads of the plant were meeting for the quarterly review. Quarterly reviews are routine processes in every manufacturing company. Today was different. Complaints from a major client site had increased manifold, and in spite of boom time in the chip industry, ABCtronics had not done well over the last couple of quarters. "Tempers are going to run high today," Phil thought as he threw his finished coffee cup in the trash can nearby and entered the office. But Phil wondered, as an intern, how he could add value to such a discussion?

2. Company Background

ABCtronics, a semiconductor manufacturing company, was established in 1997. It started its operations on a small scale. Over time, it had become a medium scale enterprise. The company offers a variety of wafer product lines, such as a mixed-signal integrated circuit, analog, and high-voltage circuit boards. ABCtronics is dependent on one major client (XYZsoft) for a good portion of its business. On the other hand, the semiconductor manufacturing industry is affected by a highly cyclical demand pattern.[1] During upturns, semiconductor manufacturers have to ensure they have sufficient production capacity to meet high customer demand. During downturns, companies must contend with excess capacity because of weaker demand and high fixed costs associated with manufacturing facilities. Market analysts already predicted that the integrated chip market would face

[1] According to noted market analyst Wahlstrom (2014), "*Given the cyclical nature of the chip industry, foundries tend to add too much production capacity as they attempt to meet burgeoning demand during the good times, yet are left with excess capacity and are on the hook for the high fixed costs associated with their equipment during the bad times.*"

shrinkage in 2008–2009, and growth would resume from 2010 onward (*The Economist* 2009). Despite the increasing market size from 2010, sales revenue of ABCtronics is not up to the mark compared to its initial year's sales.

3. Industry Background

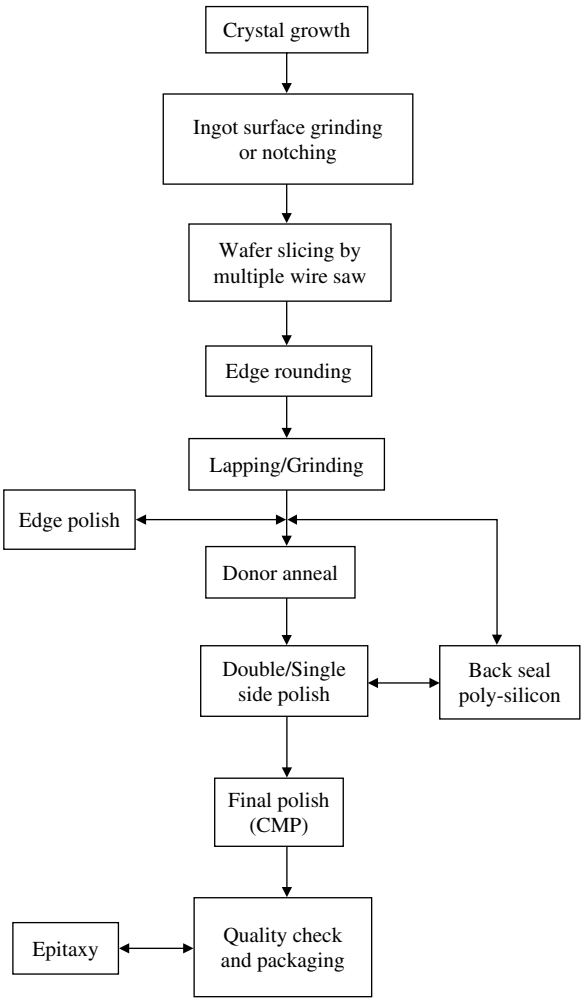
With a global sales figure approaching $24.70 billion, the semiconductor industry has experienced continuous sales revenue increases over the last three years (Semiconductor Industry Association 2013). Samsung has the highest installed wafer capacity with a production capacity of approximately 1.9 million wafers per month that represents 12.6% of the world's total capacity (CdrInfo Report 2014). Other industry leaders are Taiwan Semiconductor Manufacturing Company (10%), Micron (9.3%), Toshiba/SanDisk (8%), and SK Hynix (7%).

The industry faces an economic challenge for two reasons: (i) cyclical nature of demand and (ii) the high cost associated with research and development (R&D) (McKinsey Report 2011). Ever increasing costs related to upgrading the existing fabrication plants complicates the scenario further. Demand cycles, though bad for the entire industry, have proved to be a blessing in disguise for underperformers. Semiconductor chip manufacturers have invested heavily in R&D to meet the expectations of *Moore's Law*.[2] As a result, complexities of the chip design and costs have naturally gone up.

A high cost of R&D has also led to substantial capital requirements for building state-of-the-art facilities for wafer fabrication. A McKinsey report indicates that "*R&D spending amounted to approximately* 17% *of industry revenue for semiconductor companies* (*up from* 14% *a decade earlier*) *versus* 3% *for automakers*," (McKinsey Report 2011). As a result, the industry also focuses on quality assurance processes. In the semiconductor manufacturing lines, the uncertainty regarding the health of processes and wafers often leads to "major scrap events" as well as higher cost. In case of mixed-signal IC chips, it can be as high as 50% of the manufacturing cost. One of the main ways of tackling the quality problem is by monitoring some key parameters for deviations. These kinds of controls stem from statistical process control techniques.

[2] Moore's Law: The number of transistors in a dense integrated circuit doubles approximately every two years. There is no fundamental obstacle to achieving device yields of 100%. At present, packaging costs so far exceed the cost of the semiconductor structure itself that there is no incentive to improve yields, but they can be raised as high as is economically justified (Moore 1965).

Figure 1 Wafer Shaping Process

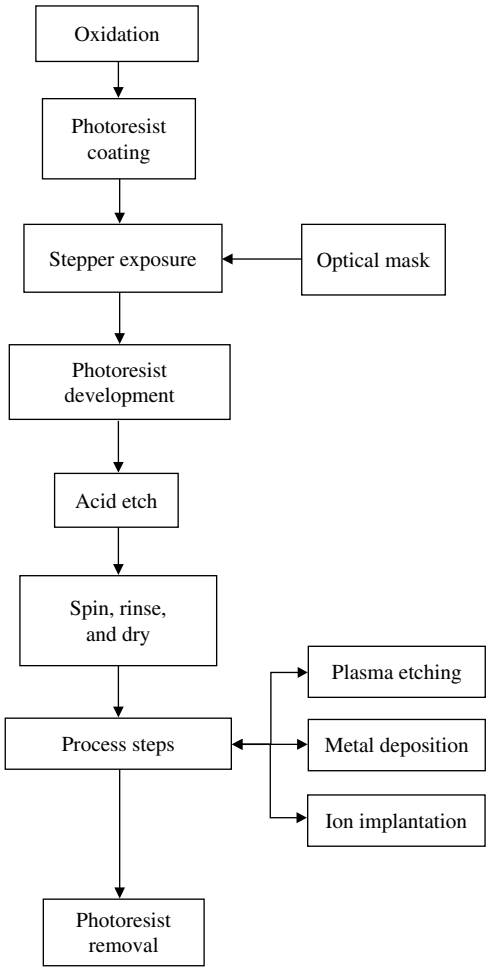


Note. CMP: Chemical Mechanical Polishing.

4. Semiconductor Fabrication Process

The fabrication of integrated circuit (IC) chips is a highly complex process that involves hundreds of separate steps. The overall process lasts for several weeks. At ABCtronics, hundreds of IC chips are fabricated simultaneously on a six by eight-inch disc of silicon, termed as a "wafer" (see Figure 1). The wafers are processed in groups called "lots." The circuit elements such as transistors, resistors, and capacitors are manufactured in layers on the wafer, with alternate deposition of material and exposure to light through a mask; finally they are subjected to an etching process that removes the unexposed material. The exposure to light is referred as photo-lithography (see Figure 2). This process itself contributes to the variability in the quality of the IC chips. The features created in this way are currently as small as 0.16 μm (1 micrometer (μm) $= 1 \times 10^{-6}$ meter), and therefore, fabrication is required to be done in a virtually sterile environment, often referred to as a "clean room." ABCtronics

Figure 2 **Photo-Lithography**



enforces a strict quality control policy. Samples of wafers from each lot are subjected to quality checks at various steps during the process to assess the impact of particular defects, the thickness of different layers, and the performance of test structures created in the areas between the chips. At the end of the line, each chip on every wafer is subjected to functionality tests (to reduce probing time, testing of each chip is stopped after the first failed functionality test; this serves as an equivalent of a rejection rule).

The quantity and the complexity of the process and associated testing have forced the quality improvement efforts to focus primarily on summary statistics such as the number of salable IC chips per lot. This kind of figure has the advantage of suggesting simple and unambiguous screening rules (e.g., mark a lot if less than a particular proportion of the IC chips are usable). However, such one-dimensional analysis fails to address more pressing issues such as the possible causes of the defects, and crucial information for process improvement. Large manufacturing houses of IC chips are therefore always looking for avenues to improve upon the quality checks and customized design of such control measures. Similarly, ABCtronics is also concerned about maintaining high quality. From an internal investigation, the fabrication process is currently facing two major problems: high downtime and chemical impurities.

5. Quality Control Tests

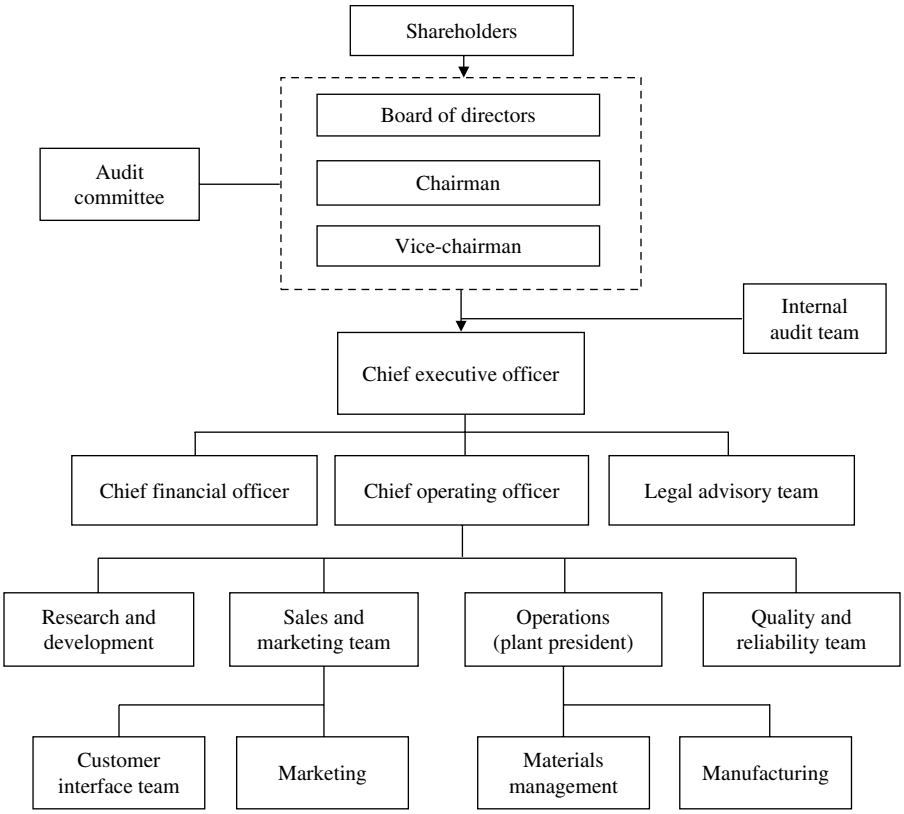
The cost of quality assurance in manufacturing IC chips is very high. Moreover, as the complexity of IC chip design increases, the probability of faulty production also goes up. Since it is practically impossible to attain 100% yield on any IC chip manufacturing, quality checks are incorporated at several stages of the manufacturing process. Industry experts put emphasis on the requirement for routinely designing statistical procedures to monitor the presence of defect clustering.

The entire industry is increasingly turning toward statistical methods for quality control. ABCtronics has also adopted a similar approach. Analysis of production data has revealed that the probability of producing a defective chip is 0.004. The company is currently considering whether to incorporate a new IC growth technology, namely, "defect-free manufacturing," which can bring down the probability of producing a defective chip to 0.002.

ABCtronics currently applies the *Lot Acceptance Testing Method* (LATM) for quality check. An automated machine is employed to take a sample of 25 IC chips one by one randomly from a lot of 500 without replacement. It means the chip already drawn from the lot is not returned to the lot when the next chip is selected, and the lot size goes down. If the sample has less than two defectives then the lot is accepted; otherwise it gets rejected. The in-house testing team has conducted their analysis and found that every lot of 500 IC chips contains two defectives on average.

The QRT has proposed a new design for quality control to the board for approval. Scrapping the existing quality control policy, LATM, they want to bring in a new type of testing called *Individual Chip Testing Method* (ICTM), designed based on "defect-free manufacturing." According to the proposal from QRT, a sample of 25 IC chips is to be taken one by one from a lot of 500, but this time they will allow replacement. It signifies the chip already drawn from the lot is returned to the lot when the next chip is selected, and the lot size remains the same for each selection. If a defective chip is found, the rework will immediately be done on that chip. The rework is usually done by performing a functional test on the internal circuitry of that IC chip (Tsai and Ho 2000). The proposal was aimed at establishing ABCtronics as a reliable brand in the IC chips market and also for retaining a good relationship with its biggest customer, XYZsoft.

Figure 3 ABCtronics Organizational Structure



XYZsoft, one of the major clients of ABCtronics, uses IC chips on their personal computers (PCs). In a component of each of these PCs, three IC chips are connected in series. It is known that the life (measured in years) of any IC chip follows an exponential distribution. XYZsoft uses chips with an identical specification in series. The ABCtronics fabrication team is now contemplating the option of rework on returned and defective IC chips from XYZsoft to investigate any problem with series connectivity of the IC chips. QRT is proposing immediate rework on IC chips with ICTM.

6. Review Meeting with the Manufacturing Unit and QRT

As Phil entered the board room, most of the executives of ABCtronics had already arrived. Mark, the head of QRT, and Robert, the head of SMT, were there. They were having a last look at their respective files before the start of the meeting. ABCtronics was a hierarchy-centric organization, typical of any manufacturing-based firm (see Figure 3). He saw that Stuart, the president of the fabrication plant, was scribbling down something in his file. Stuart would give the first presentation of the review meeting. They were waiting for Jim. Phil found a corner seat in the room for himself.

As Phil was going to settle, Jim entered the room. Like a meticulous taskmaster, he set the agenda for the meeting first: "Gentlemen, last evening, I received yet another complaint from XYZsoft. It is the third time in last six months. I have assured them that I will personally look into the matter and ensure all possible rectification measures. So, let's get started. We have a number of things such as improvement of operational efficiency, rework issue, customer feedback, and sales growth potential to discuss today."

Stuart immediately started. After detailing out the overall production of IC chips, he said, "We are currently producing 500 IC chips per lot. However, our plant is also facing the problem of downtime. This issue is particularly critical with our ion implanter." It immediately reminded Phil about one of the reports that he read earlier. Downtime of this equipment is a matter of concern for semiconductor companies. Minimization of the downtime would lead to improvement of operational efficiency (Globenewswire 2007).

At this point, Jim interrupted and asked, "In terms of downtime, what are we looking at, Stuart? How big is the problem?" Stuart said, "We ran some analysis and based on our estimate, average downtime of the machine is 6 hours (see Table 1). We need to curtail it down to 5." "How good is that chance?" Jim enquired. Stuart glanced at Mark, the head of QRT, and said, "Mark and I agree that a replacement

Table 1 Data on Downtime and Chemical Impurity

Excerpt from the fabrication plant report on downtime of ion implantation	
Data on monthly downtime of ion implantation (for last one year)	
Month	Downtime
July, 2012	3 hours 36 minutes
August, 2012	4 hours 48 minutes
September, 2012	4 hours 36 minutes
October, 2012	6 hours 40 minutes
November, 2012	5 hours 24 minutes
December, 2012	5 hours 40 minutes
January, 2013	7 hours 20 minutes
February, 2013	9 hours 24 minutes
March, 2013	8 hours 40 minutes
April, 2013	5 hours 06 minutes
May, 2013	6 hours 20 minutes
June, 2013	4 hours 40 minutes

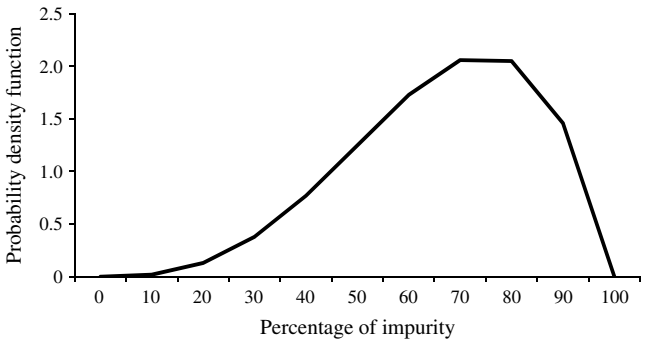
is needed. I have a minor disagreement with Mark regarding the possibility of achieving 5 hours of the downtime."

Mark was ready with his reply, "QRT ran some tests and found that downtime of ion implanter has a gamma distribution pattern and based on that we have calculated the chance of reducing the downtime to 5 hours. But Stuart says the ion implanter impacts the overall production. As per his opinion, downtime of ion implanter and subsequent activities follows a uniform distribution instead. Here lies the difference in opinions." Jim looked at Stuart and asked, "Are you sure that we are left with no other option but replacing this machine?" Stuart nodded silently. Jim pondered over the matter for some time and said, "Well, let me think over this. Now, I will look at the status of the chemical impurity problem we had last month."

IC chip fabrication process of ABCtronics involves the chemical vapor deposition method. In this technique, several chemicals such as ammonia, hydrochloric acid, sulfuric acid, etc., used in various steps of manufacturing, often contain impurities. To avoid contamination, the percentage of impurities per lot in a chemical should not go beyond a specific limit; otherwise, it results in producing defective IC chips. The manufacturing company itself sets the upper threshold of chemical impurity percentage based on the desired operating level of the production process.

Stuart went on to explain, "From the analysis of historical data, we have concluded that the percentage of impurities per lot in a chemical approximately follows a beta distribution (see Figure 4). Based on this, we have decided that if the percentage of impurities per lot in any chemical is more than 30%, it is not used in the fabrication process." Jim did not look convinced. "Is that good enough?" Mark came to Stuart's aid this time. He said, "QRT has checked that the policy is working fine." Jim remained skeptical. He waved at Phil. As Phil approached him, Jim handed him over a stack of papers and said, "Keep these with you, we will work on this issue, later."

Figure 4 Report on Chemical Impurity Found in Raw Materials (Probability Density Function of the Percentage of Impurity in Chemical X)



Note. The percentage of impurity in chemical X follows beta distribution with shape parameters $\alpha = 4$ and $\beta = 2$.

At this point Mark commented, "Regarding the proposed quality check technique ICTM, we need to make a decision. Are we going to adopt this method or not?" Now, Stuart commented, "But don't you see, our current system is flawed, and client complaints will not stop coming?" Robert supported Stuart and opined that it would affect the product delivery system. At the table, everybody seemed clueless. Jim intervened and said, "QRT gave me a report on ICTM last week. I have asked Phil to look into the analysis. Next Monday we will take the final decision on the matter of ICTM."

Phil scribbled on his scratch-pad, "*ICTM Report—urgent*." The truth was that he was yet to figure out the flaw in the current testing procedure. The meeting at hand was entering into the second phase.

7. Review Meeting with SMT and CIT

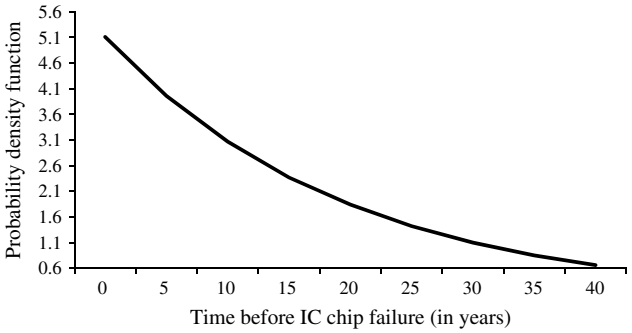
"Where are we with our client Customer PQRsystems?" Jim directed his question toward Robert. "They are looking for specifications such that the product can work for six years smoothly. I have asked Mark to give you a copy of our internal RT report[3] (see Figure 5). After looking at it, we have replied to their query. I think we have a good chance of securing this order." Mark commented, "I think we should be able to meet their expectations. I have checked the data myself. Our chips will easily last more than six years." After hearing this, Jim said, "Mark, send me a copy of RT. I would also like to have a look at the details." Mark nodded.

[3] RT report refers to Rigorous Testing (RT) report. This process checks for the lifespan of any product.

Figure 5 Related Portion of Rigorous Testing Report (Probability Density Function of Time Before Failure (in Years) of IC Chips)

Excerpt from the Rigorous Testing Report on Life Expectancy of IC Chips

The following graph represents the Early Life Failure Test (the chip is tested to check whether it can survive for 40 years or not) result of the LM98XX chip that was carried out. The result is presented in the figure below.



Salient data points from the Early Life Failure Test are presented below.

Time before failure (in years)	Cumulative distribution function of failure time
5	22.55
10	40.00
15	53.53
20	64.01
25	72.13
30	78.41

Notes. The time before failure of IC chips is exponentially distributed. The figure depicts the probability density function of IC chips failure time, whereas the cumulative distribution function of the same is presented in the table.

"OK. Now, the next issue is XYZsoft. Why has the number of complaints increased? What has happened, Robert?" Jim said as he was finishing his cup of coffee. Stuart immediately quipped, "They have again started experimenting with their quality control." Robert smiled at him and said, "A few months ago, XYZsoft started a module-wise testing of their product. Circuit module M (CM) has a path where three chips from ABCtronics get connected in a series. Before the new testing process, XYZsoft reported that in a typical lot comprising 20 CMs they are finding three defective items. In most of those cases, they observed that the problem was with our chips. Now, they have put a stricter policy in place. They have now started to calculate the number of nondefectives before they encounter a particular number of defectives, and they started the count of 3. Till this point of time nothing happened." Robert paused.

Phil could sense that the new policy did not have much impact compared to the previous one. He pondered in his mind, how would that be possible? Robert started after taking a sip of his coffee, "The problem began as their testing team proposed that they should send back the whole lot for rework and recheck as soon as one defective item is found. All hell has broken loose since then. We are now flooded with requests for rechecks from XYZsoft." At this point, Mark commented, "I am telling you, Jim, we can easily tackle this problem if we implement ICTM at our end." Jim looked at Mark but said nothing. The entire episode puzzled him. How can a change in the quality control policy of XYZsoft have serious implications on the business of ABCtronics? Jim replied, "We need to tackle this problem quickly. XYZsoft is our biggest client. We simply cannot afford to lose their business." Phil also found this development of events to be fascinating. He had quietly jotted down whatever Robert has said and looked at his pad. "What am I missing?" he wondered on his own.

Robert continued, "I had a talk with Stuart regarding this matter. He told me that [the] Susceptible High Voltage Problem (SHVP)[4] could contribute to this kind of issue. His team is looking into this aspect on the priority basis." After hearing this, Jim looked at Stuart and said, "I thought we dealt with this problem a couple of years ago." Stuart replied, "We are checking to be sure of the fact that it is not due to SHVP. Tests would be complete within next week." Jim replied, "Do you have any preliminary report on this test?"

Stuart said, "As per historical data, our IC chips produce [a] minimum 2.7 V output on an average, as HIGH signal. The variance of the HIGH signal output voltage remains 1.8 V. We have received a number of complaints from XYZsoft that the IC chips are not producing the expected voltage. Then, I ordered to take a random sample of 100 IC chips across the lots and test them for SHVP. Initial reports suggest the average voltage produced by the IC chips is around 2.3 V." At this point, Mark commented, "Is it possible that we are overestimating the output of the IC chips?" Stuart replied, "It may be the case. We would not know for sure unless the detailed report comes." Phil could sense that the entire XYZsoft episode had caused a fluttering feeling across the power corridor of ABCtronics. They need a fast fix for the problem and as of now none was in sight. A stifled silence prevailed over the board room.

[4] Susceptible High Voltage Problem (SHVP): Ideally, every IC should produce HIGH signal output at 3.5 V, LOW signal output at 0.1 V, whereas 0.4 V–2.4 V is the undefined region of signal where signal remains neither HIGH nor LOW. In reality, it is often found that the HIGH signal output is around 2.5 V–3.0 V for a good IC. A problem starts if the HIGH signal output of an IC's lies between 0 V and 2.4 V. Then the signal is LOW or undefined, whereas it should be HIGH. This problem is defined as SHVP (Tokheim 2004).

Table 2 Customer Score Sheet

Sl. no.	Customer name	Customer score	Range
1	Customer A	79	Good
2	Customer B	56	Satisfactory
3	Customer C	33	Needs improvement
4	Customer D	79	Good
5	Customer E	66	Good
6	Customer F	49	Satisfactory
7	Customer G	47	Satisfactory
8	Customer H	34	Needs improvement
9	Customer I	88	Very good
10	Customer J	77	Good
11	Customer K	67	Good
12	Customer L	51	Satisfactory
13	Customer M	53	Satisfactory
14	Customer N	74	Good
15	Customer O	85	Very good
16	Customer P	56	Satisfactory
17	Customer Q	39	Needs improvement
18	Customer R	51	Satisfactory
19	Customer S	26	Needs improvement
20	Customer T	43	Satisfactory
21	Customer U	77	Good
22	Customer V	97	Very good
23	Customer W	73	Good
24	Customer X	57	Satisfactory
25	Customer Y	66	Good
26	Customer Z	45	Satisfactory
27	Customer AA	28	Needs improvement
28	Customer AB	33	Needs improvement
29	Customer AC	56	Satisfactory
30	Customer AD	68	Good
31	Customer AE	32	Needs improvement
32	Customer AF	93	Very good
33	Customer AG	60	Good
34	Customer AH	29	Needs Improvement
35	Customer AI	41	Satisfactory
36	Customer AJ	42	Satisfactory
37	Customer AK	72	Good
38	Customer AL	48	Satisfactory
39	Customer AM	59	Satisfactory
40	Customer AN	47	Satisfactory

Note. Customer Score Range is defined as follows—Below 40: Needs improvement, 40–59: Satisfactory, 60–79: Good, and 80–100: Very good.

Table 3 Historical Sales Figure of ABCtronics

Year	ABCtronics' sales volume (in millions)	Overall market demand (in millions)	Price per chip (in $)	Economic condition*
2004	2.39	297	0.832	0
2005	3.82	332	0.844	1
2006	3.33	195	0.854	0
2007	2.49	182	1.155	1
2008	1.56	93	1.303	0
2009	0.97	98	1.265	0
2010	1.32	198	1.368	1
2011	1.42	188	1.208	0
2012	1.48	285	1.234	1
2013	1.85	264	1.282	1

Note. *Economic condition: 1 signifies favorable market condition and 0 signifies otherwise.

Breaking the silence of the room, Jim spoke, "This brings us to the last issue of the discussion today. Where are we, regarding the analysis of customer feedback?" Robert picked up a thick file and said, "It's all here. We ran the survey through 40 randomly chosen customers of the 74XX chip family. Four of them have rated us *Very Good,* eight have rated us *Needs Improvement*, and 28 have given us either *Good* or *Satisfactory* (see Table 2). So, I think we are good. Most of them are happy with our products." Jim noted something in his diary. Then he said to Robert, "That would be your hunch. That cannot be your analysis." Then Jim remembered something from an earlier meeting. He asked Robert, "In the last meeting, there was some discussion on redesigning the survey altogether. Why?" Robert looked visibly uncomfortable with this question. He cleared his throat and replied, "We have a mean customer rating of about 56. But the overall spread of the score is very high. If we want to conduct the survey to be sure of this average score with 90% confidence, even with a margin error of 4 the required sample size may exceed our total customer base." Jim said, "What is the total number of customers for 74XX?" Robert said, "Including the new clients, the total is 70." Jim said, "Sample more customers if needed. And tell me how good would be our estimate of the customer score?"

Robert presented the report on the sales figure (see Table 3). ABCtronics was using a simple linear regression model for predicting the sales figure. However, the new interns, who recently joined SMT, indicated a few problems with the existing method. They proposed a new method to predict sales. They argued that their multiple linear regression model had better explanatory power and was devoid of multicollinearity problems. Looking at the presentation, Phil figured out that he was also asked to predict the sales figure for various demand scenarios. But Phil adopted a different approach. While looking at the screen, he did some quick mental calculation, and the results were not matching with the one presented. He nervously glanced at Jim. Jim was listening to Robert's analysis with rapt attention.

As the meeting was coming to an end, Phil could sense that ABCtronics needed to deal with a number of issues, and they needed to do it quickly. The company was entering into the second quarter of the year. ABCtronics immediately had to take corrective measures; otherwise it might be too late. As Stuart, Mark, and Robert were leaving the board room, Phil waited quietly for Jim. He knew that he was asked to attend today's meeting for a reason.

Table 4 Market Demand Estimate

Total market demand for PCs (in millions)	Sales volume (YY) (in millions)			
	$YY > 3$	$1.5 \leq YY \leq 3$	$YY < 1.5$	Subtotal
$XX > 200$	0.10	0.20	0.10	0.40
$100 \leq XX \leq 200$	0.10	0.10	0.20	0.40
$XX < 100$	0.00	0.10	0.10	0.20
Sub-total	0.20	0.40	0.40	1

Joint probability matrix of the sales volume and total market demand

Total market demand of PCs (XX) (in millions)	Average sales volume (YY) (in millions)
$XX > 200$	2.385
$100 \leq XX \leq 200$	2.140
$XX < 100$	1.265

Average sales volume in different demand scenarios

Note. Based on the sales figure of ABCtronics in Table 3, Phil has calculated the joint probability matrix for the sales volume and total market demand, as well as the average sales volume in different demand scenarios.

8. The Road Ahead

As everybody left the room, Jim turned to Phil and asked, "What do you think of today's meeting?" Phil kept quiet. Many aspects of the meeting left him confused. Jim went on, "I need an honest opinion before going ahead. Look at all the reports and analyze. Tell me what do you think? You have two days to prepare. Let us meet on Monday." As Jim uttered those words, only one thought came to Phil's mind, "There goes my weekend plan!"

"Have you prepared an analysis of the sales figures I asked for?" Phil said yes (see Table 4). "Do you think we can sell more than 3 million chips this year?" Phil said nothing. He has done the calculation; the possibility stands below 50% level. Jim figured out the answer from Phil's silence. He asked, "What about 2.5?" Phil replied, "I think we will fall short of that number, the industry overall is experiencing a medium level demand. But the difference is not very large. If we get an order from Customer PQRsystems, probably we can make it." Jim sighed for a moment and said, "Let us see where we arrive independently with our analysis. On Monday, after our meeting, I shall meet with Stuart and Mark. We have gone through a prolonged rough patch. The time has come to take some course correction; otherwise competition will knock us to the ground."

9. Note

This case has been prepared to form the basis for class discussion rather than to illustrate either effective or ineffective handling of a business situation.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/ited.2016.0158cs.

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