Impact of Product Design Choices on Supply Chain Performance in the Notebook Computer Industry

by

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Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration

AND

Master of Science in Mechanical Engineering

In conjunction with the Leaders for Global Operations Program at the

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June 2010

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ABSTRACT

Intel Corporation is the world's leading manufacturer of processors for personal computers. As the company strives to maintain its leadership position in this industry, it identifies significant trends in the industry and attempts to develop product solutions that intercept these trends. One such set of industry vectors is the continued movement toward lower cost and smaller notebook system designs with a coincident shift toward fully outsourced production in China. These trends point to increased future demand for processors utilizing a ball-grid-array (BGA) package in notebook computers, which is the lower cost, smaller size packaging technology available today. This project was initiated to understand why with such a seemingly favorable environment for BGA, it still represents a small minority of Intel's mobile processor volume.

The analysis shows that significant changes must be made to Intel's product roadmap, OEM product scalability strategies, or after-sale service models to enable a full transition to BGA processors. SKU levels increase by 10x with a BGA transition resulting in much higher supply chain complexity, management cost, and inventory cost. In addition, simple modeling approaches are developed and utilized for this study that can be leveraged in the future to quantify possible product strategy impacts on the industry supply chain. They can also be used in other industries contemplating supply chain simplification strategies.

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ACKNOWLEDGEMENTS

First, the author wishes to recognize the Leaders for Global Operations Program and Intel Corporation for their support of this work.

Next, I would like to thank everyone I worked with at Intel during my internship. They provided invaluable guidance, support, and direction throughout the project and tolerated many intern questions. Jessica Marrash, especially, was an amazing teacher and helped tremendously to keep the work on track.

Jason Ku, my Intel supervisor, deserves special thanks and my gratitude for creating a fantastic internship, dispensing wisdom from his many years of experience, and being an amazing mentor.

My thesis advisors, Daniel Whitney and Sara Beckman, continually generated valuable suggestions and advice, responded quickly to all of my questions, and expertly guided me through the entire thesis process.

Finally, and most importantly, I'd like to thank my wife, Tani, for her support over these two challenging years. I would not have made it through this wonderful experience without her.

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CHAPTER 1: INTRODUCTION

Intel, as the world's leading manufacturer of semiconductor platforms for desktop, mobile, and server computer markets, provides the processor, graphics chip, and chipset that go into a majority of the world's notebook computers. In order to achieve its goal of being the preeminent provider of semiconductor chips and platforms for the worldwide digital economy[1], Intel constantly strives to develop product offerings that fully meet its customers' needs, and to anticipate and intercept major industry trends.

This thesis was part of a strategy exploration project aimed at understanding the possibility of such an industry intercept, a transition to socketless, or ball-grid-array (BGA), processors for notebook computers. This initiative started in the Mobile Platforms Group (MPG) at Intel, which is the business unit responsible for not only the mobile business P&L, but also engineering, marketing, platform architecture, and strategic planning for all Intel mobile platforms. Within MPG, previous analysis suggested that BGA should naturally become the dominant processor package for notebook computers due to a number of industry trends; however, BGA processors represent only a small fraction of the mobile processor volume. This study was undertaken to provide a greater qualitative and quantitative understanding of this paradox.

BGA is one of two primary attach methods available for most processors on the MPG mobile product roadmap.[2] The attach method refers to the method of connecting the processor to the computer motherboard. BGA is the attach method where an array of solder

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[1] Intel Corporation. (2009). Intel Corporation Corporate Strategy. Retrieved July 2009, from Intel Corporation Web site: http://www.intc.com/strategy.cfm

[2] Intel Corporation. (2009, Nov 16). Package Types for Mobile Intel® Processors. Retrieved July 2009, from www.intel.com: http://www.intel.com/support/processors/sb/CS-009864.htm

balls is present on the bottom of the processor package as shown in Figure 1.[3] The processor package is the brown substrate in these images that provides the input/output interface between the actual silicon chip (blue component in the left image) and the computer motherboard.

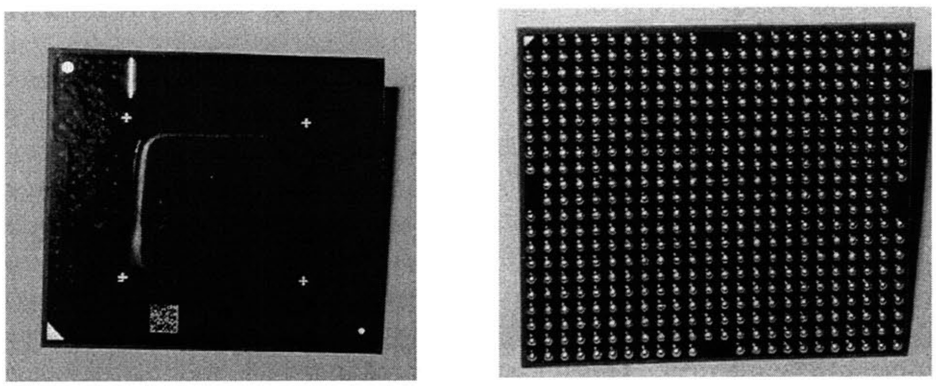


Figure 1: BGA Processor Top and Bottom View

The BGA component is soldered to the motherboard during the surface mount process step in the factory at the same time the motherboard is manufactured.

The alternate attach method, or packaging choice, is pin-grid-array packaging (PGA). On a PGA processor, shown in Figure 2, there are pins on the bottom of the processor package that mate to a socket which is soldered on the computer motherboard. The socket is shown in Figure 3.

[3] Image from www.intel.com

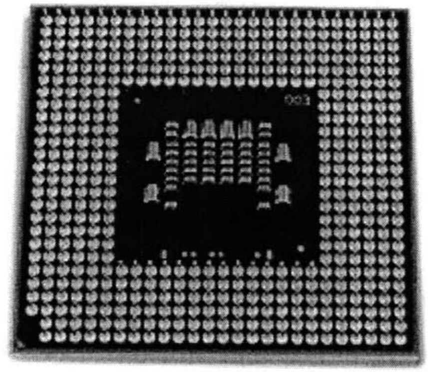


Figure 2: PGA Processor Pins (processor bottom view)[4]

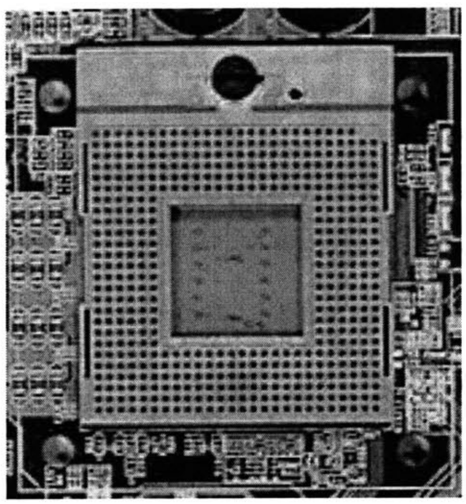


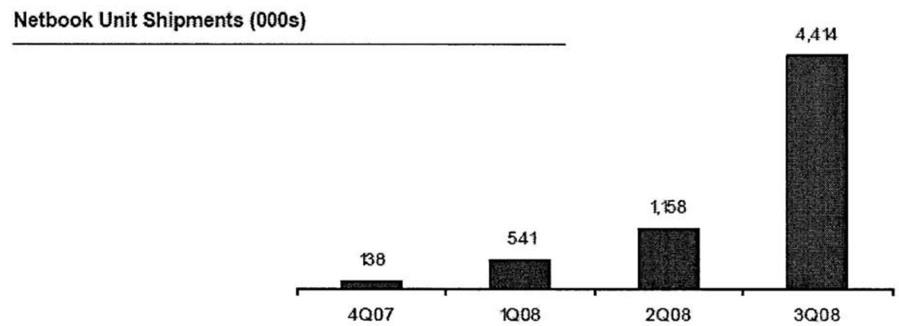
Figure 3: PGA Socket[5]

The crucial differences between BGA and PGA are that a PGA-mounted processor can be easily pulled out of its socket but a BGA processor is difficult and expensive to remove; and there is only one point in the production process when a BGA processor can be installed whereas there are many possible installation locations for a PGA processor.

There are several trends in the notebook computer industry that indicate to MPG that BGA should be a favored attach method used in notebook computer designs. These trends

[4]Image from http://www.logicsupply.com/blog/2007/08/29/new-socket-p-processors/, accessed 4/1/2010.
[5] Image from http://en.wikipedia.org/wiki/Socket_P, accessed 4/1/2010.

include continued reduction in system form factors, continued cost pressure within the value chain, and a move to almost fully outsourced production in China. First, the BGA processor is smaller than a PGA processor in the x, y and z dimensions. This enables notebook designers to create the small form factor systems that are appearing in the industry today such as the Macbook Air and Netbooks. The growth of the small form factor Netbooks is highlighted in Figure 4 (Sacconaghi, Lindsay and Moffett 2009). This data shows that Netbooks represented 22% of consumer notebook shipments at the end of 2008 and 11% of



Percentage of:	4Q07	1Q08	2Q08	3Q08
Consumer Notebooks	0.9%	3.8%	8.1%	22.0%
Total Notebooks	0.4%	1.7%	3.7%	11.1%
Total PCs	0.2%	0.8%	1.7%	5.6%

Figure 4: Growth of Netbooks

total notebook shipments (which include business notebooks). As customers are continuing to demand smaller and more powerful notebook computers from Original Equipment Manufacturers (OEM) the desirability of BGA should be increasing greatly.

Next, margins in the notebook computer industry, especially for Original Design Manufacturers (ODM), continue to decrease with current ODM gross margins between 4-5% (Compal Electronics, Inc. 2009, Quanta Computer 2007, Wistron Corporation 2009). This is due to the persistent reduction in system price points for portable systems and strong competition between manufacturers. Use of a BGA processor provides savings for both the OEM/ODM and Intel. The computer manufacturer saves the cost of the socket. This cost is $.75-1 for the current generation socket and is projected to be $1-5 for the next generation (Ku 2009). This equates to a gross margin increase of 20-30 basis points. Intel saves material costs of approximately $1/unit because of the removal of the gold-plated pins and the smaller substrate used for the BGA processor.

Finally, over the past 10 years the industry has moved to an almost fully outsourced production model using Chinese factories, and most processors are being installed in these factories rather than in an OEM factory very close to the final customer. This indicates that the well-documented model of postponement popularized by Dell to provide high customizability and rapid delivery is disappearing (Maich and George 2009). PGA packaging, by allowing processor installation into a socket, enabled this customization late in the supply chain. However, with the capability for late customization no longer used a transition to BGA is hypothesized to be eased.

As Intel looked at these forces they saw that the industry had a significant opportunity to reduce costs while further enabling system designs that are increasingly craved by customers. Incremental earnings should have been available for both the OEM and Intel and it seemed as if the industry was leaving money on the table. However, as PGA is still the dominant packaging choice, it was presumed that there are unexplored factors that explain why the socket savings and increased revenue from more desirable system designs are not enough to induce the transition. This study was aimed at improving this understanding.

The approach undertaken for this research was comprised of three components. First, face-to-face interviews were conducted at seven Intel customer sites to gain direct feedback on BGA constraints. Feedback from the interviews was consolidated and we were able to isolate key industry dynamics that drive the processor packaging design choice. From the interviews it was verified that supply chain issues, and more specifically issues with the industry service models and SKU (Stock Keeping Unit) proliferation, were the primary constraints associated with BGA.

Based on the direct customer feedback, the next study step was to document current notebook computer configuration strategies for leading OEMs and to utilize the resulting model to verify the SKU proliferation effects. Major OEM websites and major retail websites were used to develop a database of notebook system configuration offerings from five leading OEMs, capturing over 70% of the industry volume. The resulting spreadsheet model was then used to model the SKU increase effects of a full BGA transition as well as the outcome from many potential implementation approaches that were suggested by MPG's Product Marketing Group.

The SKU proliferation study further focused the research effort by showing that OEM service operations experience the greatest negative impact from a processor packaging change. Therefore the next portion of the study focused on the OEM service operation, with an inventory model for one OEM service operation created and studied. The analysis calculated the service part inventory level increase and cost increase that would result from the BGA SKU increase.

The analysis shows that SKU proliferation effects are extreme for a full BGA transition, and service inventory levels nearly double even with an implementation of more limited scope. The industry has long used well-documented supply chain techniques such as postponement and part commonality to provide highly customized products with reduced inventories (Chopra and Meindl 2004). The BGA transition effects would not only erode already thin margins, but also they would lower the amount of postponement and commonality possible in the supply chain. The analysis predicts that this either a) would not be accepted by industry players because they would continue with PGA designs or would switch to competing PGA products, or b) would force undesirable (by some players at least) structural changes in the industry supply chain, product offering, and service models.

This thesis presents a unique approach to studying SKU proliferation problems that can result from supplier choices in an industry. It also provides current information on the general state of supply chains in the notebook computer industry. Finally, simple models and approaches are provided that can help Intel and others make decisions regarding product roadmap strategies.

The remainder of this thesis is organized as follows: Chapter 2 will review applicable Intel corporate background including a discussion of their mobile product roadmap. Chapter 3 will provide a current state overview of the notebook computer supply chain and manufacturing. Chapter 4 will cover methodology used for the customer interview, SKU proliferation and inventory analysis. Chapter 5 will provide a discussion of the results, and Chapter 6 will present conclusions based on this research.

CHAPTER 2: INTEL CORPORATION BACKGROUND

The purpose of this chapter is to provide more detailed background into Intel's corporate history, supply chain, and mobile product roadmap. Details of the various brands and segmentation are provided as well as information on the product updating approach including the tick-tock cycle. Finally, specific product attributes relevant to this study are discussed in detail, including the packaging options for the processor which include BGA and PGA.

2.1 CORPORATE HISTORY

Intel Corporation was founded in 1968 in Santa Clara, CA by Gordon Moore and Robert Noyce. The company has evolved steadily since its inception, being first a producer of memory products such as SRAM and DRAM, then most notably transitioning in the 1980's into the production of microprocessors for personal computers.[6] With a combination of manufacturing prowess and design excellence, it has developed and maintained a commanding lead in this market. As of early 2009, Intel was reported to have almost 85% market share for mobile products (Shah 2009). Its primary competitor in this market is Advanced Micro Devices, or AMD, which owns most of the remaining market share.

[6] Intel Corporation. (n.d.). Welcome to the Intel Museum Worldwide. Retrieved July 2009, from www.intel.com: http://www.intel.com/museum/corporatetimeline/

2.2 INTEL SUPPLY CHAIN

Intel's process flow for processor products has been well documented in literature and is shown below in Figure 5 in simplified form (Sonnet 2005).

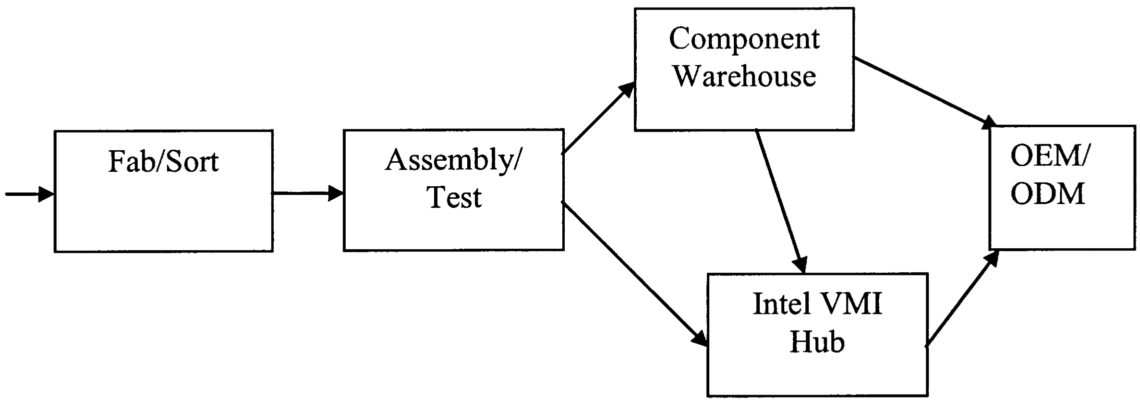


Figure 5: Intel Process Flow

All sites on this process flow map with the exception of the OEM/ODM factories are owned by Intel. Intel operates 15 Fab/Sort factories (Fabs) worldwide, 7 Assembly/Test sites (ATM), and numerous Component Warehouses and Vendor-Managed-Inventory (VMI) hubs that receive finished product and deliver to customers.[7] The Fabs are located in the United States, Europe and the Middle East while the ATM sites are primarily located in Asia. Finally, the Intel warehouse sites are located near customer factories.

OEMs are the value chain players that make the system architecture decisions and system configuration decisions. These include whether to use a PGA socket or BGA

[7] Intel Corporation. (2009). Media Kit - Intel's Worldwide Manufacturing Operations - FAQ. Retrieved June 2009, from www.intel.com: http://www.intel.com/pressroom/kits/manufacturing/manufacturing_qa.htm#1

processor in their designs and how many different Intel processors to offer for a given computer model. These firms are also responsible for marketing, pricing, and distribution strategy for their products. The OEMs design the supply chain and service operations, and in many cases handle all component buying. OEM factories are located worldwide and typically will build finished systems that are shipped to end customers. Some industry-leading OEMs for notebook computers include Hewlett Packard, Dell, and Acer.

The ODMs have primary responsibility for detailed system design, manufacturing, and in many cases distribution of the finished systems (Dedrick and Kraemer 2005). They also produce many of the service parts required including motherboards. ODM factories are mainly located in China. As will be discussed in more detail in the next chapter, the ODM will build partial or full systems in their factories. Major ODMs producing notebook computers include Quanta, Compal, and Wistron.

VMI Hubs have recently been added to the Intel supply network as part of continuous improvement of its supply chain offerings. At these VMI hubs, Intel holds processor inventory for OEM customers and can reduce the replenishment lead time for customer orders from a previous two weeks when supplied from an Intel Component Warehouse to less than one week. The OEM does not get billed for the processor from Intel until this physical shipment occurs.

2.3 INTEL PRODUCT ROADMAP

Intel publishes product roadmaps for its current processor offerings in the mobile, desktop, and server markets. Figure 6 and Figure 7 below show the current mobile product roadmaps for Consumer product and for Business product, respectively.[8]

[8] Intel Corporation. (2009). http://download.intel.com/products/roadmap/roadmap.pdf. Retrieved July 2009, from www.intel.com: http://download.intel.com/products/roadmap/roadmap.pdf

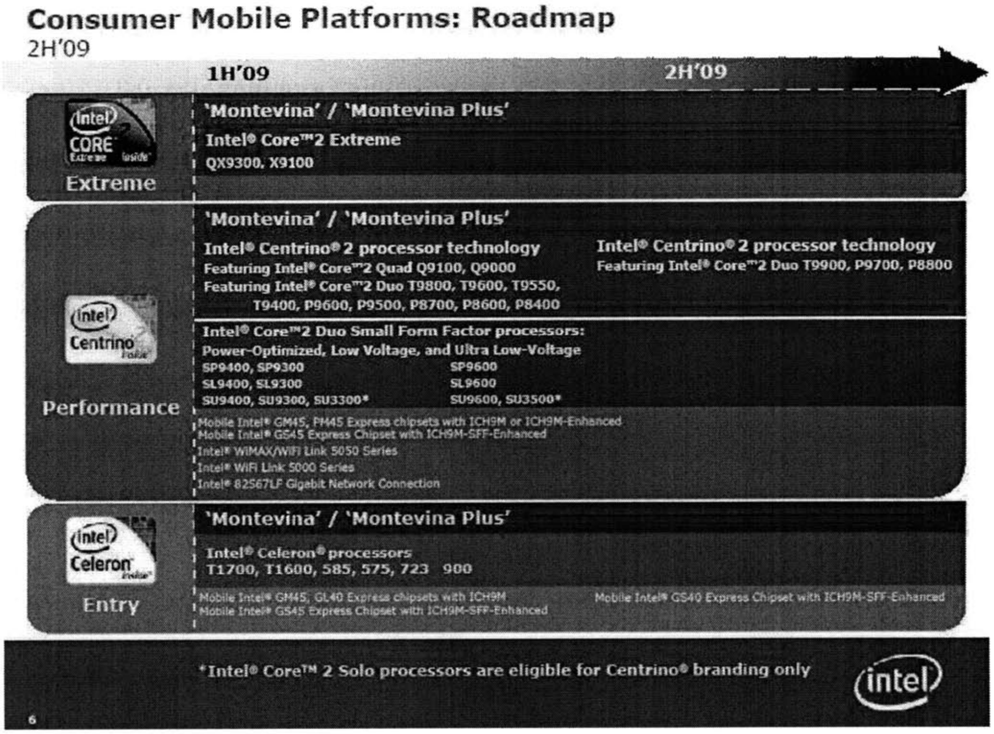


Figure 6: Intel Consumer Product Roadmap

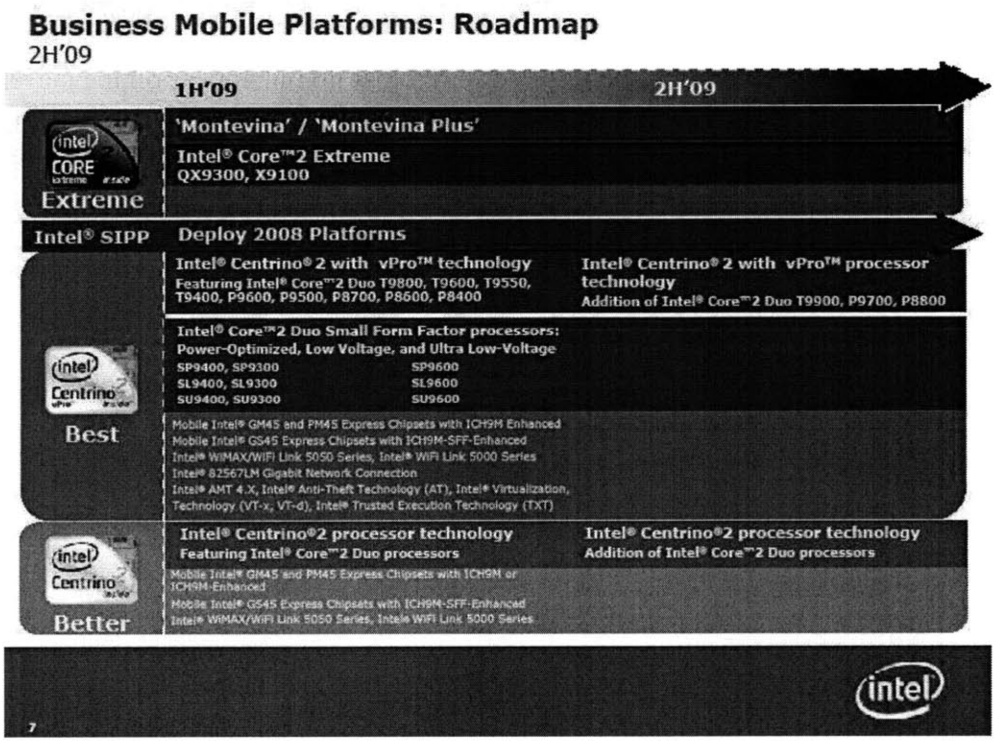


Figure 7: Intel Business Products Roadmap

Multiple performance levels are represented on the product roadmaps, differing between the consumer and business segments. For the Consumer roadmap the performance levels are labeled as Entry, Performance and Extreme. For Business platforms, the levels are called Better, Best and Extreme. In general, the higher levels on the roadmap correspond to higher levels of performance of the platform, typically in the form of processing speeds and data input/output speeds through the system.

Within each performance level there are multiple processor offerings and multiple chipset offerings. Chipset functions include providing system graphics, supporting multimedia devices such as optical drives, controlling input/output between peripherals and the processor, and providing a connection to the system memory. Chipset variations exist for different system form factors, different types of graphics cards (integrated vs. discrete) and other features. The processor is the "brain" of the computer. Intel has several processor brands, including some legacy brands such as Pentium™ that do not appear on the current state roadmap. Table 1 below shows some of these brands with their corresponding labels and also approximately how many processor types are currently available within each brand.[9]

Brand	Pentium™	Celeron™	Core™ 2 Duo
Label			
Number	30	10	36

Table 1: Intel processor brands and part counts

[9] Intel Corporation. (2009). Processors - Intel. Retrieved July 2009, from www.intel.com: http://www.intel.com/products/processor/index.htm

On the product roadmaps (Figures 6 and 7), these processors are identified by retail names, for example T9800.

Within each processor brand there are several attributes that vary between the many processors offered. These attributes include clock frequency, cache memory amount, bus speeds, and other included features, for example business security features. In general, level of pricing within the brand represents relative processing speed and functionality of the offering. Certain processors within the brand correspond to the current product roadmap and therefore represent the latest in Intel technology, however there are many other offerings as well that represent parts and technologies introduced in earlier years. OEMs will build systems using not only the current year's roadmap parts but also older parts.

Intel commonly refreshes its processor offerings throughout the year in conjunction with typical retail cycles. This can be seen on the product roadmap by the addition of several new parts in the second half of 2009. OEMs have advance notice of the upcoming processors and therefore can have system designs ready in advance of the launch to generate short time-to-market and high retail "buzz", keeping product lines fresh in consumers' minds (Beckman, Roemer and Raphel 2005, 22). Note that similar updates occur for business processors as well.

In addition to the update of processor offerings throughout the year, Intel holds closely to a tick-tock new product or new technology introduction cycle with their product offerings. This cycle is highlighted in Figure 8 (Shenoy and Daniel 2006). The "tick" in this model represents a new process technology, such as transitioning from 45nm to 32nm transistors, and the "tock" represents the design of new platform microarchitecture. Both represent upward movement along the performance/price curve for the processor. One tick-tock cycle completes in roughly two years, and because of this there is essentially a new family of Intel products introduced each year, representing either smaller transistors within the same architecture, or new architecture with the same process technology. A recent example is the 2010 introduction of a new Intel product lineup featuring 27 new processors (Murphy 2010). This cadence establishes the rate of change in the entire notebook computer industry as OEMs will offer systems featuring these new products as they are introduced.

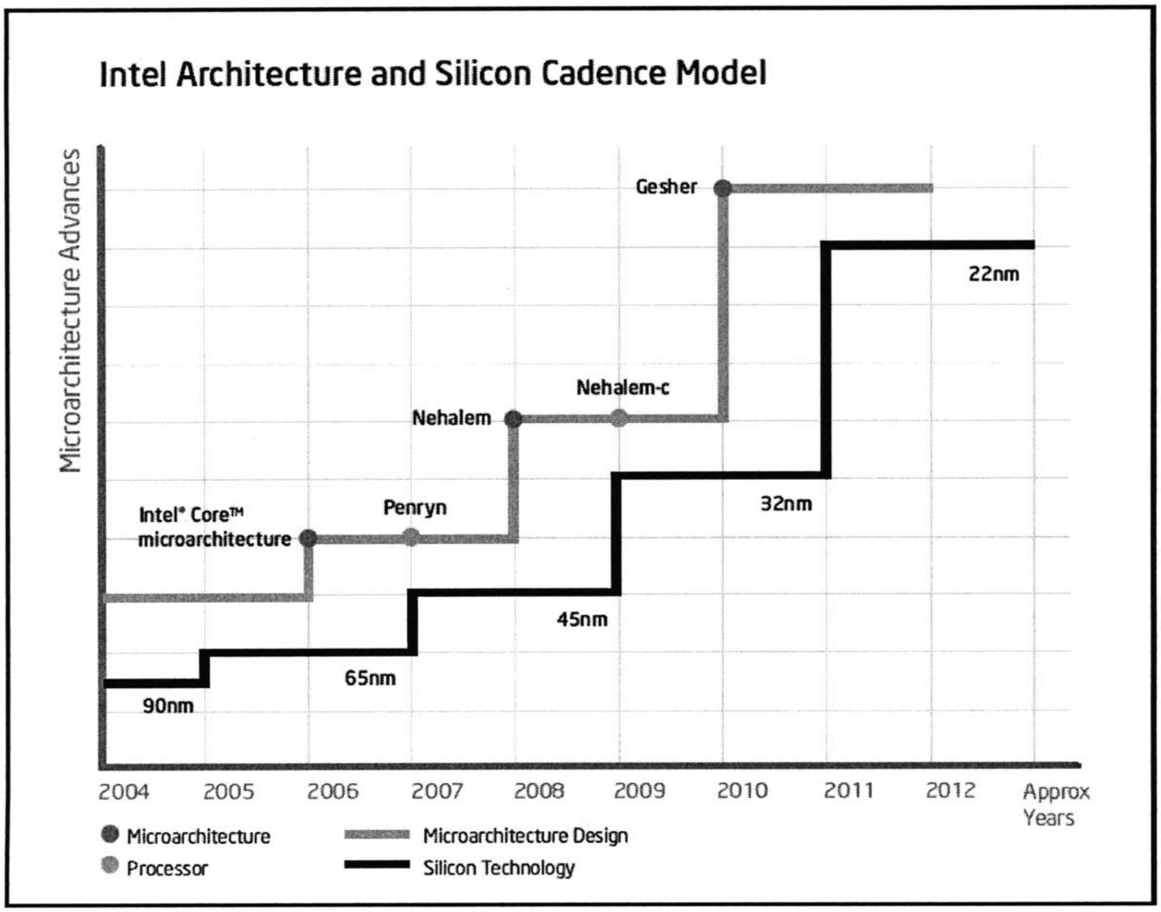


Figure 8: Intel Tick-Tock Cadence Model

Overall, the Intel product roadmap is highly complex. Multiple processor brands, each with high variety, serve most available segments in the portable computing market. The processors are updated with very regular frequency as well, including both intra-year product line refreshes and tick-tock refreshes. Adding to the complexity, Intel delivers this product line to a vast worldwide network of customers representing the majority of the personal computer business.

2.4 PROCESSOR PACKAGING CHOICE

The processor attribute of most interest in this study is the type of packaging. On Intel's mobile roadmap, both BGA and PGA packaging options are offered, although both options are not offered for all parts on the roadmap. These current packaging choices represent the latest evolution for notebook computers; as background a brief history of processor packaging is provided next.

2.5 PACKAGING HISTORY

The first laptop computer designs were produced in the late 1980's and early 1990's. Most of these early systems used the processors available at that time, specifically the Intel® 386™ and Intel® 486™ processors. These processors fit into sockets which were soldered onto the motherboard, as BGA packaging for mobile processors did not exist. Both the processor package and socket were large relative to modern designs, but this was not a concern as notebook computers at this time were quite thick as shown below by the IBM Thinkpad 700 in Figure 9, produced in 1993 (Wilson 2009).

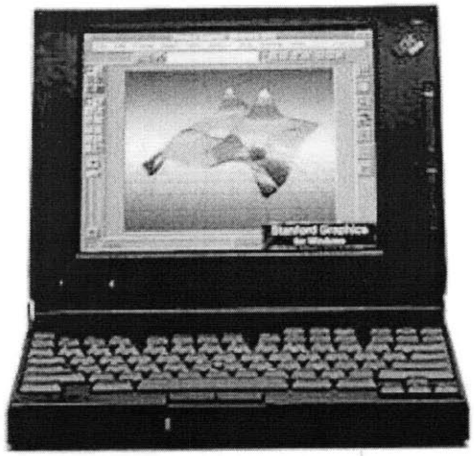


Figure 9: IBM Thinkpad 700

With the introduction of the Intel® Pentium™ processor in 1995, Intel developed a new packaging type called the Mobile Module which was intended to allow manufacturers to quickly configure notebook computer processors to customer orders, as it attached to the motherboard through a proprietary, socket-like connector. The Mobile Module combined the processor with cache memory, system bus, chipset and voltage regulator, and allowed the motherboard design to be simplified due to the amount of complexity moved to the module, reducing system design costs.[10] An example is shown in Figure 10.[11]

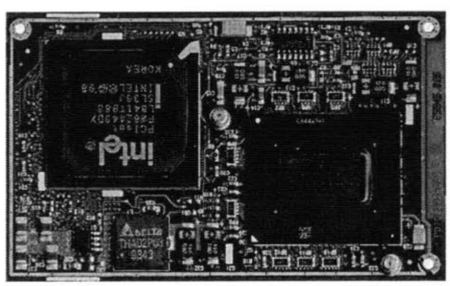


Figure 10: Intel Mobile Module

[10] Intel Corporation. (2000). Intel® Celeron® Processor Mobile Module Connector 2 (MMC-2) at 433 MHz and 466 MHz Datasheet. Retrieved August 2009, from www.intel.com: http://www.intel.com/design/mobile/datashts/243346.htm

[11] Image from http://www.tomshardware.com/reviews/mobile-cpu-mania,263-8.html

Due to the height of the connector between the Mobile Module and the motherboard, thin system designs were not possible. Also, with multiple chips present on the module the inventory cost was very high and flexibility didn't exist for the computer manufacturer to mix and match the component parts on the module (Weyden 2000).

Around the same time that the Mobile Module was introduced, Intel also released another packaging type called the Mini-Cartridge. The Mini-Cartridge moved the cache memory very close to the processor to speed data transfer between the two and enclosed both in a small metal case. The underside view of this cartridge and its connector are shown in Figure 11. This design also provided the ability to swap the processor for other variants.[12] The Mini-Cartridge has a total installed height of 10mm, similar to that of the Mobile Module, and therefore became less desirable for notebook computers as the market continued to demand thinner systems.

Figure 11: Intel Mini Cartridge[13]

[12] Intel Corporation. (1999)." Intel® Packaging Information". Retrieved August 2009, from www.intel.com: http://www.intel.com/design/packtech/packbook.htm

[13] Image from http://www.tomshardware.com/reviews/mobile-cpu-mania,263-8.html

BGA processors were introduced in the late 1990's. From that point to today the primary packaging types available for notebook computer processors have been BGA and PGA. These evolved to become the primary choices due to their lower cost and lower height, with BGA processors having installed heights of <2.5mm and PGA 5mm, and the increased consolidation of components onto the processor which eliminated the need for a separate module. While the mini-cartridge had the cache memory located very close to the processor, newest generation processors have virtually all integrated circuits that were part of the Mobile Module as part of the processor. This is shown on the processor schematic in Figure 12 (Kirsch 2010). Note that this Intel processor design represents the latest packaging evolution, as the PGA socket for this processor will have 989 pins for an increased level of input/output. Both the BGA and PGA packages have gone through several evolutions over the past 20 years.

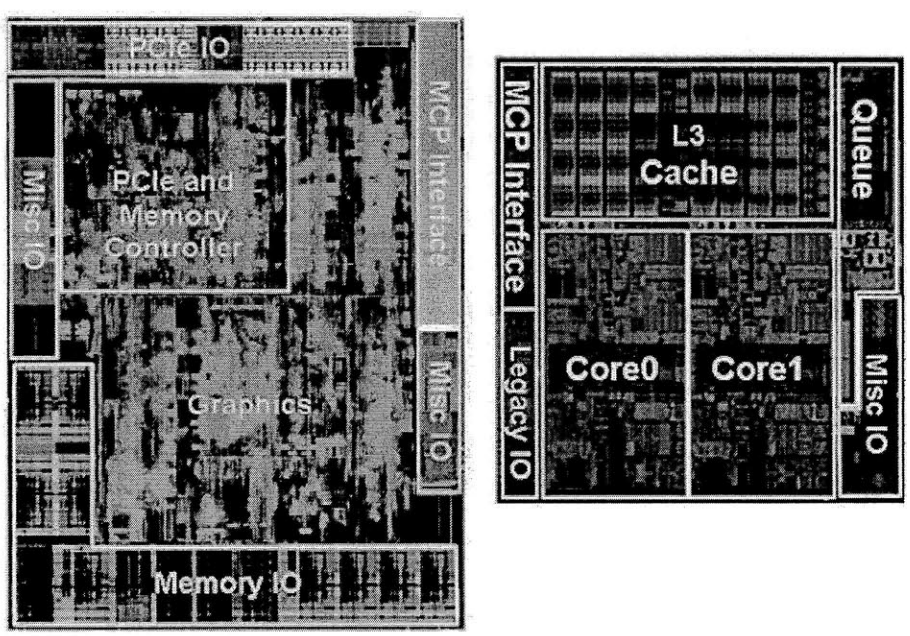


Figure 12: Newest Intel Processor Architecture

2.6 BGA PACKAGING

An example of a ball-grid-array was shown in Figure 1. The current generation BGA processor is manufactured with an array of 495 solder balls that connect the processor to the motherboard and provide the input/output connection to the rest of the system. During the reflow soldering process step at motherboard production, the BGA processor is placed and soldered along with other motherboard components. This is the only place in the computer supply chain where a BGA processor can be installed, as a board cannot be sent through a reflow process a second time for only processor installation.

From a manufacturing process perspective, there are very few issues associated with the pick, place and soldering of a BGA processor. This process technology is well understood and is not a constraint to the production of BGA systems. In fact, many products that Intel offers today are sold exclusively with BGA packaging and the industry supply chain and manufacturing is able to handle these components. These include central processing units (processors), graphics processors, and chipsets. Processors such as Ultra-Low Voltage processors, shown in Figures 6 and 7, and the Intel® Atom® processor which is included in Netbooks are only offered with BGA packaging. The key difference between these categories and the others is that they are offered with very limited choice. For example, there are three Ultra-Low Voltage processors shown in Figure 7 for 2009; in contrast there are twelve different PGA processors in the Best category. As will be demonstrated later in this paper, this expansion of product variety with PGA processors is one of the key difficulties preventing a transition to BGA.

This research and all remaining discussion focuses only on those processors on the Intel roadmap that are predominately sold with PGA packaging, as Intel's desire is to understand constraints against the transition of current PGA designs to BGA. These processors will be referred to as mainstream processors for the remainder of the paper.

2.7 PGA PACKAGING

The pin-grid-array attach method features a series of gold-plated pins on the underside of the processor package as was shown in Figure 2. These pins mate with the socket that is soldered down to the motherboard. The processor is then held in place via cam-actuated connectors that hold the pins to the socket. This design allows for very easy installation and removal of the processor by hand, and therefore much more flexibility during computer manufacturing as the processor can be installed at virtually any point in the supply chain. The PGA processor and socket also allow for *scalable* system design. Many different Intel processors can be installed in the socket, and therefore an OEM can easily expand the same base system to multiple processor performance levels.

The only physical constraint with PGA is the vertical layering of components inside a typical notebook computer; this necessitates that the installation of many other components is delayed until the processor is installed, for example, the keyboard. Based on customer feedback received during this research, the PGA socket and processor are viewed as being error-free parts that are very easy to use in manufacturing.

2.8 SUMMARY

Intel has a complex product roadmap, with several different platform and processor brands, many processor choices within a brand, and fairly rapid turnover of product offerings with updates within a year and tick-tock refreshes on a yearly basis. The recent addition of 27 new processors to the Intel product lineup is the type of change that adds high complexity for notebook computer OEMs, even with a scalable PGA socket in their designs, as they are introducing a large number of new computer models simultaneously. This combination of Intel product complexity with OEM product complexity, as will be discussed in the next chapter, becomes very significant when considering the processor packaging choice between BGA and PGA.

CHAPTER 3: NOTEBOOK COMPUTER INDUSTRY OVERVIEW

This chapter will begin with a general overview of the notebook computer industry and supply chain as it stands today. In particular, the transition to outsourced production in China and to installation of the processor in China is covered in detail as this impacts the supply chain's potential readiness for BGA processors. This discussion will focus specifically on the motherboard and processor configurations offered by leading producers as these are the components of the notebook computer supply chain that are affected by the processor packaging choice. This section will conclude with a discussion of how the OEM makes the motherboard and processor design choice and how that selection is presented to the end customer.

3.1 INDUSTRY OVERVIEW

Figure 13 provides a graphical representation of the notebook computer industry value chain. As shown by the market share numbers in each box, this industry features significant consolidation of volume in a handful of players at each step in the value chain (volume data pulled from various equity analyst reports). Note that keyboard suppliers are included as one additional example of a component supplier, and that suppliers for other components, e.g., hard drives, are similarly consolidated. As has been well documented in the literature, the PC industry has undergone a shift to mostly outsourced production with most of that production volume being handled by large ODMs based in Taiwan (Hirschheim, Heinzl and Dibbern 2009).

This industry has also undergone geographical consolidation as have many other industries in recent history. The ODM manufacturing sites for notebook computers are now almost exclusively in China, continuing the trend that started with the freeing of Taiwanese restrictions about locations in China in 2001 (Yang 2006). Also, the majority of remaining OEM notebook manufacturing is located in China (Dedrick and Kraemer 2005, 11). The only significant difference between ODM and OEM factories is the level of completion on systems they receive and finish. This will be discussed in more detail later in the section.

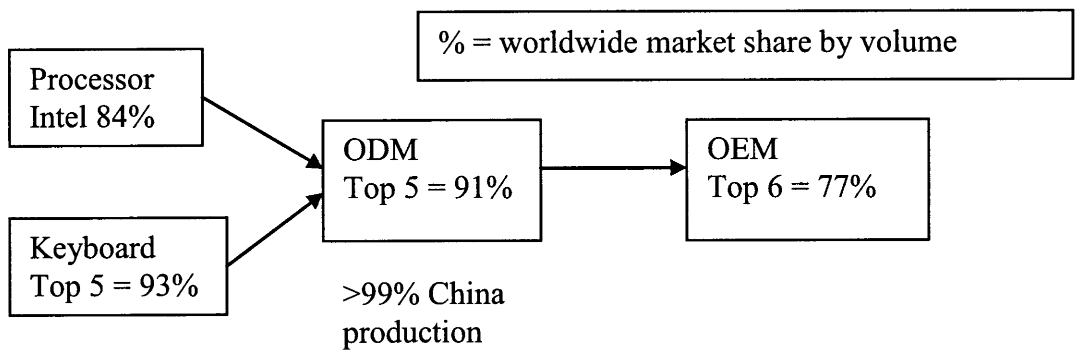


Figure 13: Notebook Computer Industry Process Flow

3.2 GENERAL NOTEBOOK COMPUTER SUPPLY CHAIN

Figure 14 presents a general picture of the supply chain for notebook computers which was constructed based on the multiple interviews conducted during this project. Intel supplies processors to this supply chain through the previously mentioned Assembly/Test factories, Component Warehouses, and VMI Hubs. Other components that make up the computer, for example keyboards and hard disk drives, are also supplied to the ODM and OEM factories.

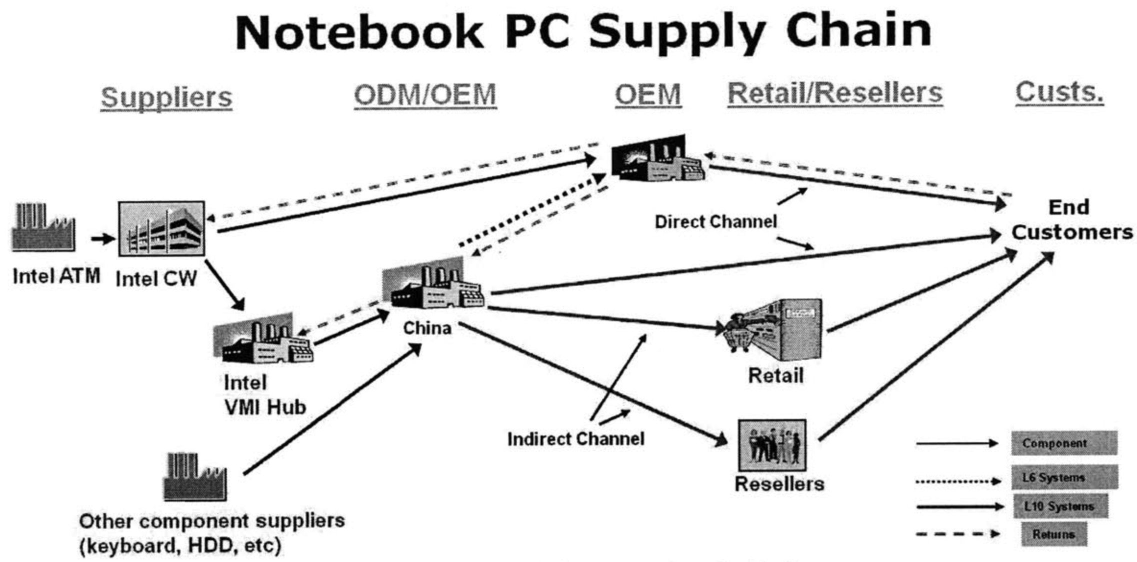


Figure 14: Notebook Computer Supply Chain

Two types of systems are built and shipped in the supply chain as detailed in Figure 15. Level 6 (L6) or "bare bones" systems, consist of the system chassis populated with screen, motherboard, battery, thermal solution (hardware for heat removal), and keyboard. These bare bones systems are typically assembled in China and then shipped to an OEM factory, either in China or another country for customization to a particular customer order. The second type of system produced is Level 10 (L10), or complete systems. As shown in Figure 15, these systems have the processor plus hard disk drive, graphics card, optical disk drive, memory, and software also installed per a particular customer order. L10 systems are finished systems, and as such are generally shipped either directly to end users or to retailers/resellers. These finished systems can be produced in either the ODM or OEM factory. Note that this supply chain description is general and excludes many real life permutations which are not essential to this research; for example, L10 systems could be shipped from China to an OEM location in another country, and then only repackaged with manuals and shipped to the end user, potentially for tax or export benefits.

The large OEMs in this supply chain are multi-national firms. Their factories, service operations, and customers – be they resellers, retail customers, or end customers - are located worldwide. This creates high complexity in the supply chain operations of a given firm. They are also competing in a high clockspeed industry, where product lifecycles are very short, component price declines sharp, and risk of obsolescence high (Fine 1998). Together, these factors create a very challenging supply chain management situation.

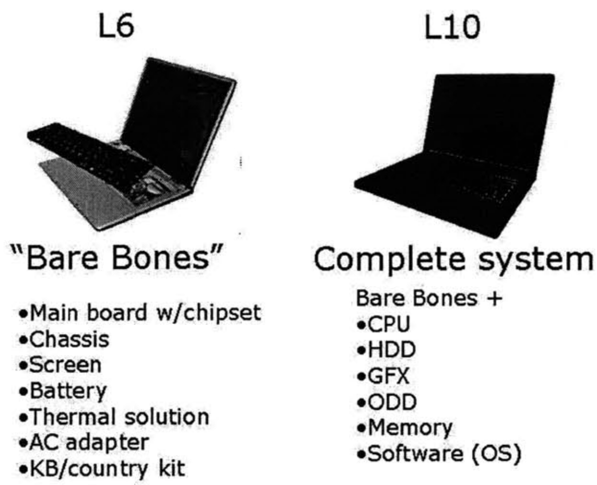
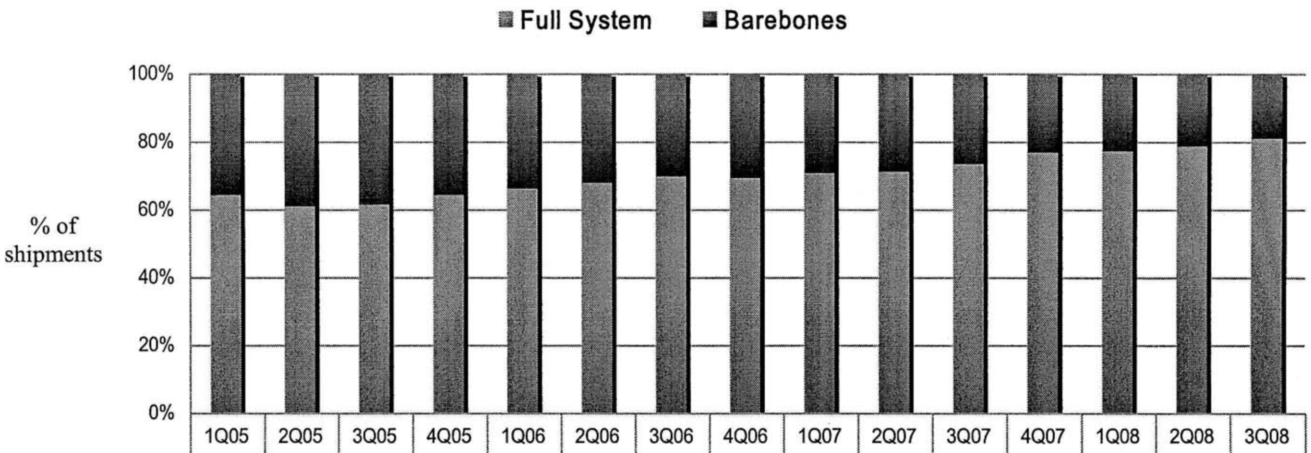


Figure 15: System Manufacturing Levels

Figure 16 provides data on the mix of system designs being shipped from the Chinese factories (IDC 2009). There has been a steady trend toward more complete system shipments from China, with over 80% today being L10. This means that, on average, the processor is being installed in a notebook computer earlier in the value chain today than possibly any time in notebook industry history. This indicates a decrease in use of the postponed customization supply chain model popularized by companies such as HP and Dell (Lee, Billington and Carter 1993). The PGA socket is essential for this postponement model as it allows for processor installation late in the supply chain.

L6 vs. L10 Shipment Breakdown



	1Q05	2Q05	3Q05	4Q05	1Q06	2Q06	3Q06	4Q06	1Q07	2Q07	3Q07	4Q07	1Q08	2Q08	3Q08
Barebones	35.60%	39.20%	38.60%	35.90%	34.10%	32.30%	30.20%	30.80%	29.40%	28.80%	26.70%	23.20%	22.80%	21.35%	19.30%
Full System	64.40%	60.80%	61.40%	64.10%	65.90%	67.70%	69.80%	69.20%	70.60%	71.20%	73.30%	76.80%	77.20%	78.70%	80.70%

Figure 16: Breakdown of Notebook Shipments from China

In contrast to desktop computers, the notebook computer end user rarely opens the system case during its lifetime to upgrade the processor. This occurs for a variety of reasons, most significantly that notebook internal designs are not standardized to the same level as desktop designs and therefore case opening may be difficult and the processor may not be accessible without significant system disassembly. This means that the processor, once installed in China, remains in place in the chassis for the entire system life unless a failure or other need for service occurs. This observation coupled with the earlier installation of the processor in the supply chain influenced the Intel team to believe that the PGA socket was not required to the same extent as it had been previously. Put simply, if you are making the processor choice in the Chinese factory and not changing it, then why not use BGA?

System return flows are indicated on the supply chain diagram in Figure 14. If the customer has a system issue they will return the computer to an OEM service depot (or 3rd party service provider). The service depot will conduct the repairs from an inventory of service parts. The motherboard service parts are supplied by the ODM and are typically produced in large batches at the start of system production. The OEM will purchase processors and distribute them to these service locations.

Based on customer interview feedback, the motherboard is one of the most common assemblies to fail in a notebook computer. With a PGA motherboard, when the system is returned to the service depot the processor can easily be removed and placed into the socket on a new motherboard. In this way, only motherboards need to be stocked in the service inventory along with a limited supply of processors. When a BGA motherboard fails, the motherboard and processor must both be replaced due to the solder connection. This motherboard + soldered processor service part is also supplied from the ODM factory in China. It should be noted that these service operations involve the only significant exception to the trend noted above that notebook computer cases are not opened post-manufacturing and processors are not changed on a motherboard. Based on feedback from our customer interviews, approximately 2% of systems end up in service for motherboard and processor issues.

The service operations are designed to provide rapid service in all geographies serviced by the OEM, with typical turn-around times of less than three days. This results in a large number of service depots that must be stocked. For example, one OEM indicated during our research that they have worldwide service locations in 60 countries.

3.3 OEM SYSTEM DESIGN CONSIDERATIONS

This paper focuses on only two design attributes of a notebook computer, the motherboard and processor, as these are the two components affected by the processor packaging choice. In general, the motherboard design for a notebook computer is unique for each system model as these models are generally targeted for specific segments, such as business or consumer, and specific performance levels. The motherboard design will reflect these specifications and must fit into the computer chassis. Additionally, the OEM makes other choices when designing the motherboard depending on its business strategy. For example, one motherboard may be designed for use across multiple systems in order to increase part commonality. The OEM may also choose to use the same board design for both PGA and BGA processors or may alter these designs. These motherboard design choices and the accompanying decision to use BGA or PGA processors are made early in the system design process.

For a typical system model and form factor, the OEM will offer several different choices of processor. In most cases, when these multiple processors are offered on a system they will all work with the same motherboard (also the same processor will work with multiple motherboards). The OEMs choose the number and types of processors to offer for a given system, spanning a range of processor performance levels. For systems sold through a direct channel (Figure 14), these choices are available to the consumer through internet selection or options presented during a sales call. An example of such a selection screen is included in Figure 17.

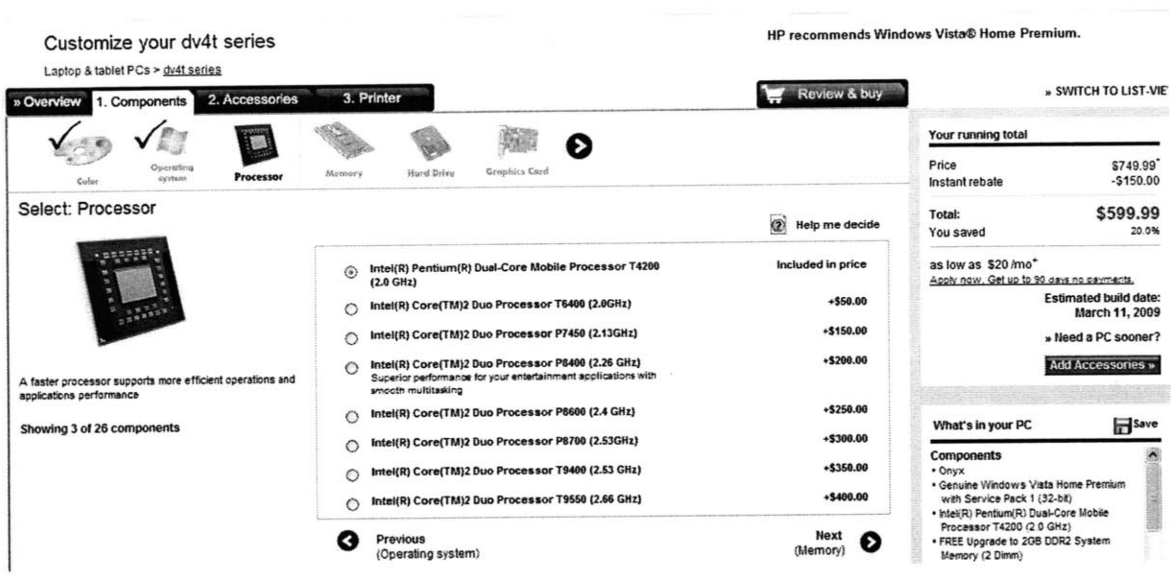


Figure 17: Processor Selection Screen[14]

Some of the processors offered on this type of selection screen might have much higher performance or much lower performance than the rest of the components that make up the base system. The OEM will offer these easy upgrades to the higher performing processors in order to potentially capture extra margin on the system. It seems reasonable to assume that the lower performance processors are offered for value-oriented consumers.

For systems sold through the indirect channel (Figure 14) the OEM makes the decision regarding which system configurations to build, as these systems are built in advance of customer purchases to retailer/reseller forecasts. After manufacturing, these configurations are then shipped to fill the various indirect sales channels, including distributors and retailers.

[14] www.hp.com

3.4 ODM MANUFACTURING OVERVIEW

Data on the current state for ODM manufacturing of notebook computers was collected during face-to-face interviews conducted at the Taiwanese headquarters of four leading firms. The feedback received from the interviews was compiled into a typical view of how notebook computers are produced in ODM factories. As mentioned earlier, the focus continues almost exclusively on the flow of the motherboard and Intel processor through the ODM operation.

3.4.1 PGA SYSTEM MANUFACTURING

Figure 18 shows the manufacturing flow for a typical PGA attach notebook computer. Motherboard components are delivered from various suppliers with an approximate two-week lead time. Processors are delivered from Intel VMI or CW sites and between 1 day and 2 weeks of these parts are held in inventory upstream of final assembly. (Triangles indicate this inventory and others held by the ODM on the diagram)

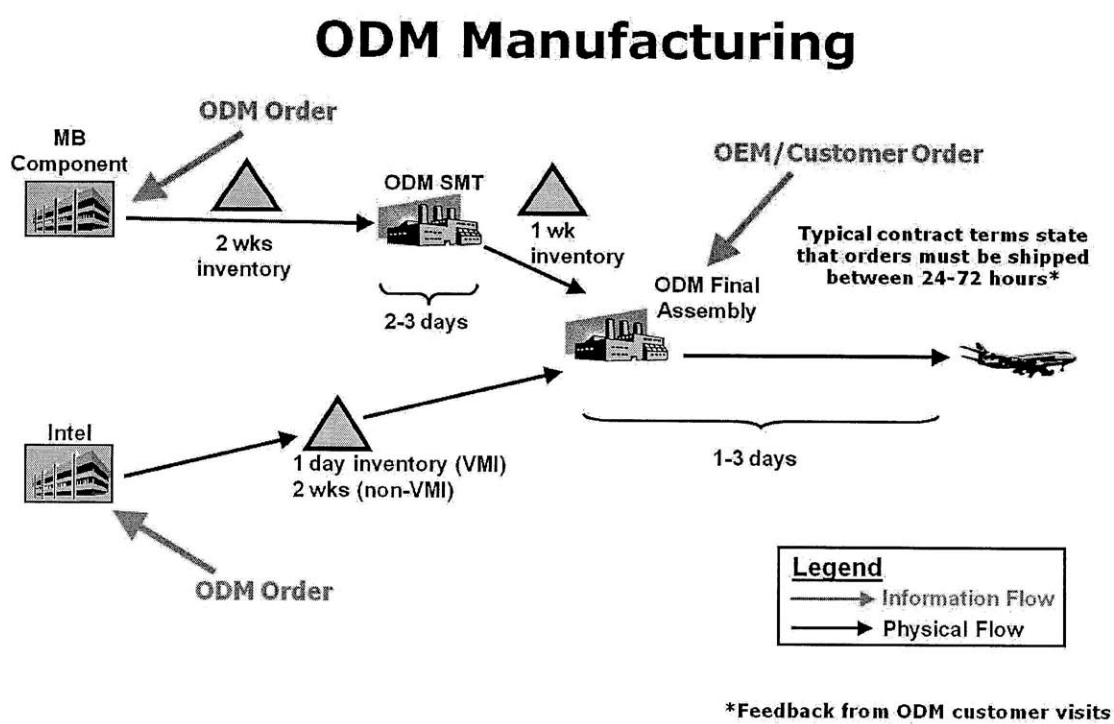


Figure 18: Typical ODM manufacturing process flow

SMT and Final Assembly are done by the ODM. SMT, where the motherboard subassembly is produced, is typically located relatively close to the final assembly line for the notebook computer. The throughput time for SMT varied in our interviews from 2–3 days, including queue time. Next, approximately 1 week of finished motherboard inventory is held downstream of SMT.

The finished motherboard inventory is necessary because typical OEM contract terms specify that finished computers must be shipped within 24-72 hours of an order being received. This configure-to-order (CTO) production model, indicated on Figure 18 by the customer order entering at final assembly, occurs regardless of whether the system is being produced for the direct channel or indirect channel. Therefore, final assembly operates in pull fashion, with necessary processor and motherboard parts being pulled from the upstream inventories, and SMT operates in push fashion with motherboards being built to a forecast. This locates the push-pull interface at the beginning of final assembly. ODMs are producing motherboards based on a forecast with a roughly one-two week horizon, and this forecast is developed with input from their OEM customers. The benefit of Intel VMI hubs for production can be seen here, as previously the same type of push procurement of processors had to take place with two weeks lead time and the resulting two week inventory of processors had very high value in the ODM factory (typically owned by the OEM at that point); with VMI hubs that lead time can be reduced to one day, moving the processor flow to almost a pull model.

During final assembly processors are placed into the motherboard socket for PGA attach. The systems are then typically air-shipped to their next destinations, be it an end-user's home or a retail store/distribution warehouse. Sea shipment is also used but from our interviews seemed to represent the minority method of transport.

3.4.2 BGA SYSTEM MANUFACTURING

For a BGA system the processor flow is routed to SMT rather than to final assembly. The contrast between the BGA and PGA process is shown in Figure 19. For simplicity the flow of only one processor is represented. The motherboard with the BGA processor soldered in place is the only input to final assembly in this case.

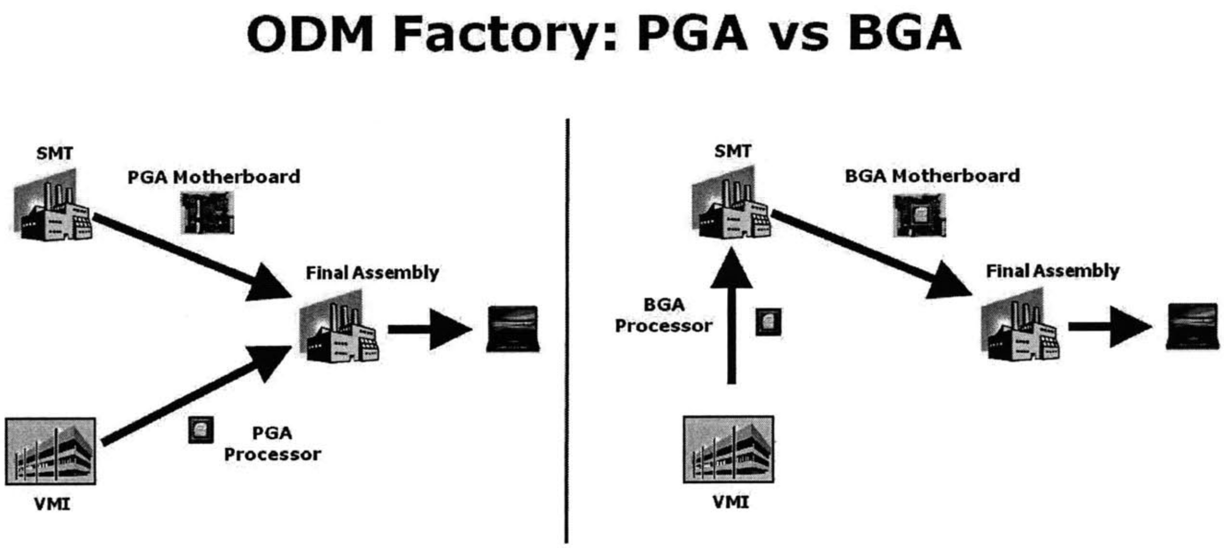


Figure 19: PGA vs. BGA Manufacturing Flow Comparison

3.5 MARKET SITUATION

Due to system price point decline, margins in the notebook computer industry continue to erode even in the face of strong cost cutting measures by most of the industry players. The system price point drops are driven by high competition, new market segments (i.e., Netbooks), and the increasingly commoditized nature of the product (Sacconaghi, Garfunkel and Yin 2008). Figure 20 shows that ODM gross margins have steadily declined this decade to between 4-5% (Compal Electronics, Inc. 2009, Quanta Computer 2007, Wistron Corporation 2009). Additionally, the major OEMs will typically contract with multiple ODMs for their manufacturing needs and will utilize the resulting competition to further drive down costs or revenues to the ODMs (Law 2009). Even given this, industry players such as Dell and Lenovo have not been able to stave off margin erosion in their PC businesses as shown in Figure 21 (Sacconaghi, Garfunkel and Yin 2008). Overall, industry players continue to look for ways to cut costs or move into higher margin businesses. OEMs are continuing a move toward outsourcing non-core competencies to reduce fixed costs including moving more system design work to the Taiwanese ODMs and outsourcing service operations (James 2004, Dedrick and Kraemer 2005). ODMs are becoming more vertically integrated, incorporating production of components such as LCDs into their operations in an effort to boost margins (Jung and Hsu 2009). In this environment, BGA processor savings of $1-5 per system from not having to purchase a socket represent a material way to increase gross margin performance. This benefit presumably would be split between the ODM and OEM but given the competitive environment it is likely that the OEM would receive the majority of the benefit.

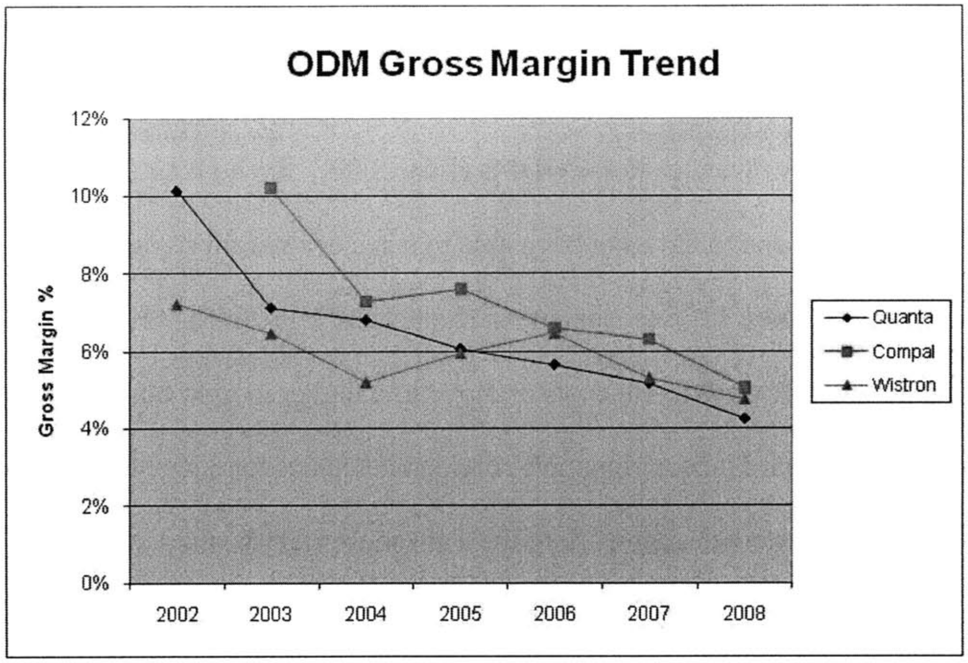


Figure 20: Gross margin performance of leading ODMs

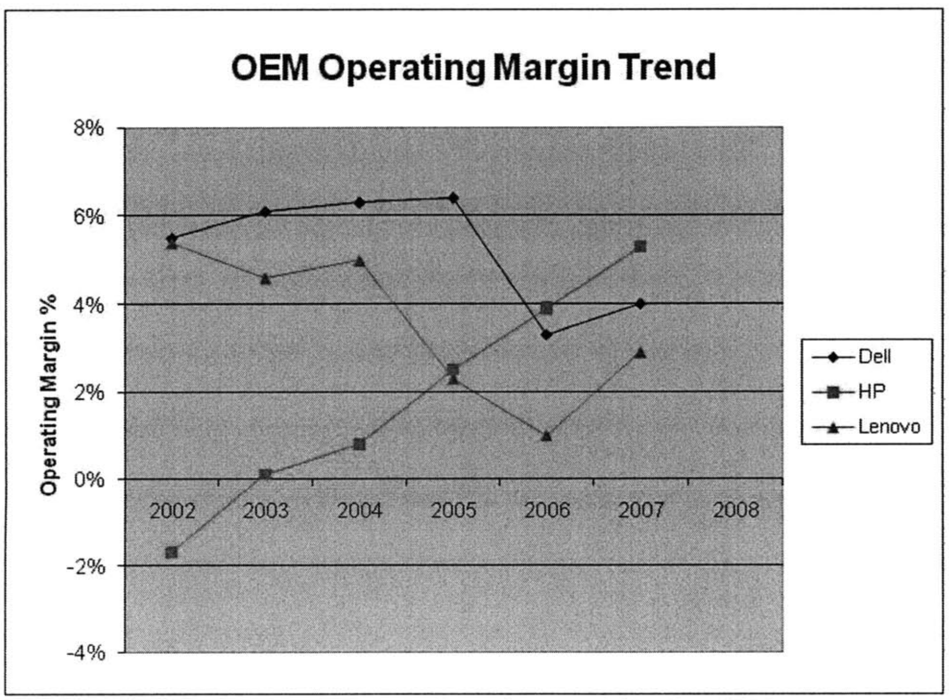


Figure 21: Operating margin performance of leading OEMs

(Dell – PC Hardware Margin, HP – Personal Systems Group Margin)

3.6 SUMMARY

The notebook computer industry has seen many shifts over the past several years. These include a consolidation of players at most points in the supply chain, a shift to outsourced production in China, a decrease in the level of supply chain postponement, and continued erosion of margins. The supply chain of the typical manufacturer is very complex with high product variety being distributed to many different countries through multiple distribution channels. Service requirements are stringent and add to the operational complexity. Overall, the industry presents many challenges, not least of which is efficient supply chain function. This situation will be reviewed again after the impacts of BGA packaging on the supply chain is considered, which is the subject of the next chapter.

CHAPTER 4: DETAILED ANALYSIS APPROACH

In order to better understand the impacts of a BGA transition on the notebook computer industry supply chain, a three-stage analysis was used with each stage increasingly focused on the area deemed most critical. First, interviews were conducted with four notebook computer OEMs and three ODMs. Feedback from these interviews strongly pointed to SKU proliferation, supply chain management, and service part management as the primary barriers to designing more systems with BGA attach. Based on this result, cataloging and analyzing of current OEM notebook system configurations, specifically combinations of motherboards and processors, was conducted. This analysis showed that SKU proliferation effects were very high in the factory setting but even more extreme in the OEM/ODM service operations. Therefore, the final stage of the analysis then focused in on the service operations, comprising a focused case study of the inventory impacts of a partial BGA transition on one OEM's service part inventory levels. This chapter provides details on the methodology used for each analysis step.

4.1 CUSTOMER INTERVIEWS

"*Inventory management outweighs all*" - quote from customer visit

Seven Intel customers were visited during the course of this research in order to gain first-hand feedback on reasons for slow BGA adoption. Four of the customers were multinational OEMs and the remaining three were Taiwanese ODMs.

Standardization was attempted as much as possible for the customer interviewing. Distinct sets of questions were developed for the OEM interviews and the ODM interviews.

The interviews were conducted as working meetings, with multiple Intel representatives and customer representatives in the room. Functions represented typically included system design, procurement, manufacturing, and service. A standard set of questions (Appendix A) was asked in each interview and answers received were clarified, if necessary, to ensure that any information obtained was consistently described and/or measured across companies. Overall, seven interview data sets were collected.

Based on the limited number of companies visited of each type, quantitative analysis was not performed on the interview results. However, the results were utilized in other ways. First, the feedback from the interviews allowed for construction of the generalized supply chain diagrams for the industry that were presented in the last chapter. Next, there were several consistent themes that emerged from the interviews. These themes include key industry dynamics that help explain the actions of the industry players with regard to BGA notebook designs. One other consistent feature from all interviews was the mention of four levers that could be used by Intel to incentivize greater use of BGA designs. These were incorporated in the options explored later in the paper. Finally, the feedback received provided a very clear focus area for the remainder of the research.

The consistent messages that emerged from the customer interviews can be summarized by three points:

1) Intel actions, such as intra-year and yearly modifications to part offerings and additional roadmap segmentation, lead to high SKU counts in the industry.
2) Supply chain complexity in the industry is very high. Product life cycles are short, on the order of 3-6 months, especially in retail. The industry supply chain is long with 16-24 weeks of estimated inventory (especially with outsourcing to

China), and systems have to be designed, manufactured and distributed to many countries. Demand forecasting in this environment was raised as a major concern by the OEMs.

3) Service complexity in the industry is very high. For corporate customers, system warranties of 3 years are common and often extend to 5 years, and promised turn-around times are on the order of 3 days or less. For these repairs, because of standardized corporate support models, the motherboard and/or processor cannot be upgraded to a newer version if a service part is not available. Therefore, large inventories of motherboards several years old must be stocked in the OEM service depots to ensure high levels of customer service and part availability.

In addition to the common themes listed above, there are also two industry dynamics that were mentioned in all interviews that help explain the OEM system design choice. The first dynamic is that Intel roadmap segmentation and product offerings drive the need for OEMs to have a scalable, PGA socket in their systems. This effect is illustrated by the feedback loop below:

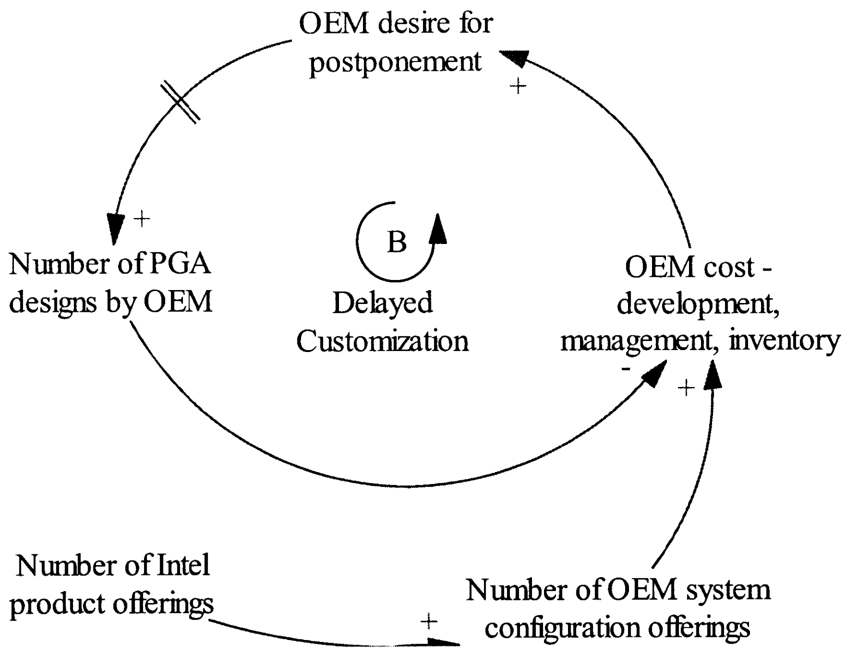


Figure 22: Postponement feedback loop

Intel adds product offerings in response to competition and market needs. During the OEM interviews, we were consistently told that as Intel adds these processors, the OEM must add system configurations with those processors as well in order to match their competitors. These additional system configurations increase the OEM costs in the form of incremental SKU management costs and incremental inventory costs. As inventory-related costs begin to rise for systems, the OEM desire for postponement increases in order to control inventory costs and still offer customers a broad selection. After a delay for the next generation of systems and motherboards to be designed and introduced, an increase in the number of PGA designs offered by the OEM is seen, as PGA and its scalable socket allows for processor customization at the last possible moment in final assembly. This increase in postponement then reduces the inventory cost and SKU management cost, creating a balancing feedback loop to the Intel roadmap action. A second feedback loop relates to the commonality of motherboard designs for systems. This is shown in Figure 23.

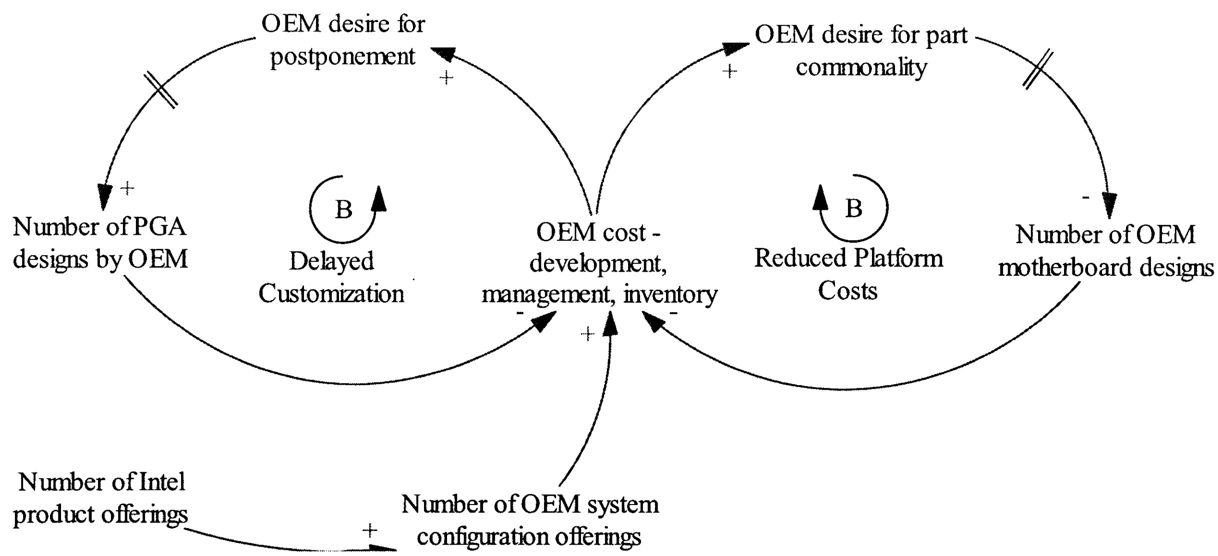


Figure 23: Complete OEM feedback loops

Again, as the number of OEM system configuration offerings increases, OEM development cost and SKU management costs see incremental increase. This increases the OEM desire for part commonality, which is a common response to issues of SKU proliferation in a supply chain. After some time delay, again for the development of the new generation of system designs, they then reduce the number of motherboard designs that they have, utilizing the same design across multiple system models and form factors. They also utilize the same motherboard design to mate with a wider performance variety of processors, leveraging the scalability of the PGA socket. For example, where previously an OEM may have had a low-cost motherboard design that mated with a low-powered processor and a high-cost motherboard design that mated with a high-powered processor, they may decide that the incremental revenue or cost savings from such a strategy is outweighed by the development and support costs of the different board designs. These leads to design consolidation and use of the same motherboard with the entire processor range, reducing design and inventory costs and creating a balancing feedback loop. Overall, this basic analysis of key industry dynamics developed from the customer interviews highlights forces that push OEM customers away from BGA system designs.

During the course of the customer interviews there were four enabling levers that were consistently mentioned as ways to incentivize greater numbers of BGA designs. These levers included:

1) Reducing Intel roadmap segmentation (number of performance levels)
2) Reducing the number of refresh cycles for Intel parts (yearly and intra-year)
3) Offering more processors in both PGA and BGA packages so OEM has choice
4) Reducing cost of BGA processors

The effect of levers #1 and #2 were highlighted by the feedback loops already presented. By lowering the number of processors offered and/or reducing the rate of change for those processors, Intel gives the OEM the chance to support less variety and therefore the chance to potentially offer more BGA designs, gaining the cost and form-factor benefits of BGA without taking an excessive inventory or other cost impact. As with most of the discussion in this section, business trade-offs exist for Intel and the OEM that must be considered and the situation is potentially unique for each OEM. By lowering the number of processor offerings, both Intel and the OEMs could potentially see incremental drops in revenue that are not fully recovered by sales shifts to other processors, for example due to lower selling prices on the remaining parts. These drops could exceed any cost savings from the program and this would obviously be considered as such a change was contemplated.

In summary, the feedback loops developed from customer interviews indicated that reduction of product line complexity costs is the primary driver for PGA, or against BGA, system designs. This complexity is most apparent in the factory and service operations.

Therefore, the remainder of this research focuses on improving understanding of the effects of various BGA strategies on these segments of the supply chain. Levers #3 and #4 above, offering more BGA-package products and lowering the cost of those products, are not explored further as they fall outside the realm of the supply chain study.

4.2 OEM OFFERINGS ANALYSIS

One of the most common refrains heard during the customer interviews was that in order for a system to be a viable candidate for BGA it had to have at most 2-3 processor choices, as this level would balance SKU and inventory impacts with incremental revenue from offering the consumer additional choice. The goal of the next section of the research was to verify this type of statement and others about significant negative BGA impacts on supply chain complexity through modeling and quantification of the SKU proliferation impacts of a BGA transition. This study accomplishes that by quantifying how many unique processors are mated with each unique OEM motherboard, as this is the critical sub-assembly unit affected by the packaging change.

As illustrated in Figure 19, after the packaging transition, processor attach to the system motherboard occurs during the surface mount process rather than during final assembly. Figure 24 expands this view by including the typical number of processors that are offered on a system. The number of processors matched with each motherboard reflects the number of unique sub-assembly SKUs that must be produced at the SMT process step in a pure-BGA world. As such, it is a primary result reflecting the effects of such a transition.

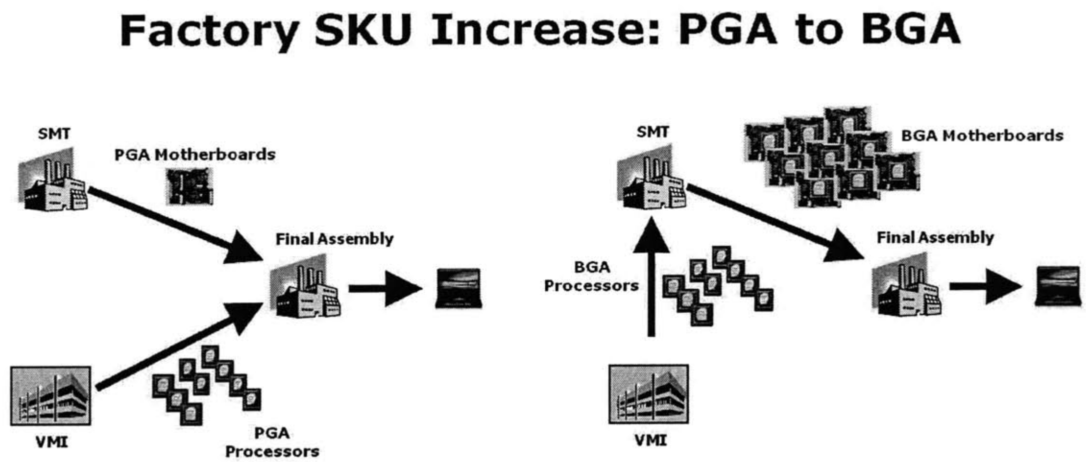


Figure 24: BGA Factory SKU increase

This SKU increase value is utilized as a proxy for supply chain complexity and supply chain cost in this study. The use of SKU or component part count as a measure of supply chain complexity and cost is developed from a review of the applicable literature. Fisher et al. (1999) presents an excellent literature review and describes how increasing part commonality decreases cost in the manufacturing environment. C.C. Bozarth et al. (2009) break down drivers of complexity into detail complexity, for example the number of parts in use in the manufacturing environment, and dynamic complexity, for example demand variability. Their findings from an empirical study show that increases in these complexity measures do have a negative impact on supply chain performance and that while an increase in the number of parts by itself is not a significant driver, the resulting increase in demand variability resulting from disaggregation of demand is a major cost driver. Huang et al. (2005) utilize data from a notebook computer manufacturer to test their model of product platform commonality on optimal supply chain configurations and find that "increased commonality…further improves material availability and reduces system complexity". Finally, Raphel (2005) modeled the costs of complexity resulting from the addition of SKUs to a product line and stated that "while SKU count is not the only driver of organizational performance issues, it is a reasonable proxy for business complexity that resonates with most employees".

With a PGA system design, the manufacturer can install the processor in final assembly only when a firm customer order is received, thereby postponing differentiation of the system (Hoffman 2006). In this case, demand for all systems using a particular motherboard is pooled across the individual motherboard design. For BGA production, each individual combination of processor and motherboard that the OEM offers must be produced for subsequent pull into final assembly. This breaks the total demand into many smaller streams as represented in Figure 24. As previously discussed, regardless of packaging type, motherboards are manufactured at SMT based on an approximate one-week forecast.

Breaking up the demand in this way impacts inventory management in the factory. First, the average inventory level will increase in order to meet the same service level. The inventory level at this point represents a mixture of cycle stock and safety stock, or buffer inventory. As total demand does not change, total cycle stock level, which is intended to serve the demand, also does not change. Safety stock levels, however, increase proportionately with an increase in demand standard deviation (Chopra and Meindl 2004, 303). The demand standard deviation increases because the sum of the individual item standard deviations of demand in the BGA case is higher than the standard deviation of the aggregate, or pooled, demand (Chopra and Meindl 2004, 314). Note that this assumes that the demand for each individual motherboard + processor subassembly is not perfectly positively correlated, with negative correlation being a stronger assumption in this case (Beckman, Roemer and Raphel 2005, 31). Because the cycle stock level does not change, the overall inventory increase is not proportional to the overall SKU increase.

Next, the average value of the inventory increases. The processor is one of the highest value components in a typical notebook computer and on average has a value approximately double that of the system motherboard. Therefore, not only does the inventory held upstream of final assembly increase, but also this inventory has three times greater value on average than if it did not contain soldered-on processors. All together, this disaggregation of motherboard inventory in the ODM factory presents a significant management and financial challenge to the operation. This fact was expressed during the ODM interviews by factory representatives. Note that a similar loss of demand pooling across a motherboard design occurs in the OEM service depot.

Five notebook OEMs are represented in this study in order to quantify the extent of the demand breakup that occurs with a change to BGA processors. Data on the OEM current system configuration offerings was collected through the OEM consumer and commercial English-language websites, and major retail websites such as www.BestBuy.com and www.newegg.com. Data was collected early in Q1 2009 and then periodically checked and updated throughout Q1 and Q2 as OEMs stagger release dates for some system configurations. In order to speed the data collection process, an Excel tool was built that automatically populated a spreadsheet with the relevant processor data based on the processor's retail name. Data such as shipping days, system price, and motherboard design was also pulled to complete the database (complete list of database fields is in Appendix B). All told, 640 unique system configurations were collected in the spreadsheet for analysis.

As this analysis focused on the movement of mainstream Intel processors to BGA designs, it excluded specialized laptop system types and processor types. Specifically, niche systems such as high-end gaming machines or engineering workstations were excluded as they represent a very small percentage of the overall market. Also, processors that serve these high-end markets such as quad-core Intel processors were left out of the study as they also represent limited volume.

The table below shows the final data breakdown by OEM.

Table 2: OEM offerings analysis input data breakdown

OEM	Number of Systems	Number of Motherboards	Number of Processors	Number of Unique Sub-Assembly SKUs
#1	36	8	14	39
#2	114	17	28	106
#3	34	20	26	111
#4	122	7	16	43
#5	53	18	17	79

Number of systems refers to the total number of complete system-level SKUs that were entered into the database, with each of these SKUs representing a finished notebook computer configuration. From an OEM perspective this value is a rough measure of the number of complete system configurations that they are making available to the various sales channels relative to the competition. These system-level SKU configurations vary by many factors, including chassis type & color, motherboard, screen size, memory, hard drive, processor, and software.

Number of motherboards refers to the number of unique motherboard designs present in the complete-system configurations studied. This result was verified during the course of this research and details on the data verification occur later in this section. Number of processors is the total number of unique Intel processors that were present in the complete system configurations studied. Finally, number of unique sub-assembly SKUs captures the previously-mentioned total unique pairings of motherboard and processor that were contained in the complete systems cataloged. This value represents the maximum SKU increase that would result from a transition to all BGA processors. Note that not every processor is offered on every motherboard; one can assume that this would be excessively expensive and would potentially represent too much choice for the consumer. Instead, the data from this study suggests that the OEM determines the processor selection based on the target segment and channel for the computer. For example, high-performance motherboards/systems will typically only be offered with a selection of high-performance processors, and systems offered to the indirect channel will have fewer processor choices than systems sold through the direct channel.

4.2.1 DATASET VERIFICATION

The data collection method for this portion of the study was chosen because Intel's customers will not willingly give up detailed information on their product scalability approaches and sales levels given obvious competitive concerns. Because this detailed visibility was not available for verification, and given that the data collection process took place through searching of almost exclusively English-language web sites, a concern for any subsequent analysis was the possibility of missing system configuration data. Systems could have simply been overlooked during the search or not been visible, particularly those sold outside the US where the OEM has a substantial share of its sales.

In order to increase the confidence that all processor and motherboard combinations offered by an OEM were captured in the database, three approaches were used. First, the prevalence of processor offerings, or sales attempts, by OEM was compared to actual processor sales for that OEM. Next, the identification of unique motherboard designs was tested using internally available expert knowledge and publicly available system information. Finally, the overall results were compared to previously completed Intel studies.

The first step in this process utilized Intel processor billing information from the time period under study. To begin, the data was sorted by segment on the Intel product roadmap for the five OEMs in the study. A generic example is shown below. Note that all values are for demonstration purposes only.

	OEM		
Intel Product Roadmap Segment	#1	#2 …	
Centrino™ 2	25%	40%	Values are % of total OEM billings for the Intel roadmap segment
Pentium™	35%	40%	
Celeron™	40%	20%	

Figure 25: OEM billings by segment example table

Next, the systems offering analysis database was sorted by processor type and OEM, and a similar table was constructed that reflected the percentage of OEM motherboard designs that were offered mated with a processor in a given Intel roadmap segment. Note that the columns do not add to 100% in this case as multiple processors are offered with most motherboards. An example table is shown below.

Intel Product Roadmap Segment	OEM #1	OEM #2 …	
Centrino™ 2	100	80%	Values are % of OEM motherboards designs that are offered with a processor in the Intel segment
Pentium™	50%	50%	
Celeron™	10%	50%	

Figure 26: OEM attempts to sell example table

The first data table represents the Intel sales to an OEM for a given processor segment as a percentage of total sales to the OEM. Roughly speaking, the second table indicates that percentage of times that the OEM attempts to sell a processor in a given segment. For example, OEM #1 above offers a member of the Centrino™ 2 segment as an option on every motherboard included in this study. Centrino™ 2 then represent 25% of their sales as shown in the first table. With this understanding, three scenarios exist when comparing the data between the two tables. First, the processor might be offered frequently but sold very infrequently. This represents a case where end consumer demand doesn't exist for the configuration for some reason, for example because the processor is too powerful, and therefore too expensive, for the remainder of the system components. Second, the processor might be offered infrequently, but sold very frequently. This represents a processor/motherboard combination that is potentially missing from the database and therefore has to be inspected before moving on with the study. Third, both % offered values and % sold values fall within an acceptable range defined by the standard error of the dataset.

Qualitative inspection of the data showed four pairs of points that fit the second condition and therefore represented potential missing data for the analysis. These points prompted further internet searching to attempt verification of that processor being offered by the OEM. One point was resolved in this manner. The remaining three were not, therefore likely represented processors that were only sold by the OEM outside the US. In the subsequent data analysis, existence of these points was simulated in the dataset to understand the impact on the analysis output and this impact was found to be minimal.

Identifying system motherboards and documenting whether or not they are unique is a difficult task with potential for error without having first-hand system design knowledge or ability to actually open the case of the various systems studied. Past Intel studies have relied on the knowledge of field teams, those closest to the customers, to provide this input. The field teams were utilized again along with additional verification steps for this study. The four-step process below was followed:

1. Assume that system configurations with common chassis and screen size share the same motherboard, especially if found with a selection screen such as Figure 17.
2. Utilize publicly available pictures, if necessary, to verify port locations on systems with the assumption that common port locations likely equal common motherboard (when comparing across models).
3. Examine system teardown data (when available) for actual inside-the-chassis looks at the motherboard design.
4. Send these results to the Intel field-teams for verification and update.

The resulting number of unique motherboard designs found in this study using this approach compares well to rough counts obtained from two OEMs, further increasing confidence in the results.

The final step in the database verification was comparison of the results from this classification process to past Intel study results. This step combines the processor information and motherboard information together and therefore provides a third perspective on the dataset validity. The previous Intel study was performed on OEM system designs for the previous generation Intel platform; therefore some differences are expected from the current study. Table 3 shows the comparison between the two studies (Intel MPG Product Marketing Group 2007). The table results are the percentage of motherboards studied that scale, or have low-high processor offerings, between two particular segments, referred to here as a segment band. For confidentiality purposes the segments and segment bands are obscured on this table.

The comparison shows that the current study results compare well with the previous results, given the differences in methodology employed. The previous study utilized field team input to classify unique motherboards and to provide the lower and upper bounds for the processors used. The previous study did not attempt to quantify all processors used between these bounds as the current study did. 23% of the results for the current study fell within segment band 5, which was not a segment band found on the previous study. Segment band 4 is broader than and includes segment band 5. Therefore the possibility exists that processor offerings were missed for segment band 5 systems during data collection and those results actually fall in segment band 4. It is also possible that OEM scalability approaches have changed between the two platforms. In either case, because the gap between the bands represents only one segment the difference in the study results is minimal and therefore not a concern for further analysis.

Table 3: Motherboard scalability study comparison

Scalability	2007 Study	Current Study
Segment Band 1	4%	12%
Segment Band 2	13%	14%
Segment Band 3	17%	21%
Segment Band 4	53%	29%
Segment Band 5		23%

The final, verified dataset does not contain every system offered by the OEMs in this study. Cataloguing every complete system-level SKU offered is a nearly impossible task given the multitude of component, chassis color, and other options that are offered by the leading OEMs, therefore this type of database will always contain a sample, possibly a small sample, of the system-level SKUs produced. However, by focusing on only two components of the finished system and by completing the verification steps outlined above, high confidence exists that the relevant variety for this study, the motherboard and processor variation, is captured. Also, while it is probable that some system motherboards are not present in the data, the motherboards that are included are supplied to the indirect and direct channels, sold to both business and consumer customers, and represent multiple levels of total system price and total system performance. Therefore it is felt that the systems present represent an accurate sampling of the system offerings and system configuration strategies of each OEM.

4.2.2 DATABASE USE

The resulting dataset provided numerous opportunities for analysis of the SKU impacts from a BGA transition. The impact was evaluated at both a factory level and service level. Multiple cases were examined, starting with a full-BGA transition for mainstream processors and then progressing to additional cases such as reduced segmentation on the Intel product roadmap and slower pace of change in product offerings. Finally, statistical comparisons were performed between OEMs to identify potential partners for BGA.

The basic logic employed to understand the SKU change effects of BGA was shown in Figure 24. For a given system utilizing PGA processors, one motherboard SKU would be produced at SMT and multiple Intel processors would be stocked at final assembly for insertion in the system per a customer order. For the system shown there are nine different Intel processor options offered and sold which is typical for the industry. When that system transitions to BGA, as shown on the right side of the figure, the processors must now be supplied to SMT and multiple motherboard + processor SKUs must be produced for installation at final assembly. To quantify the SKU increase resulting from BGA at SMT, the new number of motherboard SKUs plus the number of processors routed to SMT is compared to the original number of input and output parts at the process. Using this methodology, the example system in Figure 24 would have a 18x SKU multiplier for SMT if converted from PGA to BGA. This type of simple accounting of input and output components is extended to final assembly as well. As discussed previously, this SKU increase was chosen as the model output as it provides a reasonable, relative measure for the complexity change of the system transitioning from PGA to BGA.

Similar accounting is used when looking at the OEM service operations; however, in the service case versus the factory case a very important difference is that multiple generations of motherboard SKUs must be stocked in the service depots to meet customer requirements for rapid turnaround and extended warranty periods. Typical turnaround time based on our interviews is two days and warranties span 1-5 years. This means that not only will there be an increase in spare part SKUs (motherboard + processor) stocked for a given time period, similar to the factory case, but also incremental SKUs will be added for subsequent time periods due to the introduction of additional Intel processors (and laptop OEMs selling systems with those processors per the previously mentioned industry dynamics) and the tick-tock cadence of platform and micro-architecture introductions. Processors added to the Intel roadmap throughout the year become incremental subassemblies that must be stocked; for the tick-tock changes, however, the OEM must replace all current processors with their counterparts in the new platform. The resulting situation is depicted in Figure 27. The figure shows the initial service inventory comprising nine boards with soldered processors, three additional service parts from the mid-year refresh of Intel's lineup, and nine new parts with the next year's new platform introduction. In this example the number of unique service parts stocked increases from 2 (one motherboard in initial inventory and one motherboard for the new platform) to 21 for an approximate 11x multiplier.

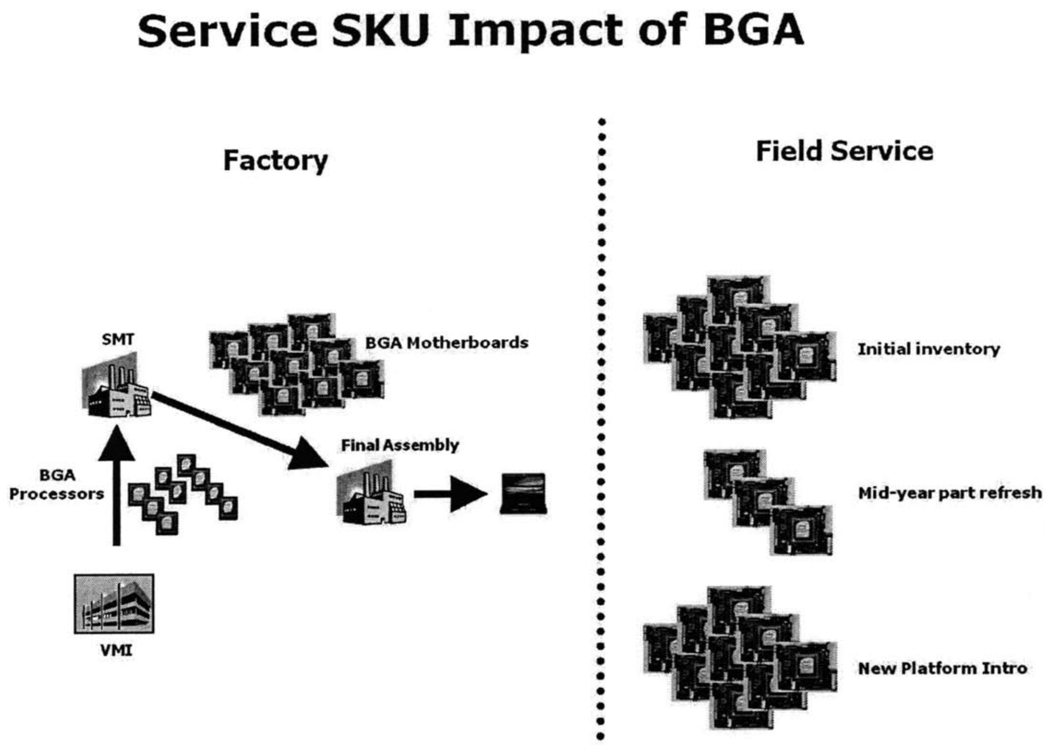


Figure 27: Service SKU increase

Several assumptions were made for the service SKU increase calculation. First, it was assumed that OEMs would actually add additional processors to their system configuration options as Intel released those processors to the market. Next, it was assumed that a platform change would require all current processor offerings for a system to be replaced with corresponding offerings from the new platform and that the total number of processors offered per system would stay constant across tick-tock cycles. Finally, an average warranty period had to be assumed. Given that consumer laptops account for 65% of all shipments in 2008 and that a typical warranty period for consumer laptops is one year and for business laptops three years, a weighted average warranty period of 1.7 years was calculated and used (NPD 2009).

With the assumptions in place, a spreadsheet model was then built that calculated the incremental SKU change for various Intel BGA strategies. To accomplish this, the math in

Figure 24 was tabulated for each OEM motherboard. Figure 28 presents a depiction of this calculation. The matrix in the figure is a map of OEM motherboards (x-axis) included in this study and Intel processor segments (y-axis). High performing, high cost processor segments are at the top of the figure and low performing, low cost at the bottom. Note that the matrix included here is only a depiction of that used in the study for confidentiality reasons. Shaded boxes represent points where a processor in the segment is offered on a particular motherboard and the total count in each column is therefore the number of unique motherboard SKUs that would be produced with BGA. Some motherboards have many processors offered and others have very few, and the processors offered on a motherboard can span the entire performance range, or only the upper, middle or lower segment. Different scenarios were tested using this matrix and the resulting SKU change, both in multiplier and total SKU count, was calculated for each OEM.

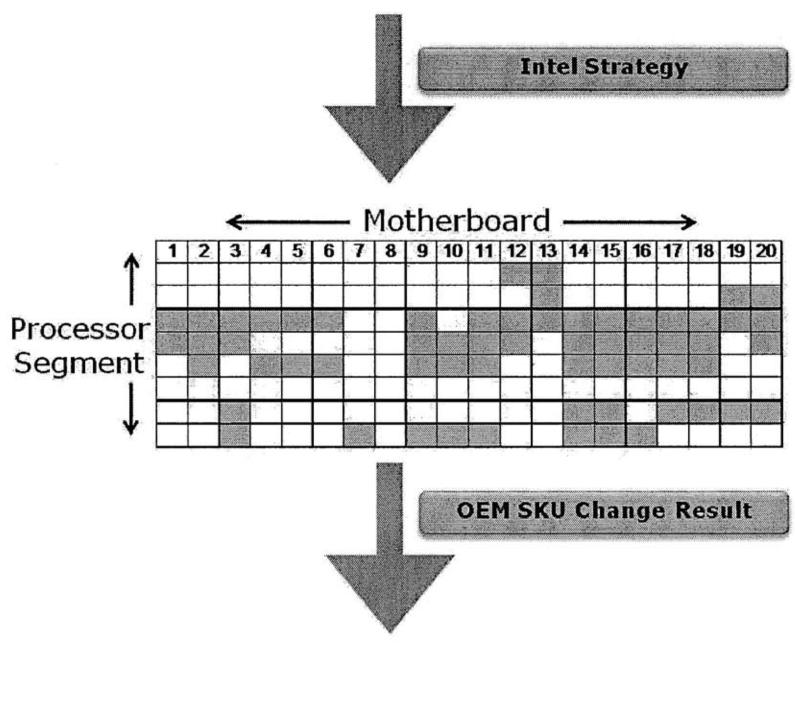


Figure 28: SKU Increase Calculation framework

The output from this spreadsheet model, in addition to quantifying the SKU proliferation impacts of BGA transition strategies, was also used to perform comparisons between the five OEMs in the study. The desire was to identify potential Intel partners and types of systems that would be more amenable to BGA designs. The metrics used for comparison were motherboard leverage, motherboard scalability, and service SKU increase, and these measurements were considered to be indicative of the OEM's particular system design strategy. These metrics were compared for both the full BGA transition case and for the other Intel strategies simulated. Student's t-tests were used to perform the comparisons at a 95% confidence level.

Motherboard leverage is defined here as the total system price range spanned by a particular motherboard design. The individual motherboard ranges were averaged for all motherboards offered by the OEM and were then compared by OEM. This total system price varies not only because of the processor choice, but also because of other component and software choices in the system, for example amount of memory or hard drive capacity. OEMs with a high leverage strategy tend to design their systems to meet the needs of a broader spectrum of end users; for example a motherboard may have leverage of $1000, spanning a $500 entry-level system and a $1500 high-end system. These systems are designed with high motherboard commonality across a wide spread of final configurations in order to offer high variety with lower inventory and design costs, and therefore these OEMs will be less inclined to move toward BGA with the lower commonality it forces.

Motherboard scalability refers to the number of unique processors mated to a particular motherboard. Previous discussion has covered the inventory and SKU increase impacts of this factor. Similar to leverage, scalability was calculated for individual motherboards, then averaged by OEM. Statistical comparisons were then made between OEMs. OEMs with a high scalability strategy tend to design motherboards that can accommodate many Intel processors spanning from entry-level to high-performing, presumably to gain benefit from part commonality. OEMs with a low scalability strategy will construct their motherboards specifically for entry-level and high-level performance. The entry-level motherboard and therefore finished system will have a lower cost befitting that segment, and the high-performance motherboard and system will provide a much more powerful computing experience. OEMs with low scalability are considered better candidates for BGA as they have chosen a design approach with less part commonality.

Finally, service SKU increase was calculated as discussed above and also compared between OEMs. Similar to the previous rationale, as service SKU increase rises, the OEMs desire for BGA from a general strategic perspective should decrease as the inventory and associated management costs should increase as well.

4.3 SERVICE MODELING

Once SKU increase results were obtained and various OEM and Intel strategies evaluated, the next phase in the analysis was building a model of OEM service operations to better understand the inventory impacts of the BGA SKU increase. Service operations became the focus of the inventory analysis for two reasons. First, the SKU increase analysis showed that the SKU proliferation impact of BGA was greatest at the service operations as multiple generations of parts must typically be stocked to meet warranty requirements. Second, performance of service operations is becoming increasingly important in the computer industry. Kumar (2005) discusses how higher margin potential may exist from after-sale operations, as end customers look to minimize total cost of ownership, especially in the business segment. Lee (1990) references how "after sale service" can improve consumer perception of the OEM and drive market share increases. It also discusses "design for serviceability", which are product design changes that enhance serviceability. Finally, Ogg (2008) covers the recent service troubles experienced by Dell Computers, one of the leading laptop OEMs, and how these service troubles have coincided with a drop in market share for Dell. As the impact of BGA attach is primarily negative for service operations, this focused study of the impacts seemed particularly relevant.

One OEM was chosen for the service modeling as a case study. Basic data on the OEM service operation was obtained in the interview with the firm, and general knowledge about industry approaches to providing after-sale service was gained both from Intel sources and through the various customer interviews. Based on this input, the basic model shown in Figure 29 was developed.

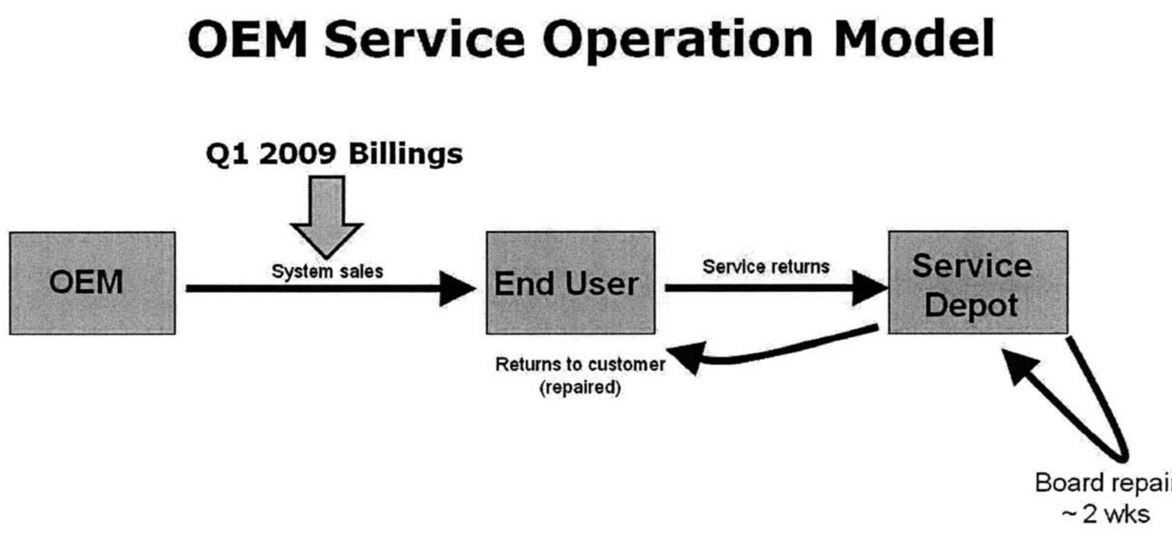


Figure 29: OEM case study service model

As the need was for basic understanding of the BGA effect on inventory levels, the model was kept as simple as possible to speed the calculations and a single inventory location was modeled rather than the actual multi-echelon system that exists in the industry.

OEM laptop sales were measured indirectly by Intel processor sales data, and were assumed to be independent and identically distributed across all systems offered by the OEM and across all geographies that the OEM serves. These sales to end-users were then converted into flows of systems requiring repair back to OEM service depots. Inventory levels, including both cycle stock and safety stock, were calculated for the OEM service operation assuming 95% service level. In this model, which focuses on motherboard and processor inventory, returned motherboards are repaired and cycled back to the service depot's inventory in 2 weeks. This inventory replenishment time is an aggressive estimate of the industry repair time obtained from customer interviews which leads to a conservative estimate of the service inventory requirement. Sensitivity analysis was conducted to verify the critical assumptions.

Damaged system flows into the service depot, shown in Figure 30, were modeled using fairly common failure rate assumptions (Khawam, Hausman and Cheng 2007).

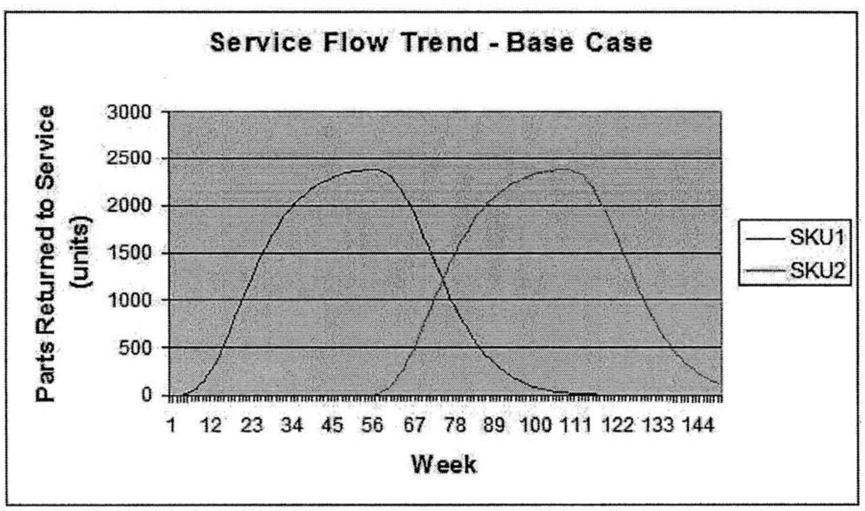


Figure 30: Part failure flows used for service model

After systems are shipped, there is an initial slow increase in the failure rate as systems take some time to get into the hands of end users, either during shipping or sitting on a retail shelf, and end-users typically have lower usage levels at the start with their new systems. As the installed base grows and customers begin to fully utilize their computers, the failure rate rapidly increases as manufacturing and material defects appear. Finally, a rapid drop-off in failures takes place as most latent defects exhaust themselves and shipping of the system configuration stops. There is then a long tail of failures at a low level, representing prolonged system use and wear out failures of components. For this modeling it is assumed that there is no long-term upward swing in failure rates, the other side of the common bathtub curve, as product lifecycles tend to be short in the notebook computer industry, customers will normally replace their systems within 2-3 years, and typical system life exceeds the warranty period. Overall, the model assumes a 2% motherboard failure rate.

Another major assumption required for this analysis was the rate of change of Intel's product roadmap, as the timing and number of parts added is not necessarily consistent between periods. For the service modeling, it was assumed that a new Intel platform is introduced every year per the tick-tock cadence. It was also assumed that over the course of a year, four new parts will be introduced on the roadmap, representing processor speed increases. Finally, the modeling assumed that the BGA transition only occurred on a limited portion of the Intel roadmap represented by the Pentium® and Celeron® brands to simplify calculations.

The final assumption necessary for the inventory modeling was the level of variation present in the product return flows. Obtaining empirical evidence of this variation proved challenging with only limited data being available from Intel's Channel Products Group, which produces desktop system boards for the retail channel. Rather than extrapolate that data to the mobile market, an approach similar to that found in literature was chosen. See and Namkoong (2005) utilize forecast error standard deviation rather than demand standard deviation but they assume a constant error rate for all line items as line item forecasts were not available. Khawam, Hausman and Cheng (2007) assumed that a constant value represented the coefficient of variation (CV) for each individual demand stream under study for a high-volume computer hard drive manufacturer. For this study a constant CV was assumed for all demand streams studied, and sensitivity analysis was performed on this assumption.

4.4 SUMMARY

Three levels of study were completed to answer the primary question of this project: what is the impact of BGA packaging on the notebook computer value chain and what can be done to mitigate the impact? The customer interviews provided the qualitative understanding of the situation, demonstrating that Intel and OEM product design choices lead to SKU proliferation in the industry that is magnified with BGA packaging. The OEM offerings analysis quantified this SKU proliferation for each OEM in the study. Finally, the service operation modeling provided visibility to the actual inventory and cost impacts in the most affected area of the value chain. The output from this modeling is presented next along with study conclusions.

CHAPTER 5: RESULTS AND DISCUSSION

This chapter presents key results obtained from the analysis. For confidentiality reasons the results are generalized in many cases or reported as aggregates. Typical output from the SKU and inventory modeling is presented along with discussion on key outcomes from the analysis. Potential improvements to the models are included as well.

5.1 SKU INCREASE RESULTS - FACTORY

SKU increase results from SMT and final assembly are shown in Table 4.

Table 4: Final output from factory SKU modeling

OEM	SMT Multiplier	Final Assembly Multiplier
#1	6.6	1.8
#2	7.9	2.4
#3	6.9	2.4
#4	8.4	1.9
#5	5.3	2.3

This data shows that with full BGA implementation, the total number of input and output subassemblies at the surface-mount process step increases by 5.3x – 8.4x, depending on OEM. For example, in the current state OEM #1 SMT may produce one motherboard design for a particular system and model. If that same system were fully BGA the SMT process would have approximately 7 input + output subassemblies. At final assembly, the total number of input/output SKUs rises by 1.8x – 2.4x.

5.2 SKU INCREASE RESULTS – SERVICE

Table 5 below includes the service SKU increase results.

Table 5: Final output from service modeling

OEM	SMT Multiplier	Final Assembly Multiplier	Service Multiplier
#1	6.6	1.8	10.9
#2	7.9	2.4	12.4
#3	6.9	2.4	9.8
#4	8.4	1.9	10.6
#5	5.3	2.3	8.7

As discussed previously, due to the need for multi-generational inventory for service parts the SKU increase in service operations is greater than in the factory. Combining the information in table 5 with the number of motherboards per OEM in table 1, we calculate the total number of unique SKUs that would have to be managed at steady state in a service part operation. With a full BGA implementation the increase becomes very large; for example OEM #2 has 30 service part SKUs today and 380 with a full BGA product lineup.

As stated earlier, various BGA transition options were run through the model to evaluate the SKU impact of each and develop a more comprehensive understanding of constraints. The graph below (Figure 31) shows the typical output from this analysis. This approach was used to develop final recommendations that were provided to the Intel team. Options evaluated included alternate product refresh cycles, reduced segmentation of the Intel product roadmap, and partial or phased implementation approaches.

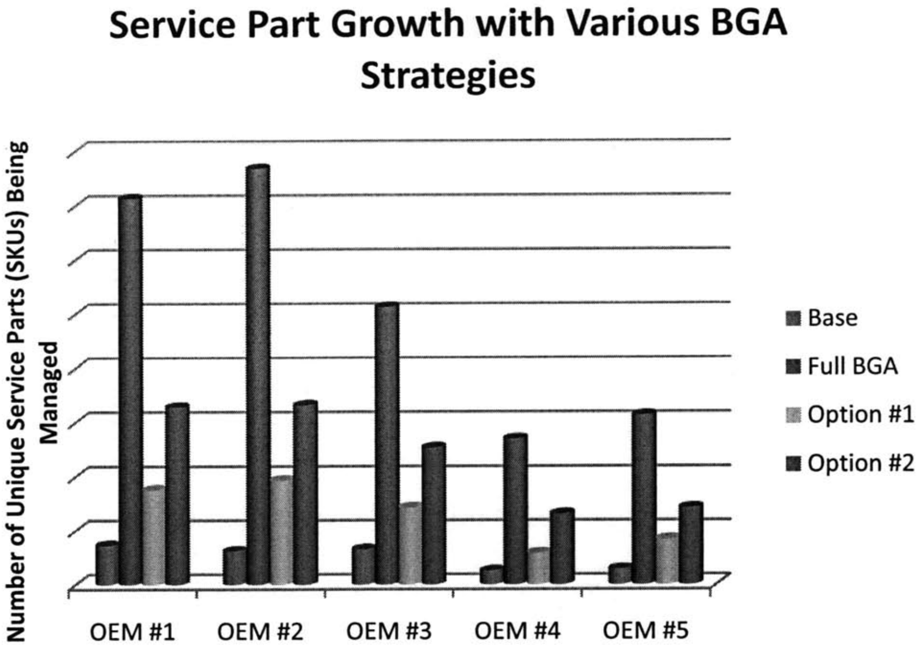


Figure 31: Typical output from SKU increase analysis

5.3 CHANNEL IMPACT ON COMPLEXITY

The database was separated into fixed configuration, or indirect channel systems, and customized configuration, or direct channel systems in order to calculate the complexity impact from each channel. This was undertaken to further Intel's understanding of which channel is driving the complexity and to test possible BGA hypotheses; for example does BGA make more sense for indirect channel systems?

Fixed configuration systems were defined as those that were available within three shipping days when selected on the website, as this implied that the system had already been built to a forecast and was in a distribution center or on a retail shelf awaiting sale. Direct channel systems were defined those that took more than three days to be received. On average, direct systems in the database take 11.5 days to be received after order. With these definitions in hand, the average number of processors offered per motherboard, or motherboard scalability, was calculated for each OEM and channel. Results are shown in Table 6:

Table 6: Channel impact on product complexity

OEM	Indirect Channel Processor/Motherboard	Direct Channel Processor/Motherboard
#1	2.9	4.7
#2	2.9	6.9
#3	1.3	5.5
#4	4.9	4.3
#5	3.2	5
Average	3.0	5.3

Table 6 shows that, on average, OEMs offer 43% fewer processors per motherboard for the indirect channel versus the direct channel. Part of this can be explained by the up-selling potential provided by the direct channel as discussed in Chapter 3, as OEMs do not have to build those finished system configurations when selling direct until they are actually sold. This data supports the hypothesis that BGA might be better suited for the indirect channel, especially with OEM#3, as the SKU increase from BGA will be minimized.

5.4 STATISTICAL COMPARISONS

Using JMP software, the results from the factory and service SKU analysis were compared between OEMs with the intent of identifying possible OEM partners for a BGA pilot. The variables reviewed included motherboard leverage, motherboard scalability, and service SKU increase. Student's-t tests were used for comparisons in each case. Sample output from these comparisons is provided in Figure 32.

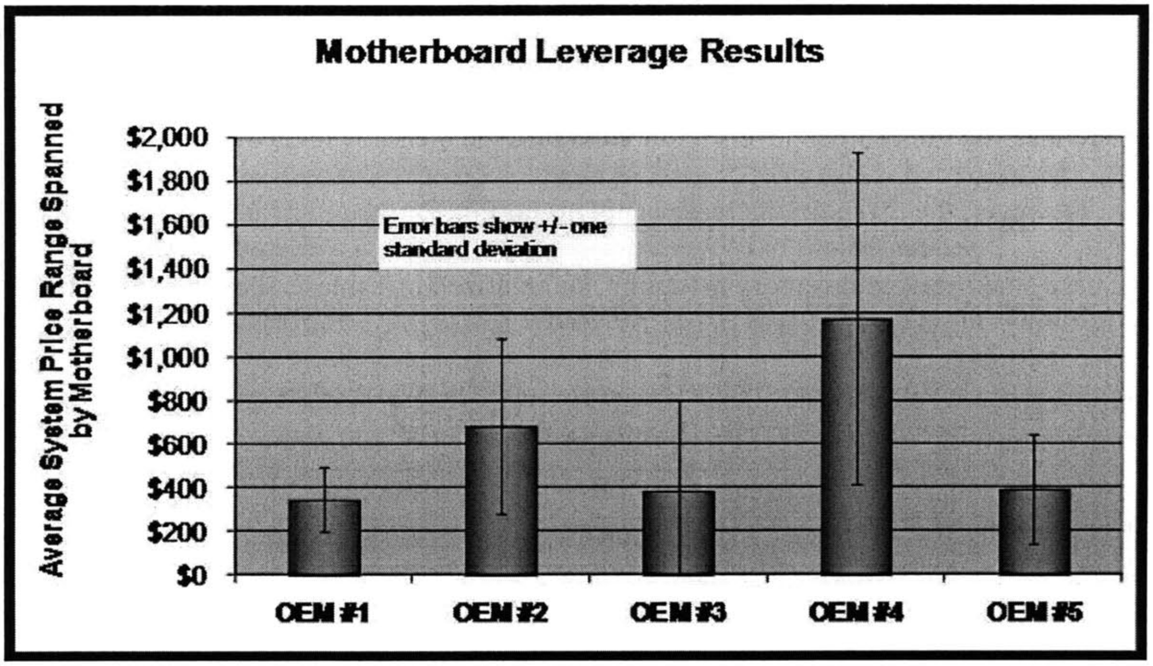


Figure 32: Typical output from statistical analysis

OEM #2 and #4 had average motherboard leverage that was statistically greater than other OEMs with 95% confidence. Again, motherboard leverage is defined as the system price range spanned by a given motherboard design, e.g. the same motherboard used in a $500 and $1500 system has leverage of $1000. The conclusion from this chart is that OEMs #2 and #4 would be less desirable as potential BGA partners as they design their product offerings for higher part commonality.

Enough data points were included in the database to make statistically valid comparisons between OEMs at the aggregate level shown in Figure 32. However, there were not enough data points to make good comparisons at higher levels of granularity. For example, if only processors in the Consumer "Good" category were to be studied as converting to BGA the resulting output would not produce valid comparisons as the OEMs produce only a limited number of system designs in this category.

5.5 INVENTORY MODELING

As discussed earlier, supply chain theory has shown that as the benefits of demand pooling are lost, the safety stock levels required to provide the same level of service will increase. However, the inventory increase is not proportional to the SKU increase. Results from the case study service inventory modeling, summarized in Table 7, show this to be the case.

Table 7: Service inventory modeling results

Measure	% Increase
Service SKU Count	800%
OEM Service Inventory	87%
OEM Service Inventory Cost	130%

As expected, the SKU increase is much greater than the total inventory increase. While the inventory increase is much smaller proportionally, it does represent an almost doubling of the service inventory. The cost of the service inventory increases at an even higher rate due to the fact that a high cost processor is now mated to the system motherboard. Note that this data reflects only a partial transition to BGA, representing only two segments on the Intel roadmap.

5.6 DISCUSSION OF RESULTS

The results presented here are almost certainly conservative estimates of the total SKU increase for the manufacturers studied. Additional complexity such as chipset variations on motherboards add to the base level of motherboard SKUs that have to be produced. Also, the data gathering method keeps open the possibility that system designs were missed for some OEMs. These results therefore provide for average strategy and SKU impact comparisons on an OEM level, but when looked at as total SKU count for the OEM represent a low estimate. The total final service SKU count of 380 referenced earlier is most likely higher in actuality.

That being said, even the conservative estimates of the SKU increase levels are high enough to cause significant increases in management costs and inventory costs for the OEMs and ODMs studied, as shown by the doubling of service inventory value with a limited BGA implementation. In the decreasing margin environment that exists in the notebook computer industry, these increased costs may prove difficult for the participants to absorb and therefore represent the primary reason for limited adoption of BGA packaging. Even the lower impact steps studied had resulting SKU levels above the base case and therefore would likely result in supply chain cost increases and/or performance degradation.

Due to the high level of competition that exists between the Taiwanese contract manufacturers, the bulk of the cost increases from BGA would likely be absorbed by the ODMs. These would include both manufacturing complexity and inventory costs, and also the bulk of the service complexity and inventory costs. Such an increase in costs could potentially drive one or two of the weaker competitors from this space, thereby increasing the scale and power of the remaining players. With decreased competition at that point in the value chain, both Intel and the OEMs could see a decrease in their profits as their ability to negotiate terms is lowered.

Because of this, it is felt that a shift to more BGA product would either not be accepted by industry players if pushed by Intel or would force/require structural changes in the value-chain or product offering strategies. First, the feedback loops presented earlier demonstrated that if Intel were to introduce more BGA-packaged processors without a corresponding decrease in the number of total processors offered that the OEM would still have strong incentive to use PGA designs. If not available from Intel, they would purchase from another competitor such as AMD.

Next, structural changes in the industry could be pushed by either Intel or the OEMs, or may occur naturally over time due to the forces presented indicating a BGA future. From a product offering standpoint, this could be accomplished by Intel reducing the complexity of its product roadmap or the OEMs minimizing the practice of offering all Intel processors on their systems. Apple, for example, utilizes only BGA processors in their notebook computers but only offer a choice of 2-3 Intel processors on each system.[15] From a value-chain design perspective, the necessary changes could take on many forms. Intel could leverage their VMI service to mitigate the increases in ODM factory and service inventory costs. OEMs could fully outsource their service operations, thereby removing that fixed cost burden. ODMs could offer higher levels of factory service and could possibly consolidate service responsibilities from several OEMs, provided that the necessary scale economies could be developed. Finally, having the ability to manufacture BGA motherboards with SMT close to end customers would be necessary as well, rather than shipping these subassemblies from China.

The models used in this study could be improved in numerous ways. When creating the database of current OEM system offerings, inclusion of offerings from additional geographies could give additional confidence in the results developed. Also, additional permutations of motherboard designs could be included, such as chipset variations, to more accurately capture the SKU increase. Finally, additional OEMs could be included in the study as they may have significantly different business models.

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[15] www.apple.com

From an inventory modeling standpoint, there are many simplifying assumptions that were made in order to balance the speed/cost of the analysis with its intended purpose, which in this case was providing rapid input and multiple scenario modeling for higher-level strategy decision making. The assumption of independent and identically distributed demand across all product platforms and geographies would alter the final inventory total, as certain systems will represent the bulk of the demand and therefore bulk of the service inventory. Also, the analysis assumed constant CV for all demand streams regardless of level. Due to the effects of variability pooling, the lower volume demand streams would typically have higher CV, and therefore considering these values independently would add realism to the results. Abernathy et al. (2000) provide a good discussion of this approach.

Finally, the method employed in this study provided enough resolution when results were aggregated (n high) to make comparisons between the OEMs studied, providing some insight into the strategic direction and potential partnerships. However, when attempting more detailed analysis, for example looking at options involving only limited processor segments, not enough OEM systems were available to reduce the standard error of the estimate. Therefore, comparisons could not be made in these cases. As mentioned above, adding additional systems to the database would help provide greater resolution.

CHAPTER 6: CONCLUSIONS

A paradox existed between notebook computer industry trends that suggested BGA adoption would be desirable and the actual industry behavior. This project examined the paradox and discovered that service inventories and carrying costs increase dramatically with BGA processors, amounting to a 10x increase in the number of SKUs and doubling of service inventory cost. Costs also rise due to the increased supply chain and manufacturing complexity resulting from the SKU increase as strongly suggested by existing literature. While these complexity costs were not quantified in this study, it seems apparent that the total cost increase outweighs any cost savings from socket elimination. Overall, from the customer interviews, SKU modeling, and service modeling a greater qualitative and quantitative understanding of the barriers to this adoption has been obtained.

One key conclusion developed is that major structural changes must occur in either OEM system offering strategies, Intel product offering strategies, or industry service models for a full BGA transition to occur. Recommendations based on this work were provided to the necessary stakeholders within MPG at Intel. This included recommendations as to which OEMs may be the best candidates to partner with for a BGA pilot program, as they have system scalability and leverage strategies that are more appropriate for BGA.

This study highlighted how relatively simple modeling approaches could provide very useful insight in product design and product roadmap decisions. By limiting the SKU increase study to two attributes, the processor and motherboard, and by utilizing corroborating data to increase confidence in the resulting database, an almost complete mapping of OEM product design strategies was developed. This in turn allowed for rapid evaluation of many strategic options using SKU counts as a proxy for supply chain cost.

This approach could potentially be applied in other industries as well to gain deeper insight into downstream value chain impacts of product design strategies.

Companies look at how their product design strategies may affect their supply chain performance with increasing frequency in today's business environment (Amaral and Cargille 2005). This study broadens that by providing a glimpse into how the product design choices of a powerful supplier can affect an entire industry supply chain. By considering these impacts, firms such as Intel can make choices that could conceivably better maintain or increase the total profits from the value chain.

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APPENDIX A: OEM/ODM INTERVIEW QUESTIONS

- What are your barriers to greater BGA adoption?
  - Supply chain constraints?
  - System design constraints?
  - Service constraints?
  - Other issues?
- Do you see the same industry trends?
- Who decides to use the socket?
- Who pays for the socket?
- What would encourage more BGA usage?
- Are there product lines or segments that would lend themselves to greater BGA usage?
- What rate of field returns requires processor replacement? Board replacement?
- Supply Chain
  - What would be the inventory impact of more BGA designs?
    - Locations, levels?
    - Does VMI mitigate the inventory impact?
  - How do you respond to late customer demand changes?
  - What is your cost of managing BGA board SKUs?
- General
  - What are the biggest challenges you've had to deal with from rapidly increasing BGA CPU volumes?
    - What can Intel do to enable more BGA designs?
- Manufacturing Floor
  - What are the manufacturing impacts of BGA designs?
    - Can PGA and BGA systems be built on the same line?
    - Can you build motherboards JIT?
  - What are the manufacturing differences between build-to-order and build-to-stock systems?
    - Is one better suited for BGA?
  - What is your total manufacturing lead time for a typical system? Order fulfillment lead time?
  - Service
    - What are your system warranty responsibilities?
      - Do you maintain any regional repair capabilities?

APPENDIX B: SYSTEMS OFFERING ANALYSIS DATABASE FIELDS

OEM
System Name
Motherboard
Base Price
Segment – Business or Consumer
Processor Retail Name
Processor Segment
Processor Type – e.g. Intel® Core™ 2
Processor Architecture – platform name
Number of cores
Thermal design power
Packaging type
Speed
Bus Speed
Cache
Junction Temp
Price Delta from Base – extra price from base price due to processor upgrade
Comments
Total Price – Base price + price delta
Screen Size
Shipping Days – number of days from customer order to system shipping

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