AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Companies working on new product development of smartphones seek to adopt designs and methodologies to help them stay competitive. Due to its high cost contribution to a smartphone, optimizing display cost is an important part of a smartphone's cost reduction activity. Hence, strategically sourcing displays in the development of smartphones leads to a significant decrease in production costs. The objective of this study is to utilize data available from the smartphone industry and separate the display cost based on the technical features of a display. Reports containing data on three hundred and fifty eight smartphones were collected from smartphone research firms and similar sources. Based on available data and by reviewing the literature on the subject, features of sub-components of a smartphone were identified to build a Bill-of-Material (BOM). The BOM was utilized to filter the database of smartphones at each stage of the analysis. A step wise analysis was performed to identify components that help define the retail price of the smartphones. After

performing analysis to predict retail prices, the analysis is narrowed down to a smaller subset of detailed data to separate display features. A regression model with only display features was created. Cross-validation of data was performed to include all smartphone samples collected in the testing of the analysis. The outcome of the regression analysis was used to build a Should-Cost Model to predict display pricing. The resulting should-cost model can help analyze various causes that add to the cost of sourcing and hence serve as a good first hand basis for analyzing components/materials. As a result, this model would assist in effective negotiations ahead of sourcing.

Developing a Should-Cost Model to Predict Display Pricing in Smartphones

by

Viswanath Parameshwaran Kashi

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Viswanath Parameshwaran Kashi, Author

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Developing a Should-Cost Model to predict display pricing in Smartphones

1 INTRODUCTION

1.1 Background

Smartphones are widely used in daily life activities by almost all individuals in today's world. A large variety of these phones are available in the market. Due to high product variety and intense competition, companies have adopted various measures to attract customers. The mobile phone industry has been experiencing unprecedented cost pressures with increasing competition across the globe (Giachetti & Marchi, 2010). With high-technology products being developed within shorter cycle times by various product developers, the ability to sell in the market is weighted between the technological features of the product and cost competitiveness.

A widely practiced method in smartphone development is having a high-tech company design smartphones and building (including prototyping) them at Original Equipment Manufacturers (OEMs) (Ali-Yrkko, Rouvinen, & Seppala, 2011). A major part of the development process is choosing materials based on development needs and effective sourcing of these parts from various suppliers. This is because a large portion of the products' cost is contributed by materials used in them. Companies, which are smartphone developers, do not always receive the best possible prices for certain components being procured.

The essence of strategic sourcing is creating a system where multiple vendors are competing for a company's business. In this way, each of these vendors is improving quality and performance of their products; while at the same time driving prices down. But in the electronics industry, for products like smartphones and tablet displays, which is the area of interest of this research, the number of suppliers is limited. The technical capabilities and manufacturing complexity of modern smartphones restricts the production to very few key suppliers such as X, Y and Z. These items in many cases are custom built, complex to manufacture and purchased in low volumes during the development stage.

Although factors such as technological improvements and competition improve cost and quality, negotiations based on technical know-how and visibility into the right cost based on a specific configuration of display further improve the cost of sourcing. In order to get this technology based cost insight, this thesis employs a statistics based model to predict display cost from the limited information available on smartphones. In the due course of this research, understanding the technological varieties in smartphone displays, being able to refer to data on manufacturing, sub-components and other aspects of the displays that could help during price negotiation with suppliers are considered important.

1.2 Objectives

For the purpose of this research, the work presented in this thesis focuses on displays in smartphones for two reasons: high percentage of cost contribution of smartphone manufacturing coming from displays, and lower visibility into display technology due to intellectual property. The main objective of this study is to develop a model that could be utilized to predict smartphone display cost and also extend the technique to possibly other similar fields. To reach this main objective, broadly five secondary objectives needed to be established. Each of these secondary objectives is better defined and addressed in the methodology section of this thesis.

i. To understand the technological aspects in smartphones through available data and literature review
ii. Identify data points used in the procurement of major smartphone components,
iii. Identify existing cost models that could lend itself to be adopted in this model's development
iv. Perform a step-wise evaluation of important vs unimportant parameters in model development
v. Checking the validity of the model for a robust output.

Therefore, a model to analyze available smartphone data and separate the cost of a type of display becomes imperative. When smartphones are released in the market, smartphone research firms such as IDC, Techinsights, Strategy Analytics, etc., break the smartphone down to its sub-components. In some cases high-end smartphones and few others that involve newer features and technologies in them are broken down further and a detailed report of their findings is published for industry use. Various teardowns of smartphones give an idea of the components used and rough estimates of cost in some cases. Along with a few other sources used in this research, the data is refined and analyzed to scrutinize factors affecting cost of the overall cost of the phone and later separating the cost of the display.

1.3 Research Questions

While the development of Should-Cost Model is unique to the problem context it is developed for, it may share core structures with a broader spectrum of similar problem contexts. To provide this broader context, it was necessary frame an outline of questions; the results of which would help answer if this method is suitable.

Research Question 1: Can a display cost model be developed using the available smartphone component data?

Research Question 2: Can a display cost model developed predict display cost within a margin of error of $10?

1.4 Tasks

Task 1:

Breakdown the component structure of a smartphone and build a Bill-of-Material (BOM) table for reference

Task 2:

Identifying primary factors contributing to the retail price of the smartphone and develop a retail price predicting model

Task 3:

Develop and test a display cost model using display features to build a Should-Cost Model

1.5 Hypotheses

The BOM structure developed in Task 1 is used as the basis to build models developed in Tasks 2 and 3. Two general hypotheses were setup to address the two research questions posed. They are presented respectively.

General Hypothesis for research question 1:

Restrictions on data availability could restrict the outcome and applicability. This is setup in the form of a hypothesis.

a) Information available on smartphones from various resources is adequate to generate a display cost model.

General Hypothesis for research question 2:

Since the outcome of the final model created needs to be utilized on actual display cost predictions, the ability of the generated model is to be hypothesized.

a) The display cost model does not provide a prediction within ±$10.

1.6 Thesis Overview

Multiple tasks were carried out in order to meet the objectives of this research. These are enlisted below:

1. Data for a wide-variety of smartphones phones was collected from reliable smartphone teardown research firms and highly valued smartphone reviewers.
2. Data in the teardown reports were reviewed to evaluate the method of analytical model that can be used.
3. Based on the data from point 2, a Bill-of-Material (BOM) breakdown was performed at various levels of components.
4. Testing of regression models at various BOM levels and different combinations of BOM level variables was performed.
5. Finally, a display model from a subset of data was created to generate display component cost.

This thesis consists for six chapters.

Chapter 1: Introduction

Chapter 1 covers the background of the research, objectives, and an overview of the thesis.

Chapter 2: Literature Review

Chapter 2 reviews a selection of past work and research deemed relevant to this thesis, and consists of three broad sections: technology components, existing cost models and other relevant techniques used for the research.

Chapter 3: Methodology

This chapter explains data collection, evaluation of available data, breakdown of smartphone components to suit analysis, identifying components affecting price, development of initial analysis and finally the display cost model.

Chapter 4

This chapter includes the paper titled 'A Should Cost Analysis through Significance Testing using Statistical Tools' that outlined the initial steps to the development of this thesis. This paper was also presented in the Industrial and Systems Engineering Research Conference conducted at Montreal, Canada from May 31^{st} to June 3^{rd} 2014.

Chapter 5

In this chapter, a paper summarizing the steps in developing the Should-Cost Model created in this thesis is included. This paper contributes to the academic literature for creating such models for other similar fields.

Chapter 6: Conclusion

Chapter 6 summarizes the results, main conclusions and findings from this research. It includes a discussion on the creation of the final Should-Cost Model, the applicability of the model, limitations, as well as recommendations for further study.

1.7 Research Outputs and Outcomes

a. A display cost model development methodology that can be generalized for similar contexts.
b. A Should-Cost Model interface to be used in display cost prediction.
c. One peer-reviewed conference paper, containing the theoretical model, and literature review on relevant areas. Target Conference: 2014 Industrial and Systems Engineering Research Conference.
d. One peer-reviewed journal paper containing the display cost model development and its outcomes. Target Paper: Journal of Engineering Management

1.8 Limitations

Most data collected for this research is based on smartphones released in the past few years in the market. This provides insight only into display features that have been utilized in smartphone introduced in recent past. Since technology changes seem to happen within shorter time spans, types of features being used in future smartphones might make this

Should-Cost Model less usable. In order to avoid this, data on technologies from contemporary smartphones need to be periodically collected and inputted in this analysis.

The model produces display cost with an estimated standard error of $8.95. Although this is known, other factors such as volume of production and maturity of display feature's technology are not fully reflected by the model. As proven in the outcome of the model, highly matured technology for display type such as LCD would cost lesser compared to OLED. Due to unavailability of data, Touchscreen Panel IC, display driver, and touchscreen panel lamination type are not broken down in the BOM and hence not in the model.

CHAPTER 2

2 LITERATURE REVIEW

The following literature review is divided into three sections describing the background with which the research was initiated, and contains an overview of the technological breakdown of smartphones and their components, existing analytical methods to build cost models and finally other tools and techniques used in the analytical section of this research.

In this section, numerous references to the term smartphone components are used to specify individual members that are combined to constitute a smartphone. These components can be broadly classified as Hardware and Software items. A high level classification of hardware components are Display, Camera, Battery, Memory, Sensors, etc. Software components include Operating system, Applications, etc. A general architecture of mobile device is shown in Figure 2.1. Different types of each of these components are used in the development of a smartphone. Manufacturing methodologies for these components also vary based on the type of component considered.

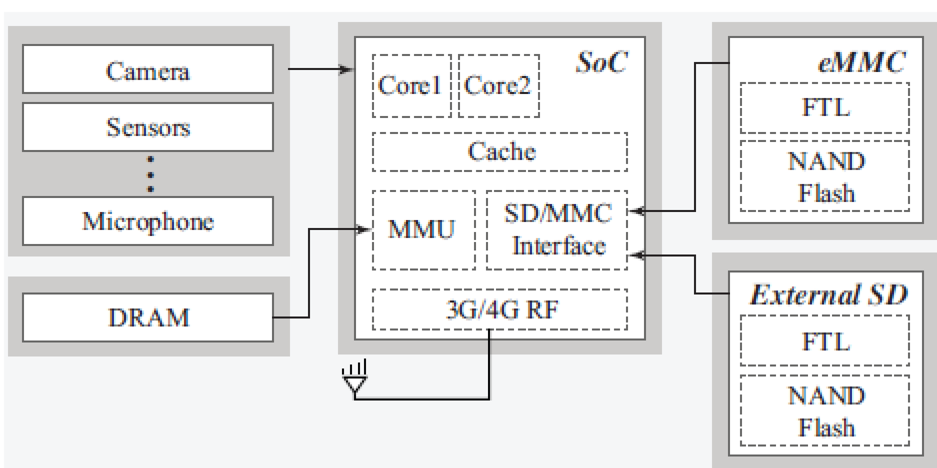

Figure 2.1: General architecture of mobile device

2.1 Component Technologies and Classifications

A typical smartphone is a more sophisticated model of a basic hand-held device called Cellphone. In addition to a cellphone that is used to make calls and text, the smartphone allows addition of more features (Yu, 2012). Although there is not a standard definition for smartphone in the industry, it is useful to broadly mention the features and capabilities of a smartphone for the purpose of this research. In the process, we also elaborate on the term Operating System and on its development. A smartphone works on a platform created by an operating system that helps run applications. In 1999, since the time Research In Motion was introduced by Blackberry, various operating systems have been introduced in the market by different application developers and device makers (Lin & Ye, 2009; Hall & Anderson, 2009). A few of the dominant operating systems by market share are Android from Google, iOS from Apple, BB from Blackberry and Windows from Microsoft (Tracker, 2014). Although applications are mostly developed for aftermarket purchase, the operating system forms an integral part of the phone. The hardware features of a phone are developed across a wide range of companies and outsourced by smartphone developers, as mentioned in chapter 1. The hardware components with features sets, data points and classifications are explained in the section below.

2.1.1 Overview of Hardware Components

This section breaks down the components used in the construction of a smartphone. Two sections exist based on the detail of literature: Display Technology and Other Component Technology. Since the focus of this research is Display, a broader focus on display technology literature is provided. Comparatively, other components are explored only to an extent that is deemed necessary for the analysis. Each section provides a summary of the technology classification for the component, data points used in the measurement of its features and other important developments that are deemed relevant to this research.

Display Technology

Displays used in smartphones broadly constitute three underlying structures: the cover class, the touchscreen panel (TSP) and the display module, in the respective order from the outer end of the phone as shown in Figure 2.2. A variety of differences in characteristics and functions have promoted use of different types of these components in current smartphones. Percentage of phones and smartbooks with touch technologies is projected to be 50% and 93%, respectively in 2014 (Lee, 2011). Eleven categories of touch technologies are listed by DisplaySearch (Colegrove, 2012): resistive (both analog and digital, surface capacitive, project capacitive, infrared (traditional infrared), optical imaging (camera-based), acoustic wave (both surface acoustic wave [SAW] and bending wave), digitizer, in-cell, on-cell, combination, and other touch technologies. Amongst these, the widely used Projected Capacitive (Pro-Cap) was first used in the iPhone in 2007 (Lee, 2011) and since then it has increasingly been used. It is expected that approximately 70% of the mobile phone market will use this technology (Lee, 2011). Variations in Pro-cap TSP are available based on the material (Glass Vs Film) on which the sensors are placed and also based on the patterning of the sensors themselves. Measures to reduce the thickness of smartphones have led to newer technologies, integrating touch with the display module, such as in-cell and on-cell touch technologies (Colegrove, 2012). Relative cost of adding touch technologies, as shown by Synaptics (Incorporated, 2012), seems to be decreasing from two layer discrete touch panel to single layer touch panel solutions to display integrated touch panel technology.

Liquid Crystal Display (LCD)

The electronics industry has been developing various kinds of display technologies for use in electronic products such as personal computers, smartphones, tablets and various other applications. The most prevailing for a few decades has been the LCD that consists of liquid crystals that are activated by electric current. Dramatic increase in manufacturing has led to significant decrease in the cost of LCD based products (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). A number of suppliers exist, each providing displays in a various range of parameters, of which the major ones are: Kyocera, Sharp, Samsung, Optrex, Hitachi (Fujitsu Microelectronics America, 2006). The structure in Figure 2.3 shows an LCD display module from top to bottom consists of a polarizer, glass, two layers of color filter enclosing the liquid crystals, a TFT glass substrate, another polarizer and finally a back light unit.

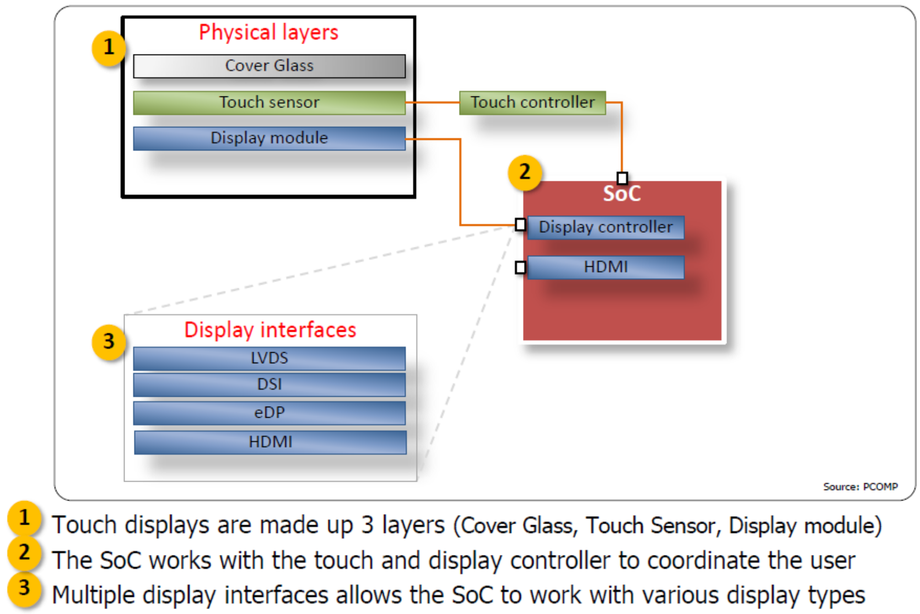

Figure 2.2: Display Structure and Circuitry

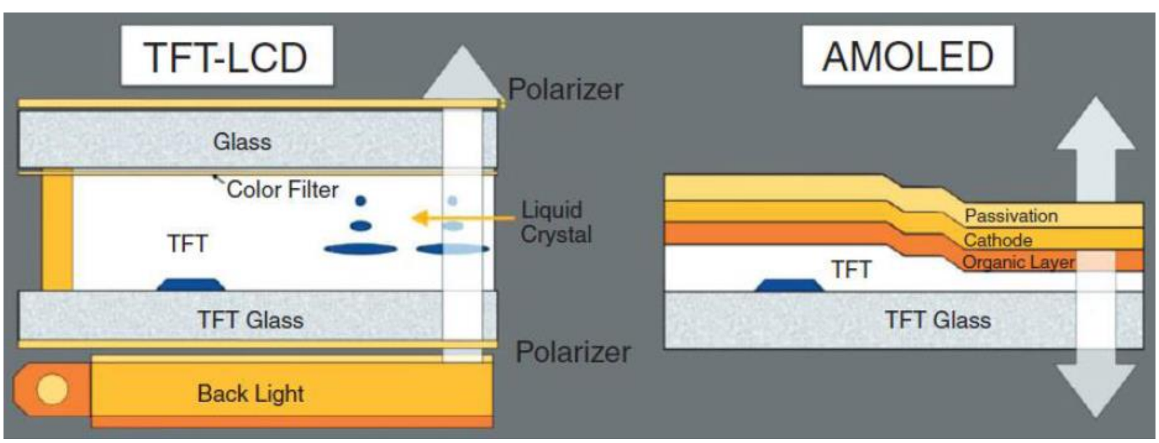

Figure 2.3: LCD and OLED Display Module

LCD modules can be categorized based on different characteristics, of which the two general types are: passive matrix (PMLCD's) and the newer and the most widely used active matrix (AMLCD's) (Fujitsu Microelectronics America, 2006), which uses individual TFT per pixel. The most widely used of the three LCD products based on liquid crystal alignment: Twisted Nematic (TN), Super Twisted Nematic (SN) and Thin film Transistor (TFT), is the TFT, which is otherwise known as Active Matrix LCD (Fujitsu Microelectronics America, 2006). The TFT industry has grown by a large extent since 2003 (Pan, Hsieh, Su, & Liu, 2008). The TFT-LCD contains three major manufacturing sectors: the array, cell and module processes (Wang & Su, 2006; Ukai, 2007). High performance of display has led to the growth of today's Amorphous Silicon (a-Si) TFT and Low Temperature Poly silicon (LTPS) TFT-LCDs. Active research is being done in developing metal-oxide TFT such as Indium-Gallium-Zinc-Oxide (IGZO) (Hausmann & Knowles, 2011). With circuitry, discrete driver IC has been in use for the most part. Newer methods such as Chip-on-glass (COG) packaging directly connects the driver IC to the glass substrate with advantages such as easy producing, high through-put and weight minimization.

Organic Light Emitting Diode (OLED)

OLED is a relatively new superior display technology and regardless of the higher price and limited production volume (Colegrove, 2012), promising factors such as light weight, wider color gamut, better contrast, wide viewing angle and low bill of materials (Bardsley J. N., 2010) has led to the adoption of organic light emitting diode (OLED) display technology by various smartphone makers. Typically, OLED devices shown in Figure 2.3 are formed with either one or more layers of emissive organic layer located between a cathode and anode and deposited on a substrate (Kunic, 2012). Top-emitting, bottom-emitting and inverted top-emitting AMOLED structures are the different kinds. The substrate can be made of glass or flexible material or metal. Almost exclusive manufacturing of AMOLED is done on small glass substrates compared to LCD in which glass sheets are cut after TFT manufacture. Such process and equipment compatibility pose technical barriers to scaling up of OLED manufacturing (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Nevertheless, cost savings as much as 40% to 60% (although for 55" displays without TFTs), with reference to LCD, is seen as a result of lower material consumption, lower fixed dues to reduced maintenance and tooling (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Another advantage of AMOLED is that integrating circuitry with TFT substrates are also made possible (Bardsley J. N., 2004).

Based on technology review above, we identify five features that define the feature set of a display module: display type, screen size, pixel density, number of colors and cover glass type. Each of these features is detailed in the Table 2.1.

Table 2.1: Display Features

Feature	Units of measurement	Feature Explained
Display Type	No units	Two broad types: LCD and OLED
Screen Size	Inches (")	Diagonal length of the smartphones' screen, measured in inches
Pixel Density	Pixel Per Inch (ppi)	Formula to calculate Pixel density utilizes resolution type and screen size (d_i). Resolution type provides total number of pixels present (represented as numbers in the form: a x b). The formula for Pixel Density is $\frac{\sqrt{a^2+b^2}}{d_i}$. Resolution of FHD (1080 x 1920) and Screen Size of 6" is calculated as $\frac{\sqrt{1080^2+1920^2}}{6}$ yielding 367 ppi.
Number of colors	Thousands (K) or Millions (M)	The color depth of the display module is represented by this feature. Standard color depths in smartphones include: 62K, 256K, 262K, 16M and 16.7M.
Cover Glass Type	Varies by strength of glass	The most widely known based on industry usage are from Corning named Gorilla Glass: CGG, CGG2 and CGG3, in increasing order of strength. Other types used by few smartphone developers are Scratch Resistant (SR) and Shatter-Proof (SP).

It is to be noted that in this thesis, the terms display and display module are used interchangeably. Display can used to mention Display Module but not vice versa.

2.1.2 Other Smartphone Components

Processor

In the semiconductor industry, the building of Integrated Circuits (ICs) rolls back to the times of Personal Computer development. These ICs over the years have been cut down in size according to Moore's Law and are currently being used in Smartphones. Since the area available to place this circuit (also called a processor or a System-On-Chip (SoC)) is limited, there have been various developments in integrating other components with the SoC.

Table 2.2: SoC and RAM Features

Feature	Units of measurement	Feature Explained
System-on-Chip (SoC)		
Clock Speed	Giga-Hertz (GHz)	Processors are scaled based on their voltage/frequency and this is measured in terms if GHz. The architecture in PoP designed by different brands change the number of cores and speed needed to run applications on a smartphone. (Liu, Maxiaguine, Chakraborty, & Tsang Ooi, 2004)
Number of Cores	Number	
RAM		
RAM Type	No units	Based on technology advancement, various types in RAM exist. They are: DDR, DDR2, DDR3, LPDDR2, and LPDDR3
RAM Capacity	Gigabytes (GB)	The capacity of the RAM is measure in GB.

The RAM which acts as a memory in the smartphone is packaged along with the SoC. These packages are of different types: Single-Package (SiP), Package-on-Package (PoP) and Package-in-Package (PiP). Of these three, the PoP type has been widely accepted and used in the development of smartphones (Apte, Bottoms, Chen, & Scalise, 2011). From the data available for this research, two features help define the characteristics of each; Processor and RAM. Clock Speed and Number of Cores for the processor, and RAM Type and RAM Capacity to define the RAM. They are discussed in Table 2.2. Various smartphone developers have patented in-house PoP designs and others outsource this part.

Camera

As a functional addition to the smartphone, most phones in the market include cameras, called Rear Facing Camera. In the development of higher end smartphones there exist two cameras: the Rear Facing Camera and a Front Facing Camera. The available data points related to smartphone cameras are: type, camera capacity, optical size, number of lens elements and optical zoom.

Table 2.3: Camera Features

Feature	Unites of measurement	Feature Explained
Camera Type	Based on Sensor type	The most widely used sensor in smartphones is Complementary metal-oxide semiconductor (CMOS). Since no other kinds of technology were present in the data for this research, other sensor type is not covered in the literature.
Camera Capacity	Mega-Pixel (MP)	Broadly, the capacity of a camera is mainly defined by this feature. Similar to resolution measured by ppi in displays, the resolution in camera is measured in megapixels. Based on the data collected, the resolution of smartphone cameras varies from VGA to 0.3 MP to as high as 41MP.
Optical Size	Inches	The size of the sensor used in smartphone cameras are measured in inches. This is measured along the diagonal of the sensor used.
Number of lens elements	Number	The number of lens elements used in a camera module is represented by this variable.
Optical Zoom	-	Optical zoom is a method of moving the internal lens elements, in order to change the focal length.

Storage

The storage component of a smartphone is classified broadly based on their modularity: Internal and External. Internal memory is in-built and is part of the smartphone when manufactured. Whereas, external memory is optional and is part of the total storage via a memory card slot. The data points defining features of the two storage types are shown in Table 2.4.

Table 2.4: Storage/Memory Features

Feature	Units of Measurement	Feature Explained
Internal Memory		
Storage Capacity	Gigabyte (GB)	The amount of data stored is positively related to the capacity, measured in GB.
Storage Type	NA	Usually eMMC, or UFS for Windows operating system based smartphones
External Memory (along with features as Internal)		
Extendability	Gigabyte (GB)	For external memory the storage is provided via a storage slot in the smartphone in which a memory stick can be inserted. The maximum capacity of the memory stick, measured in GB, that can be used is defined by this variable.

Based on the data available from a wide range of smartphones used in this research, the storage capacities vary from 2GB to 128GB.

Battery

Batteries form the power source for all the components of the smartphones. Two types of widely utilized batteries are Lithium Ion and Lithium Polymer. They can be categorized similarly based on the type of packaging. Other data points that define the specification of batteries used are in table below.

Table 2.5: Battery Features

Feature	Units of Measurement	Feature Explained
Battery Package	Soft (or) Hard	As revealed in the teardown reports, this feature is explained by the removability/modularity of the back cover of a smartphone. Soft package is included in smartphone in which the back cover is non-removable, whereas hard packaged battery is used when the cover is removable.
Battery Voltage Rating	Volts (V)	The voltage rating of the battery is explained by this variable. Based on the teardown data, this feature varies from 3.7V to 3.8V.
Battery Pack Rating	mAh	The power rating of the battery in smartphones is explained using this feature and is measured in milli-ampere hour (mAh)

Connectivity

Features and components that help connect to external source for either data connectivity or other devices are broadly classified under this section. The components that are included in this section are Infrared (IR), Wifi, Bluetooth, GPS, FM Radio, USB and HDMI. Without breaking these features further down, based on available data, the presence of these components in each of the smartphone is checked.

Sensors

Most smartphones released consist of a package of sensors along with camera, wifi, Bluetooth and other additional features. A rich set of smartphone embedded sensors that are widely used include Accelerometer, Digital Compass, Gyroscope and GPS. Few other sensors used based off information from the smartphones used in this project include temperature sensor, ambient light sensor, proximity sensor, barometer, humidity sensor, magnetometer, and geomagnetic sensor (Lane, et al., 2010). The presence of each of these sensors has been considered without breaking them further by their sub-components.

Accessories

All elements that are provided along with smartphone but are not physically a part of the smartphone are considered accessories in this context. Common accessories include headset, adapter, charging cable, exterior packaging and any relevant documentation. Other accessories include docking station, external memory card and SIM tray pin. Common accessories mentioned here are the highly standardized across most smartphones and smartphone brands. Although this is the case, in a few cases accessory such as headset might not be included as a step of cost cut down.

2.2 Cost Estimation Techniques and Analytics

In this section, we review literature related to analysis/techniques used in cost estimation. Costing techniques relevant to both projects and products were important to be explored, since smartphone development could be considered as a project or product development. In regards to the tools used for cost estimation, four different methods have been identified: Analogy, Parametric, Bottom-up, and Extrapolation from actuals. These techniques have been utilized in different scenarios based on the type of data available.

Newnes et al (Newnes, et al., 2008) mention the availability of a number of cost estimation techniques, Generative Estimating and Parametric Estimating being the two basic types. Detailed data being gathered in the due course of a project is used in the generative approach, whereas estimation based on prior projects, past experiences and expected costs is utilized in the parametric approach. Each of these approaches possesses their own pros and cons. Although greater detail is demanded by the generative approach, estimation of cost per part is possible. On the other hand, applying relationship to cost evidence from previous products is used in the parametric approach. Application to low volume products and novel designs although proves less effective by this method (Watson, Curran, Murphy, & Cowan, 2006). These two techniques are included in the IMD Cost Methodology Book (IMD Cost Methodology Guidebook, 2013) by the Department of Defense, along with other such as Analogy and Expert Opinion. Their methodology and applicability presented in Table 2.6.

Table 2.6: Existing Cost Estimation Techniques

ANALOGY	PARAMETRIC	ENGINEERING (or) BOTTOM-UP	EXTRAPOLATE FROM ACTUALS
Compares new/proposed system with on homogenous system (i.e., similar) in which the form, fit and function are alike	Uses statistical regression analysis of a database of two or more similar systems	Reflects a detailed build-up of labor, material and overhead cost	Uses the actual (past or current) cost of an item to estimate future costs
Should include accurate cost/technical data from recent past	Develops cost estimating relationships (CERs) which estimate cost based on one of more system performance or design characteristics	Most detailed of all the techniques and the most costly to implement	Best suited for estimating follow-on units of the same item when there are actual data from current or past production efforts
Needs logical correlation between the proposed and past systems identified by the cost estimator	Performed in the initial phases of product description. CERs used to evaluate the cost effects of changes in design and performance and other characteristics	Data is available to populate the Work Breakdown Structure (WBS)	Essential to have accurate at the appropriate level of detail, and the cost estimator must ensure that the data is validated and normalized
Uses of additive and multiplicative factors	Based on statistical inferences about the relationship between cost and schedule	Estimate is based on standards, either company-specific or industry-wide	Reliance on historical costs to predict future costs

General classifications based on analysis are: analogous cost estimation (ACE) - otherwise known as ‘top-down approach’, ‘bottom-up approach’, and computing technology with artificial intelligence (Chou, Tai, & Chang, 2010). The top-down approach constitutes of the estimation of overall cost of the product and subsequent break down to sub-component level costs; the bottom-up approach is vice-versa (Watson, Curran, Murphy, & Cowan, 2006). Each of the estimating methods based on information available can be categorized into top-down and bottom-up approaches. The collection of cost data for each sub-component and the rolling up to the highest level in the bottom-up approach hold similarities with the generative estimation technique mentioned in the beginning of this section. Application of each of these techniques is also related to the stage of development of a product (IMD Cost Methodology Guidebook, 2013).

Watson et al (Watson, Curran, Murphy, & Cowan, 2006) state that the estimation methods can be further divided into explicit (rule-based) cost estimating, rough order magnitude (ROM) (ratio) estimating, parametric cost estimating, and detailed estimating using activity-based costing (ABC) and/or resource costing; each of which are often based upon past experience. Approaches involving the use of artificial intelligence such as fuzzy logic and neural nets are rapidly developing which mimic the human thought process. Also, Variant (analogy) estimating (Watson, Curran, Murphy, & Cowan, 2006) involves identifying a similar part/ completed project cost and then using this actual cost as a basis for the estimate of the new part/project.

2.3 Other Tools and Techniques

In this section, we review the concepts of tools and techniques that have been utilized in the analysis of this research. Linear regression model, Pareto Chart, Pareto Efficiency, variable selection and finally software used in this research is explained.

2.3.1 Linear Regression

A linear regression model is a type of analysis which can help model one particular variable as a function of one or more other variables. The variable being regressed is called the dependent/response variable and the variables used to explain the response variable is called the regressors or independent variables. The dependent variable in the model is regressed as a linear function of the regressors (Wackerly, Mendenhall III, & Scheaffer, 2008). For representative purposes, a linear model consists of coefficients for each regressors. A general representation of a linear model is shown in Equation 2.1.

$$E(Y) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k$$

Equation 2.1:Multiple linear regression equation

In the equation shown in Equation 2.1 above, the expected value of the response variable is represented by the E(Y) on the left side of the equation. The β's (except β_0) represent the coefficients and the x's represent the regressors. The β does not have a regressor and is referred to as the intercept of the model. The intercept is considered to be the baseline for the linear model. A model with only one regressor is known as simple regression, whereas a model with more than one regressor as is the case in this research is called a multiple regression. When a linear regression is performed, coefficients for each of the regressor are estimated and these coefficients also define the response variable. In addition, three parameters: R-squared (R^2), Adjusted R-squared (Adj-R^2), and Standard Error (S.E) are computed. These explain different aspect of the regression model and are considered important and are often used in this research. In addition, Mean Square Error or Root Mean Square Error is also used in the context of prediction analysis in the research.

The term R^2 measures the proportion of variability in the response variable that is explained by the regressors included in the model. Larger R^2 is better, but this does not necessarily imply that higher R^2 is good. Addition of variables always increases the R^2 in a model regardless of whether the variable is significant or not (Montgomery, 2009). As a result, a model can have high R^2 and still yield poor predictions.

Since addition of variables could increase R^2 without yielding good predictions, the term adjusted R^2 is utilized. The adjusted R-squared is a modified R-squared that has been adjusted for the number of predictors in the model. The term Adj-R^2 does not always increase as variables are added to the model. Unnecessary terms included in the model in fact reduce the Adj-R^2 (Montgomery, 2009).

Standard Error (S.E) of the estimate in a regression model refers to the measure of accuracy of predictions. It is represented as the square root of the average squared deviation. The lower the standard error, the more accurate the predictions are from the model. In the research, the parameter S.E is used in building the model. On the other hand, Root Mean Square Error (RMSE) is the measure of difference between the actual values and a predicted values based on a regression model used. It is derived by summing the square of these differences, dividing them by the number of test points and finally taking the square root. Similar to S.E, lower RMSE results in better prediction. In the context of the research, this parameter is used in price prediction analysis.

2.3.2 Pareto Chart

Pareto analysis is a technique used in various scenarios in Six Sigma. Roughly, pareto principle states that 80% of benefits can be addressed by focusing on efforts in 20% of key actions. For example, 80% of cost of quality is produced from 20% of the sources of error. This is named the 80/20 rule (Cano, Moguerza, & Redchuk, 2012). One of the tools available in pareto analysis is Pareto Chart that is used to help prioritize and focus on important factors from a collection of factors available. As seen in Figure 2.4, the pareto chart employs a bar chart in which the factors/causes are ordered in the descending order of their effects.

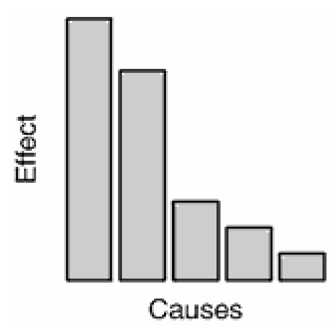

Figure 2.4: Pareto Chart example (Cano, Moguerza, & Redchuk, 2012)

Based on the 80/20 rule, the top 20% of the causes that can explain a major portion of the effects are prioritized for review. In the context of this research, the components used in smartphones are related to the cause, and cost of a smartphone is related to the effect in the pareto chart.

2.3.3 Pareto Efficiency

Pareto efficiency is an economics concept which helps efficient allocation of resources. This concept is used in various fields for optimization purposes. A pareto efficient allocation is one for which there is no way to make all agents/resources better off. In the context of this research, pareto efficiency is used to optimize model selection based on different parameters. An example of a completely developed pareto frontier is shown in Figure 2.5. The model in Figure 2.5 analyzes the optimal point between resource u_1 and u_2. The point close to the utility frontier by optimality is chosen. The utility value of the two resources at this point is considered to be pareto efficient and optimal (Saraydar, Mandayam, & Goodman, 1999). Similar charts are produced between regression parameters to help assist model selection in the analysis.

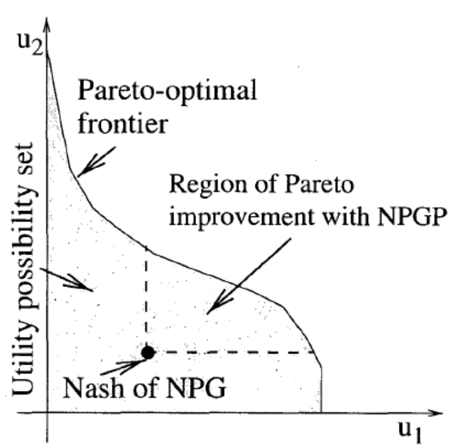

Figure 2.5: Pareto Efficiency sample graph

2.3.4 Variable Selection

Since the objective of this research is to evaluate the features affecting retail and display price, the variables related to these features were to be taken in a selective manner. For this, existing methods such as forward selection, backward elimination and stepwise methods were used. In the forward selection method, during regression model creation in the context of this research, the model is started with no variables and at every step a variable is added. This is continued till all the regressors are exhausted. In backward elimination process the process of elimination begins after all variables are included in the model. At step of the process, regressors that do not contribute to the model are deleted. The stepwise selection process of variable selection is a combination of both forward selection and backward elimination. The model follows the forward-selection technique by starting with no variables. But it differs from forward selection such that at each step of variable selection, any variable that does not contribute to the model are eliminated. It is to be noted that for the variable selection methods used from here, the parameters R^2, Adj-R^2, S.E and RMSE are used to judge the contribution of the variable to the model.

2.3.5 Software used

All regression models, cross-validations and price predictions for this research were performed in R. R-Studio which is an interface for R was used for this. R is an open source based statistical computing platform. All codes and outputs for this research are included in APPENDIX I. Residual plots for data setup during initial analysis was created using statistical software named JMP. The data collection for smartphones and model creation for cost modeling were performed on Microsoft Excel.

2.4 Summary

The literature presented in this chapter show that work has been done to evaluate the various kinds of technologies, their specifications and their usage over years. It is also clear that there has been significant research done in modeling different cost estimation techniques based on types of data available to analyze. However, very few studies exist that have broken down components for a single study, compared different cost estimating techniques, and combined them to develop a model for an industry relevant situation.

Thus, although the main objective of this research is to develop a single model to predict display costs, various other sub-objectives have been setup to help assist in achieving the main objective. The literature reviewed in this chapter helps accomplish the different objectives presented in the beginning of the next chapter.

CHAPTER 3

3 METHODOLOGY

3.1 Introduction

The purpose of this chapter is to provide an outline of the research methodology used in this research. The chapter provides details on how the tasks established in Chapter 1 would be addressed as primary objective for the research and help outline the procedure for the methodology. In this research, there are three primary objectives (PO) and five secondary objectives (SO). The primary objectives are established to create and analyze a model that helps breakdown either retail price or display cost of the phone based on available data. The POs established are:

PO# 1 – Breakdown of the Bill-of-Material for a smartphone

PO# 2 – Identifying the primary factors those contributes to the retail price of the smartphone and hence develop a good retail price predicting model

PO# 3 – Evaluate the display only model to establish a model for display cost prediction

The secondary objectives established to support the primary objectives are:

SO# 1 - Collection of data on smartphones mostly released in the last three years

SO# 2 – Identify existing cost estimating models that could be utilized in the analysis for costing these phones

SO# 3 – Eliminating irregularities in the properties of the smartphone characteristics used in the study, by segmenting smartphones

SO #4 - Screening data to help structure them for the analysis

SO #5 - Derive smaller sample set with detailed display features

Based on the secondary objectives established, multiple methods have been utilized in order to carry out the research. The relationship between different objectives and methods utilized is shown in Figure 3.1.

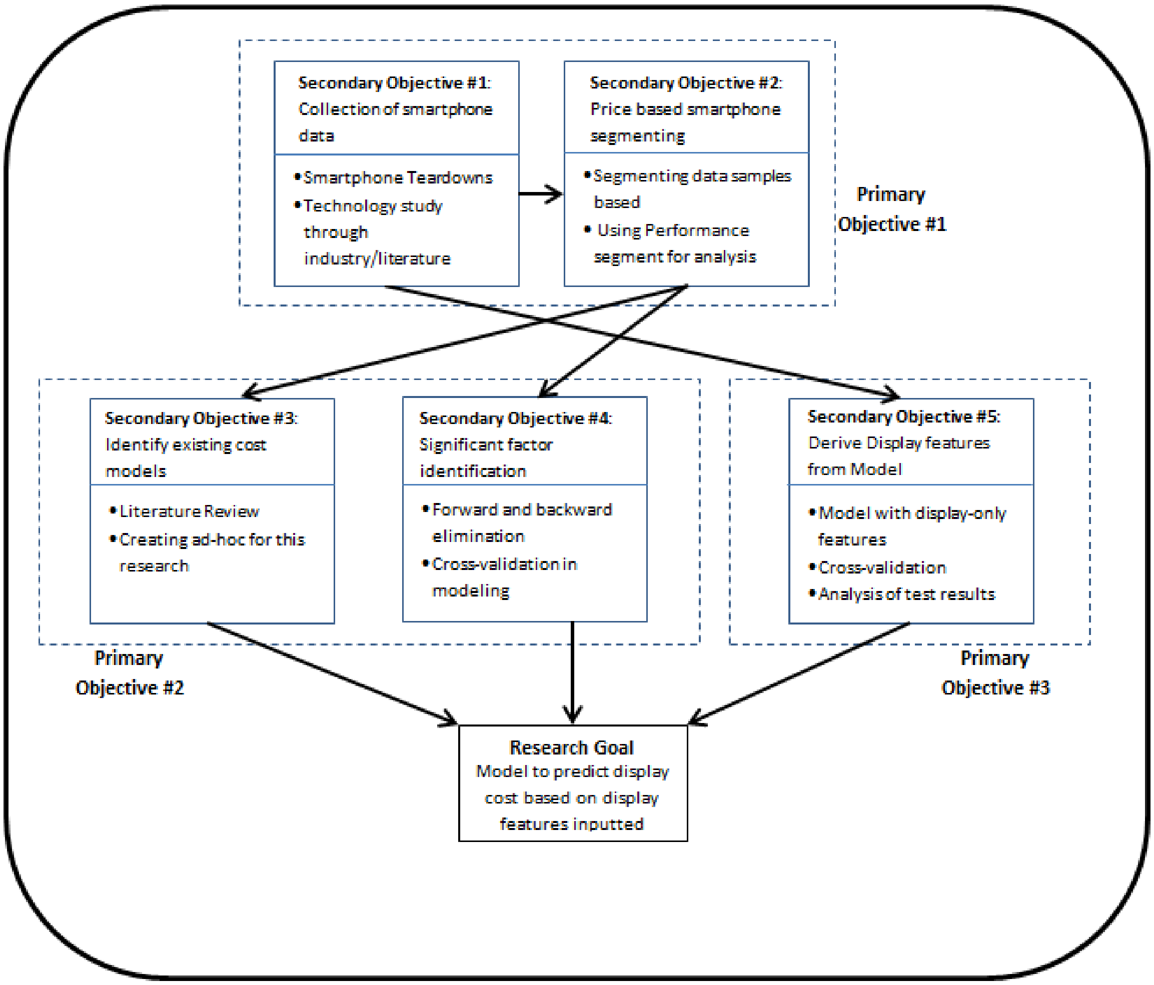

Figure 3.1: Research Scheme

To meet primary objective #1, both SO#1 and SO#2 were deemed necessary. Although both these secondary objectives were needed, they were realized at different stages of the research. Identification of different cost models through literature review (SO#3) along with outcomes from the primary objective #1 formed the basis to begin the analysis. As a first step, the data obtained from the execution of primary objective #1 was used to eliminate features that are not required through SO#4. This formed the basis to accomplish PO#2. After identifying the elements defining the model predicting retail price, a subset of smartphones with detailed data are identified for the display cost prediction analysis (PO#3).

3.1.1 Research Hypothesis Restated

General Hypothesis - 1

In Chapter 1, two general hypotheses were stated. The first aimed to determine if the available information is sufficient to analyze and produce a display prediction model. The primary objectives formed above develop the methodology for this hypothesis. The result obtained from the research scheme in Figure 3.1 decides the outcome of the hypothesis.

General Hypothesis - 2

One of the general hypotheses stated is to validate the applicability of the model. This is to test the hypothesis for $8.9 margin of error in the display model created. By this, we construct the limits within which the display prediction model would need to operate. Therefore, the null hypothesis is set with limits of $8.9 and beyond which would not be suitable and the alternate hypothesis is set up to prove that the model perform within this limit.

Null Hypothesis:

H_0: Display Cost Error = ± $10

Alternate Hypothesis:

H_a: Display Cost Error < ± $10

Although the second hypothesis is presented in this section, it is addressed in the display feature testing section presented in Chapter 5.

3.2 Data Collection

In order to establish an outcome that is relevant to current practices and improve usability, the data would need to be from smartphones released in recent past. In addition, reports on smartphones needed to contain as much detail on the phone's components as possible. Although this is a core necessity for the research, various intellectual property (IP) issues and competitive necessities of companies restrict the amount of detailed data available.

As a result, electronics teardown companies such as ABI, IDC, Techinsights, and recognized smartphone review companies such as CNET and GSM Arena are utilized to collect as much data on smartphone teardowns as possible for this research.

Table 3.1: Teardown Report Sample

Product Description	
Product Type	Smartphone
Brand	
Product Name & Model	
Official Release Date	
Retail Price	
Product Features	
Operating System	
Connectivity	
Processor details	
Storage details	
Sensors	
Key Subsystems	
Battery details	
Main Display details	
Main Camera details	
Front Camera details	

As a first step, all smartphones released mostly released in the last three years (2010 to 2014) were compiled from GSM Arena and CNET. This list enlisted seven hundred and fifty five smartphones released in the market by various companies. The list is shown in

APPENDIX II. The next step was intended to obtain reports for each of these smartphones that could provide data on the components included in them.

Search through reports from research firms and review companies for these seven hundred and fifty five phones resulted with detailed and/or non-detailed teardown summary for three hundred and fifty eight phones. Irrespective of reports being detailed/non-detailed, each report included the items shown in Table 3.1.

Non-detailed reports provided broad breakdown of each component used in the assembly of the phone except the components of on the board. Detailed reports summarized part by part breakdown, manufacturing cost, electronic cost, cost of display subsystem, camera subsystem along with a few other subsystems in addition to the data shown in the non-detailed report represented in Table 3.2. These reports on smartphones were across twenty-three different smartphone brands.

Table 3.2: Additional Data from Detailed Teardown Report

Cost Metrics	
Manufacturing Cost	
Electronics Cost	
Manufacturing Cost Breakdown	
Battery Subsystem	
Display/Touch Subsystem	
Camera Subsystem	

3.3 Selection of Analysis method

After thorough review of existing literature in cost estimation techniques for both projects and products, four broad methods were identified: Analogy, Parametric, Bottom-up and finally Extrapolation from actuals. All of these methods although were usable for this context, the extent of data availability limited the usage of each of these methods to certain extent.

Analogy

This method helps compare similar form-fit-function of products and use accurate data from the past to develop a cost function for a new product. Variation of features in smartphones from different companies makes this method time taking and difficult to adapt. On the other hand, this model incorporates logical correlation between past and present systems. Similar logical correlation is derived from the analysis to help extrapolate the results of this research to be applied to display features being selected for future projects.

Parametric

Models using parametric techniques utilize statistical regression analysis. As mentioned in the earlier chapter, regression analysis establishes cost estimation relationships (CERs) on design characteristics of a system. These CERs are used to help evolve cost for an overall desired system. A major portion of the analysis involves this method, in addition to involving selective features from the other three methods.

Bottom-up

This method as its name reveals involves very detailed cost estimation by rolling up cost of each sub-component used to the top most level. As a result of its methodology, it is used when detailed data is available and also considered very expensive. As mentioned in the beginning of this section, the nature of electronics industry does not permit the use of this method for our purpose. Although we are unable to use this method in its entirety, there exists rolling up of cost factors to the top level to some extent in the analysis.

Extrapolate from Actuals

In this method, actual data is utilized to estimate the cost of the same/similar products being re-created in the future. Similar to Bottom-up method in terms of data, this methods demands accurate data for better results. Since various companies provide derivatives of phones, such as the most relevant Galaxy series from Samsung and iPhone series from

Apple, a number of smartphone samples in our data are such. Also, since market is driven by competition between companies, the smartphones released at a particular instant in the market are mostly contemporary in their feature set. Therefore, the feature set of phones not only within a company but also across brand are possibly similar along time.

With all of the contributions from the above cost estimation methods, we setup the base for a statistical regression method to begin analyzing the collected data.

3.4 Bill-of-Material (BOM) Breakdown

Data obtained from three hundred and fifty eight non-detailed reports were extracted into an excel format. Based on technological details from the literature review and relevance to the data obtained from reports, each subsystem of the smartphone was broken down to four levels (Level 0 to Level 3) to form the bill-of-material for a generic smartphone. Before forming these levels, two basic categories of materials were defined: Mandatory and Optional. The mandatory portion consists of sub-system without which a generic smartphone cannot be constructed and the optional portion consists of features that could be added to a smartphone along with the mandatory parts. These two sections are listed in Table 3.3 below. It is to be noted that the each of these sub-systems are not disintegrated to their lowest component level.

Table 3.3: Mandatory versus optional smartphone sub-systems

Smartphone sub-component systems	
Mandatory	Optional
Display	Camera
Battery	Sensors
PoP	Connectivity Parts
Storage	Accessories (except Adapter and Cable)
Operating System	Hard/Soft Keys
Note: Mandatory in this context refers to parts that are required to build a basic phone	

The bill-of-material framed from Level 0 to Level 3 include the mandatory section first and then the optional. Each of the levels breaks down either the material from the previous level or includes data points that further define the feature from the level above.

It was to be noted that although there are various features or components that help define a particular subsystem in the BOM, unavailability of data for some features/components makes them unusable. An example of such an instance is the display components. Although the kind of lamination of a cover glass contributes to the cost, unavailability of this data in the teardowns limits the analysis from using this feature. Therefore, the BOM is defined in accordance with all available characteristics obtained from the teardown reports. A partial BOM breakdown is shown in Table 3.4, and a detailed table is included in APPENDIX III.

Table 3.4: Bill-of-Material (BOM) breakdown for smartphone (partial)

LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3
Smartphone	Display Type • LCD • OLED	Display Module • Screen Size • Resolution Type • Pixel Density • Number of Colors • Backlight	
		Touchscreen Panel • Resistive • Pro-Cap • Surface Cap • Infrared • Acoustic Wave	Lamination Type/ technology: • C/G/G • ToG (touch on glass)/ SoL (Sensor on Lens) • In-cell • On-cell
		Cover Glass • CGG • CGG2 • CGG3 • SR • SP	

3.5 Data Setup

A comprehensive list of teardown data was included against smartphones added to APPENDIX II. Both detailed and non-detailed data from teardowns were compiled in this sheet to form a reference database for this research. Since only three hundred and fifty eight teardowns were available out of the seven hundred and fifty five phones collected, these three hundred and fifty eight smartphone reports were usable for the research.

For employing regression analysis, the variables to be used in the model were to be defined into two groups based on how well they could be represented: continuous and non-continuous (otherwise known as categorical) variables. When a variable is considered continuous, it is included in the model with no changes and is modeled as numbers. On the other hand, non-continuous/categorical variables are categorized into two or more sections before being included in the analysis. A simple categorical variable is framed a binary digit with 1 and 0. One states that the feature exists and zero represents the absence of the feature. A more advance categorical variable helps breakdown variables that are continuous as per data, but are not correctly represented when added as such. In such cases, bins are created to categories them for better representation.

To setup the data in the input file for the analysis, initial screening of each factor in each subsystem was performed. In order to begin initial analysis setup, every variable from Level-1 and Level-2 was screened. For the 358 smartphones considered for the analysis, the residuals of retail price were plotted against each factor present in Level-1 and Level-2 of the BOM breakdown. These plots were used to determine the structuring of each factor into categorical or continuous variables for the analysis. The residuals are plotted in the y-axis and the specific variable is plotted on the x-axis. In addition, a line is fitted to determine if the points on the plot represent that specific variable well. An example of a residual plot showing residual versus screen size is shown in Figure 3.2 below. The remaining residual plots are listed in APPENDIX IV.

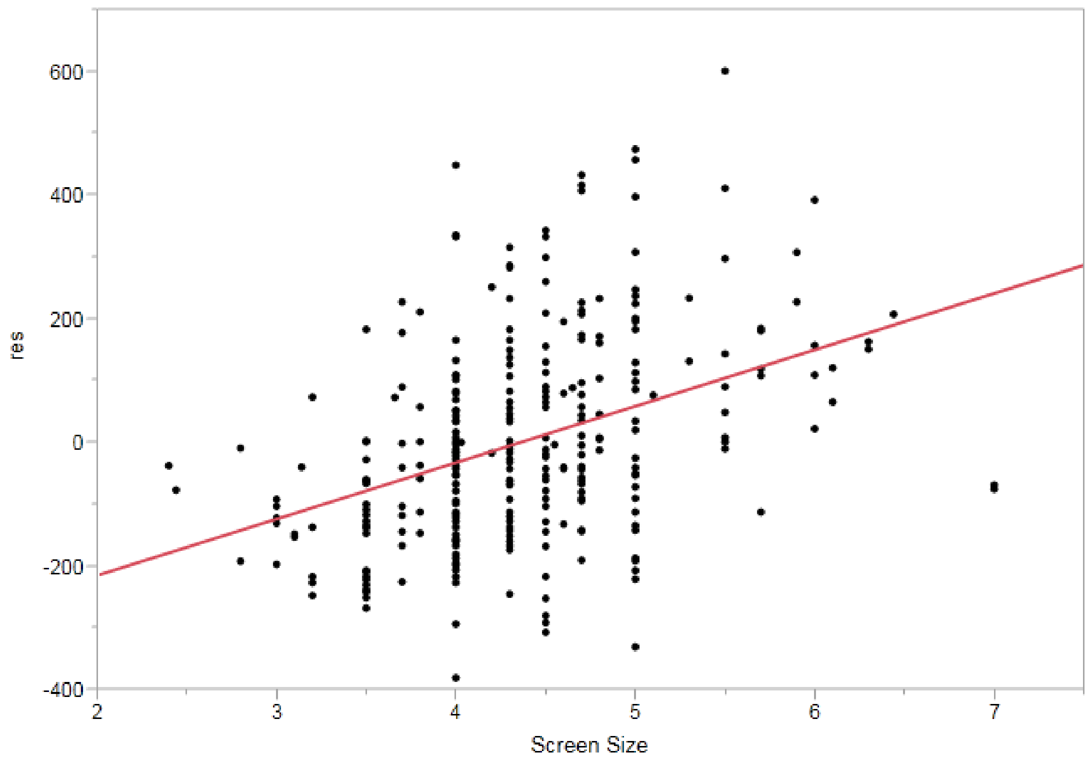

Figure 3.2: Residual Plot for Residual versus Screen Size

After analyzing the residual plot and defining continuous and non-continuous variables, all features are structured according to the input file to begin initial analysis.

3.5.1 Random Sample

Before beginning the first stage of the analysis, it was necessary to separate a set of phones that could serve as a working sample for predicting retail price. About ten percent of the entire sample set was removed from the complete sample set (three hundred and fifty eight smartphones) and kept out of the model creation. Since all types of smartphones from the database needed to be represented in the random sample, it was assumed that 10% of the total sample would be a reasonable random sample size. A random sample of thirty five numbers between one and three hundred and fifty eight was generated and the smartphones with the respective numbers allotted to them were removed. This random sample of smartphones is shown in APPENDIX II. Since this sample was not included in the analysis, the result of the analysis was used to predict the retail price of these randomly sampled phones.

3.6 Initial Analysis and Findings

3.6.1 Initial Analysis

In this section, we elaborate on the initial steps of the analysis and provide directions for further analysis based on the results. The initial intention was to employ all factors, level by level (i.e., Level 1 through 3), in a forward selection manner. All variables from a particular level are included at step of the analysis. At every step, the prediction for the randomly sampled phones is performed.

In order to begin with a basic model, a simple regression by regressing retail price on all Level-1 variables was performed. It is to be noted that smartphones that are missing some data are categorized under "Unknown" for every feature included in the analysis. In such cases, for every feature, the variable "Unknown.Feature" is marked one and other corresponding sections for the feature are marked zero. The response variable, retail price, was regressed on variables shown in Table 3.5.

Table 3.5: Level-1 independent variables

Variable Category	Variable Type	Independent Variable
Display Type	Categorical	LCD,OLED, Unknown.DisplayType
Battery Type	Categorical	Lithium-Ion, Lithium-Polymer, Unknown,BatteryType
Processor Brand	Categorical	Apple, Broadcom, Hexa-Core, HiSilicon, Intel, Marvell, MediaTek, Nokia, NVIDIA, Samsung, Spreadtrum, STMicro, ST-Ericsson, TI, Unknown.ProcessorBrand
Operating System	Categorical	iOS, Blackberry, Android, Windows, Symbian, Unknown.OS

The regression table for Level One regression is shown in Table1 of APPENDIX I. Using this outcome to predict the retail price for the thirty five randomly sampled phones resulted with prices with high variability between smartphones. A partial outcome of the prediction is shown in Table 3.6, and the complete prediction is attached in Table 2 of APPENDIX I.

Table 3.6: Prediction with Level-1 variables (partial)

#	Retail.Price	pred_price	error
1	490.00	415.74	74.25
2	450.00	363.48	86.51
3	449.99	498.01	-48.02
4	799.99	498.01	301.97
5	599.99	498.01	101.97
6	649.99	363.48	286.50
7	200.00	338.55	-138.55
8	387.93	497.27	-109.34

The table above lists the details for eight different phones from the random sample. There are three columns present: Retail Price, pred_price and error. The Retail Price is the actual price of the phone obtained from the teardown reports. The second column, pred_price, shows the predicted price that is calculated based on the variables included in the regression model. Finally, the last column showing error is the difference between retail price and predicted price (i.e., Column-1 minus Column-2).

Visual inspection of the error term across all the eight phones reveals that there exists large variation in price prediction using variables only from Level-1 of the BOM breakdown. This is more apparent by looking at the prediction across the complete set of thirty five phones in Table 2 of APPENDIX I.

To follow the process of forward selection and also due to high variability between price predictions using level-1 variables, it was anticipated that including Level-2 variables from the BOM along with Level-1 variables might help improve predictability for the same set of thirty five phones. As a result, the variables that better explain the Level-1 variables (i.e., Level-2 variables) from the BOM were added to the regression analysis. The display features from second level added are shown in Table 3.7, and the complete set including Battery, Processor, Camera, Storage and Connectivity variables are shown table in the APPENDIX III.

Table 3.7: Level-2 independent variables (partial)

Variable Category	Variable Name	Variable Type	Independent Variable
Display Module	Screen Size	Continuous	Screen Size
	Resolution Type	Categorical	Retina, DVGA, FHD, FWVGA, HVGA, nHD, qHD, QVGA, SVGA, WQVGA, WSVGA, WVGA, WXGA, XGA, Unknown.ResolutionType
	Pixel Density	Continuous	Pixel Density, Unknown.PixelDensity
	Number of Colors	Categorical	65K colors, 256K colors, 262K colors, 16M colors, 16.7M colors, Unknown,NumberofColors
	Backlight	-	No included due to lack of data

Before proceeding to discuss the prediction results from this analysis, it is necessary to note that the variables of optional components such as camera, storage and connectivity discussed in Table 3.3, are included at this stage of the analysis.

Table 3.8: Prediction with Level-2 variables (partial)

#	Retail.Price	pred_price	error
1	490.00	671.72	-181.72
2	450.00	228.94	221.06
3	449.99	480.53	-30.54
4	799.99	836.56	-36.57
5	599.99	509.70	90.28
6	649.99	464.13	185.86
7	200.00	289.70	-89.70
8	387.93	421.61	-33.68

Similar to the analysis with Level-1 variables, prediction of retail price for the same partial set of eight phones is shown in Table 3.8.

In comparison to Level-1 regression model, the intention of this step is to reduce both: the error in the prediction of retail price and the variability in prediction across the random sample. It can be noted that although there seems to be minor reduction in variability, the error still seem to be pretty high. This can be further reinforced by the prediction results shown in Table 4 of APPENDIX I. Therefore, any further addition of variables might not improve either of these factors.

3.6.2 Findings

From the results obtained from the analysis of just level-1 and both level-1 & level-2 variables, a few points including high error and variability across price prediction were noted. First, irrespective of the retail price and other features, smartphones with similar level-1 variables yielded the same predicted price. This is because only few variables defining the smartphones were included in the regression model. Second, few smartphones that had smaller error in the first model had much higher error in the second model. This could be attributed to detailed features (added from Level-2) of the same variable that might be highly correlated and hence been double counted, thereby increasing the predicted price and hence the error. Finally, the sample set including the random sample consists of smartphones across a wide range of retail price in them. As a result, the feature set of these smartphones would also vary widely. Hence it can be inferred that a regression model consisting this wide feature set would be unable to provide better prediction of retail price.

With these findings, during the course of the analysis, changes to the data set and the analysis technique were employed.

3.7 Segmenting of Smartphone sample

Since the collection of 358 smartphones ranged from $70 to $968, the range of features included in these phones was identified to differ to a large extent. This difference to a large extent, accounts for variation in the prediction of retail price in the analysis above. In order to eliminate this variation, based on retail price segmenting followed in the industry, the database of phones were divided into four separate segments: Entry Level Phones, Value Phones, Mainstream Phones and Performance Phones. Retail price brackets for each of these segments are shown in Table 3.9. The table also includes the sample size available in each of the segments.

Table 3.9: Segmented Smartphone Data

Phone Segment	Retail Price ($)	Sample Size
Entry Level	(, 100]	6
Value	(100, 200]	56
Mainstream	(200, 400]	135
Performance	(400,)	161

The sample size in the segments shown above includes the 35 smartphones from the random sample used for testing predictions. Removal of these smartphones from the working list resulted in reduced sample sizes shown in Table 3.10.

Table 3.10: Segmented Smartphone Data without Random Sample

Phone Segment	Retail Price ($)	Sample Size
Entry Level	(, 100]	6
Value	(100, 200]	49
Mainstream	(200, 400]	124
Performance	(400,)	144

Since the sample size and the number of detailed teardown reports in the Entry Level and Value segment were not sufficient, these two segments were filtered from the dataset at this stage. In addition, about 69% of the smartphones released in APPENDIX II were in the Mainstream and Performance segments. Of these, 130 performance smartphones and 117 mainstream smartphones were released in the last two years. Although this is the case, 45 of 55 detailed smartphone teardowns available for the 69% smartphones was constituted by Performance Phones.

3.8 Retail Price Model Development

Based on the finding from the initial analysis and segmenting of smartphones based on retail price, two actions were taken to improve predictions. First, for the purpose of this research, retail price model development was performed on smartphones only from the performance segment. This was for two reasons: 1) better data availability for smartphone reports collected for this research, 2) the purpose of segmenting was to perform the analysis segment by segment and improve the price predictions. Second, the hierarchy of adding variables to the regression has been setup from this stage of the analysis. Previously, during Level-1 and Level-2 of initial analysis, variables were assumed to be affecting price based on BOM levels. Therefore, all variables were added to Level-1 regression and all variables from Level-1 & 2 were added to Level-2 regression models.

The second action mentioned above refers to improving the method of adding variables to the model and hence setting a hierarchy. In addition, accounting for maximum amount of cost in the model with the least amount of explanatory variables was considered important. Therefore, subsystems (i.e., all variables explaining the subsystem shown in the detailed BOM breakdown) are added to the regression model in descending order of price contribution to the overall cost of the smartphone.

To identify the amount of cost contribution, smartphones with detailed teardowns were utilized. Since detailed teardown reports provide approximate subsystem costs, the averages of each of these subsystem costs were utilized to generate a Pareto chart. The averages of subsystem costs available from the reports are shown in Table 3.11. Since costs of all subsystems are not available from teardown, the sum of all available subsystem costs is considered to form 100% of the Pareto Chart Analysis in Figure 3.3. The complete list of smartphones used to create this analysis is shown in APPENDIX V.

Table 3.11: Average pricing of subsystems from detailed teardown reports

Components	Cost	Percentage of total	Cumulative Percentage
Display Module	$37.82	44.99%	45.0%
Processor/SoC	$27.5	32.71%	77.7%
Camera(s)	$14.2	16.89%	94.6%
Battery	$4.54	5.40%	100.0%

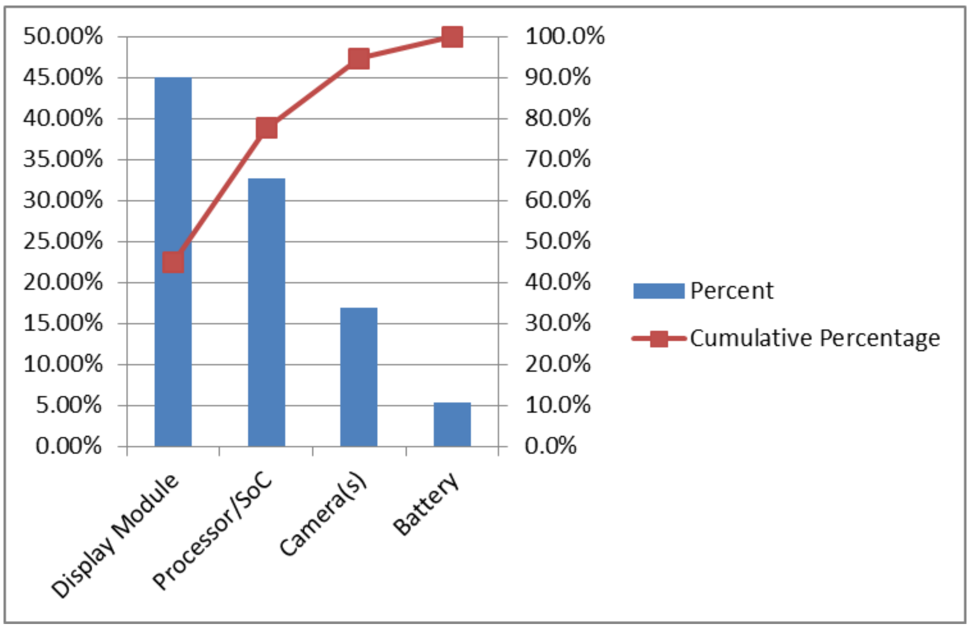

Figure 3.3: Pareto Chart for component subsystems

Based on the Pareto analysis above display module, processor, cameras and battery are initially added to the regression model, in the respective order. All other subsystems are subsequently added to the regression model based on industry trends and correlation with other variables in the analysis.

3.8.1 Sample One Model

The regression analysis was performed on a sample of 146 performance segment smartphones. The remaining 15 of the randomly sampled smartphones from this segment were used for retail price prediction using the outcome of the regression analysis. In order to identify any time effects on retail price or on cost of other components, two parallel regression analyses was carried out. The first regression did not have release dates included whereas the second model did include release of smartphones from the beginning of the analysis. The analysis with release dates is performed in the section 3.8.2.

Since the final objective of the model is to predict display cost, it is necessary to include all of the display feature variables in the analysis. As a result, at first, the retail price was regressed on all display variables, except lamination type, from the BOM breakdown. Although data on variable “lamination type” is unavailable from teardown reports or other sources, it is included in the detailed BOM breakdown only for representative purpose of display features.

At every step of variable addition, four parameters were noted in the regression analysis and in the prediction analysis: R-squared, Adjusted R-Squared, Standard Error in the regression model, and Root Mean Squared Error of predicted retail prices on from random sample.

The model began with Display Type and then adding all display feature variables. The order between display variables is random since all of the features are necessary in the model to define display cost. Subsequently, based on pareto analysis, processor, RAM, cameras – both rear camera and front camera, storage, battery, and other features of sensors, accessories and connectivity were included. Every line in Table 3.12, refers to a model. And each of the models includes all variables from prior models including the variables in the corresponding line.

Table 3.12: Regression Parameters (without Release Date) for Sample One Model

Without Release Date						
Performance Phones						
Model	**Variables**	**Additional Variable(s)**	**R-Sq**	**Adj. R-Sq**	**S.E**	**RMSE**
1	Display Type	NA	0.001797	-0.00523	133.8	131.78
2		Screen Size	0.06698	0.05374	129.8	124.21
3		Pixel Density	0.2502	0.2342	116.8	125.26
4		Colors	0.2834	0.252	115.4	120.08
5		Cover Glass	0.3107	0.2476	115.7	121.99
6		Processor Brand	0.3797	0.2482	115.7	115.65
7		Cores	0.3818	0.2245	117.5	111.93
8		RAM Type	0.4247	0.2383	116.5	113.96
9		RAM Capacity	0.4419	0.2471	115.8	113.58
10		Rear Camera Capacity(MP)	0.4607	0.2585	114.9	110.88
11		Rear Camera Optical Size	0.4714	0.2589	114.9	111.37
12		Rear Camera Lens Elements	0.476	0.2506	115.5	110.04
13		Front Camera	0.4987	0.2685	114.1	115.21
14		Front Camera Capacity(MP)	0.5029	0.2595	114.8	116.04
15		Log(Internal Memory)	0.5137	0.2602	114.8	115.01
16	-RAM	Battery Type	0.4934	0.2608	114.7	107.74
17	-RAM	Battery Pack Rating	0.4958	0.2567	115	109.38
18	-RAM	Gyro, Baro, Temp Sensors	0.5347	0.2688	114.1	123.21
19	-RAM	Headset	0.5584	0.2905	112.4	114.80
20	-RAM	USB Version	0.5675	0.2891	112.5	114.07
21	-RAM	- Rear Camera Optical Size	0.5658	0.3023	111.5	115.21

After exhausting all variables, backward elimination of specific variables based on the four parameters is performed. Variables that induce high error when added to the regression model are immediately removed and are not shown in Table 3.12. Variables that cause minute increase in error are continued to be retained in the regression model for evaluation later in the analysis. Elimination of variables in Table 3.12 is indicated by a minus sign in front of the variable.

Of the four parameters considered above, three are considered essential in selection of a model with the right combination of parameters. They are Adjusted R-Squared, Standard Error, and Root Mean Squared Error. To select a model out of the 21 models listed in Table 3.12 above, analysis similar to pareto efficiency is performed. All three parameters are plotted against each other to identify the best possible points on each chart. Each point in the chart represents one of 21 models presented in Table 3.12.

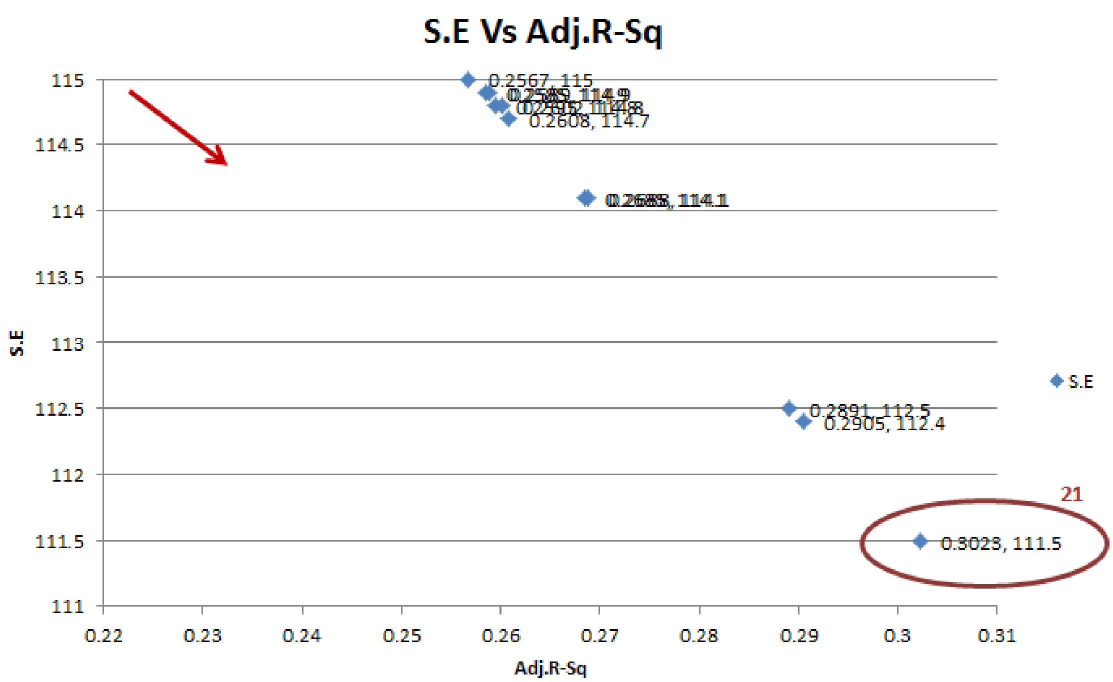

Figure 3.4: Sample One (without release) - S.E Versus Adj.R-Sq

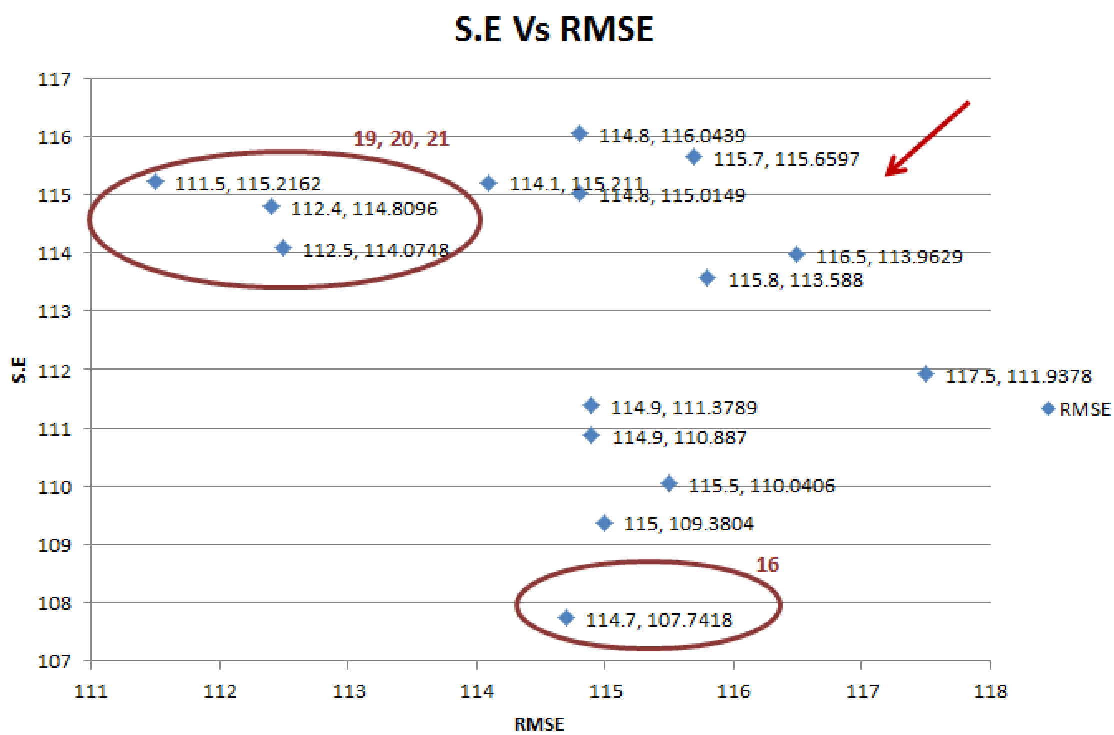

Figure 3.5: Sample One (without release) - S.E Versus RMSE

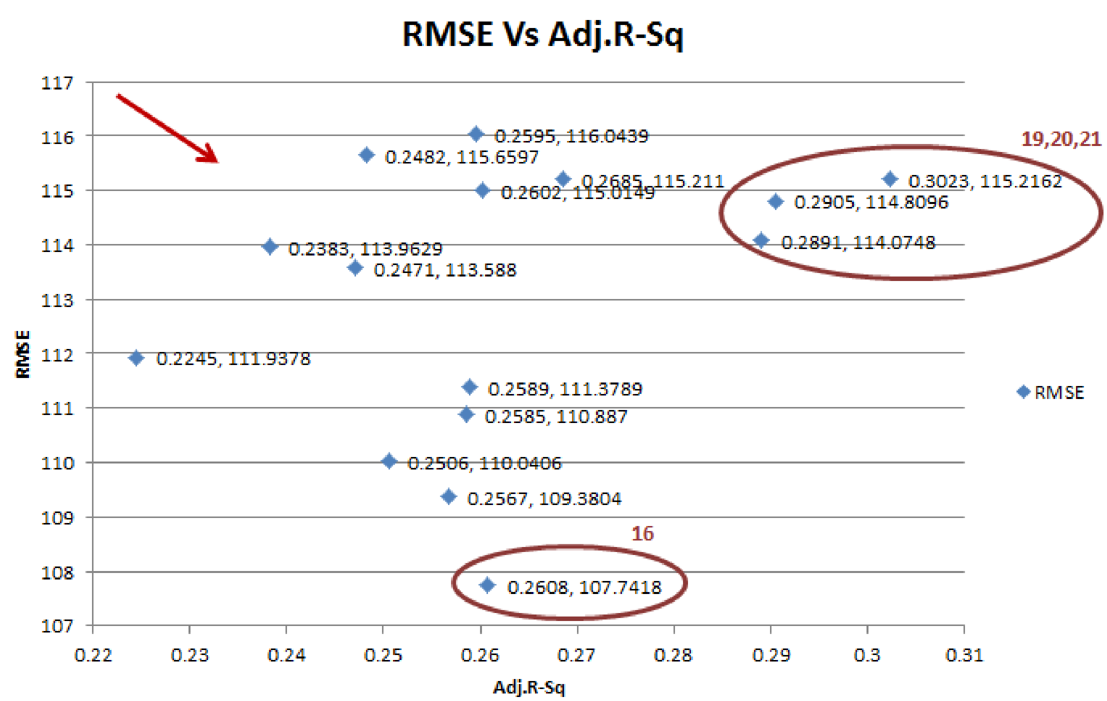

Figure 3.6: Sample One (without release) – RMSE Versus Adj.R-Sq

The points that have the best of values of both parameters in each chart are identified. Arrows in each chart points the desired direction in which both parameters in the plot would produce best results. Common points from all the three charts were picked. From the pareto efficiency charts above, although other models are highlighted, only model 21 was present in all three charts. As a result, it was summarized that variables in model 21 are found to produce, not only the lowest errors but also, the best possible retail price prediction compared to all other models.

3.8.2 Sample Two Model

The second half of the regression analysis that includes release dates is performed in this section. The steps in the analysis are exactly similar to that of Sample One Model, except for addition of release dates from the beginning of the analysis. The release dates of phones are clustered in quarters of the year in which it was released. For example, a smartphone released in from July to September of 2013 would be clustered under one variable named Q3'13. Similarly all 146 phones from the performance segment are clustered into twenty quarters including the variable Unknown.ReleaseDate for unknown release date. The same set of 15 randomly sampled smartphones is used for predicting retail price from the analysis outcome. Twenty one models with selection and elimination of variables similar to Sample One Model are shown in Table 3.13.

When all the three charts above are considered together, points 19 and 21 are found common. This was unlike one single point being chosen in Sample One Model. Selection of either model in this case would not lead in drastically different results. But selection of Model 21 from Sample One Model could justify favoring the selection of the same from this analysis as well.

Table 3.13: Regression Parameters (with Release Date) for Sample One Model

With Release Date						
Performance Phones						
Model	**Variables**	**Additional Variable(s)**	**R-Sq**	**Adj. R-Sq**	**S.E**	**RMSE**
1	Display Type	Release Date	0.1433	0.03542	131	143.57
2		Screen Size	0.1929	0.08404	127.7	126.19
3		Pixel Density	0.4115	0.3268	109.5	124.88
4		Colors	0.4485	0.3536	107.3	120.28
5		Cover Glass	0.4787	0.3573	107	124.49
6		Processor Brand	0.5421	0.3642	106.4	117.05
7		Cores	0.5537	0.3553	107.1	125.89
8		RAM Type	0.5889	0.3678	106.1	128.38
9		RAM Capacity	0.6135	0.3926	104	128.12
10		Rear Camera Capacity(MP)	0.619	0.3879	104.4	120.86
11		Rear Camera Optical Size	0.6289	0.3901	104.2	115.45
12		Rear Camera Lens Elements	0.6332	0.3829	104.8	115.27
13		Front Camera	0.6534	0.4029	103.1	121.15
14		Front Camera Capacity(MP)	0.6535	0.3883	104.4	120.68
15		Log(Internal Memory)	0.6586	0.3821	104.9	117.35
16	-RAM	Battery Type	0.6472	0.3922	104	112.33
17	-RAM	Battery Pack Rating	0.6472	0.3847	104.7	112.32
18	-RAM	Gyro, Baro, Temp Sensors	0.6699	0.3789	105.2	119.92
19	-RAM	Headset	0.7004	0.4211	101.5	102.95
20	-RAM	USB Version	0.7015	0.4071	102.7	99.728
21	-RAM	- Rear Camera Optical Size	0.7009	0.422	101.4	99.22

To evaluate the best model, pareto efficiency charts below were created.

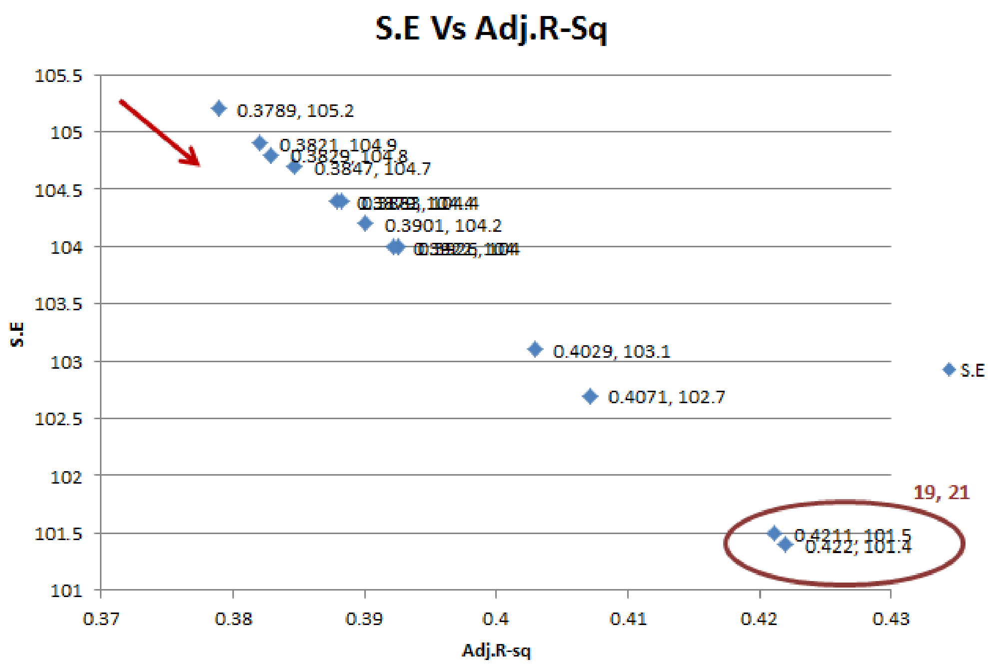

Figure 3.7: Sample Two (without release) - S.E Versus Adj.R-Sq

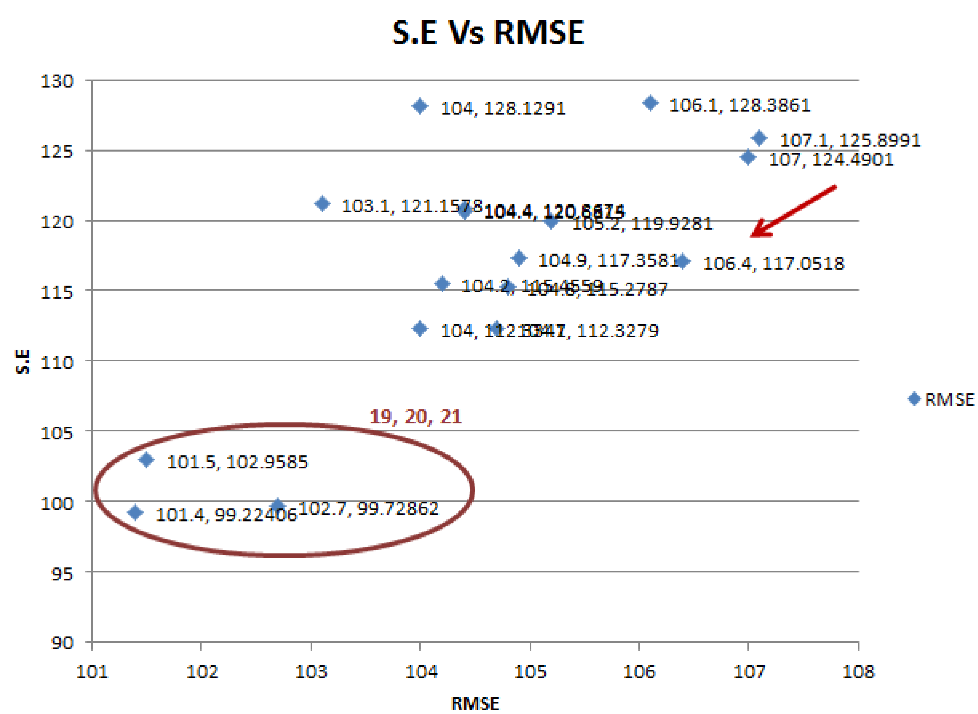

Figure 3.8: Sample One (without release) - S.E Versus RMSE

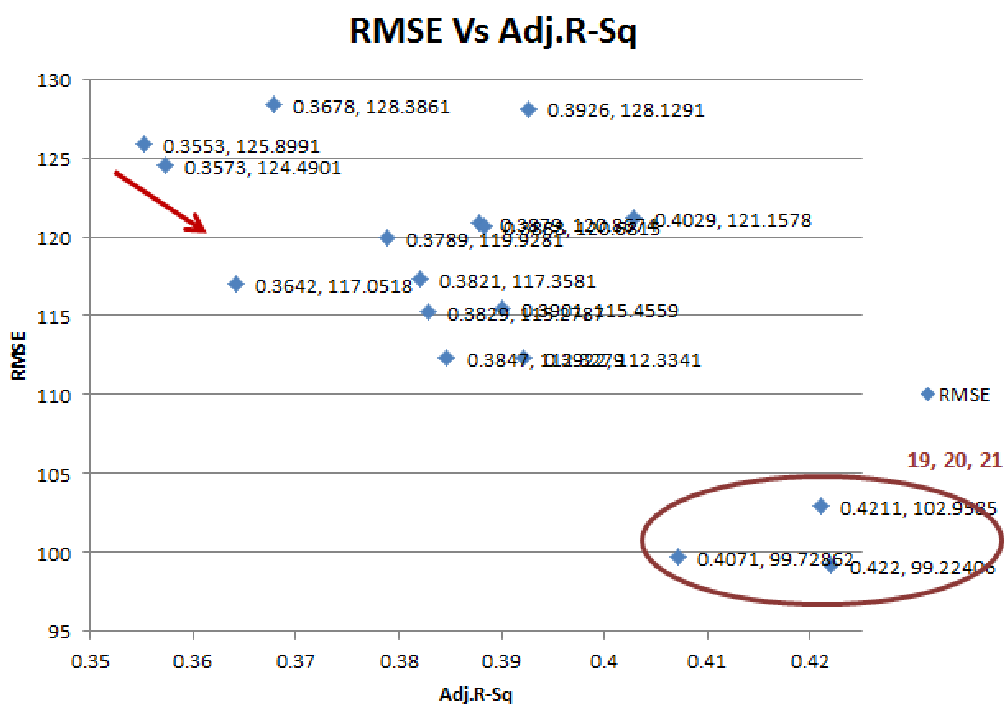

Figure 3.9: Sample One (without release) – RMSE Versus Adj.R-Sq

3.8.3 Cross-Validation of Retail Price Model

In order to improve the outcome of this analysis, cross-validation was performed. In cross-validation, the complete sample of smartphones was broken down into various groups. To maintain consistency, the sample was broken down into 10 distinct groups named folds. This ensured similarity with 10% of phone randomly sampled for Sample One and Sample Two Models. Each fold from the 10 folds was eliminated once to be used as a random sample for retail price prediction. The other 9 folds were used in the analysis used for prediction. As a result, ten separate groups of phones predict retail price and validate the analysis performed.

Table 3.14: Cross-validation for Retail Price (without release date)

Without Release Date			
Performance Phones			
Model #	**Variables**	**Additional Variable(s)**	**RMSE**
1	Display Type	-	133.61
2		Screen Size	129.86
3		Pixel Density	118.48
4		Colors	120.08
5		Cover Glass	123.18
6		Processor Brand	123.96
7		Cores	128.72
8		RAM Type	128.83
9		RAM Capacity	130.58
10		Rear Camera Capacity(MP)	132.98
11		Rear Camera Optical Size	133.63
12		Rear Camera Lens Elements	135.71
13		Front Camera Capacity(MP)	138.56
14		Log(Internal Memory)	140.04
15	-RAM	Battery Type	137.19
16	-RAM	Battery Pack Rating	139.93
17	-RAM	Gyro, Baro, Temp Sensors	151.07
18	-RAM	Headset	155.10
19	-RAM	USB Version	156.73
20	-RAM	- Rear Camera Optical Size	152.40
21	-RAM	- Cores	145.92
22	-RAM	- Processor Brand	130.51
23	-RAM	PoP	132.14
24	-RAM	- Gyro, Baro, Temp Sensors	124.74

As seen in Sample One and Sample Two models, forward selection and backward elimination of variables created various models to consider. To check all of the models, the cross-validation technique explained above was to be performed on every model. As a result, at least 21 separate models were to be cross-validated. Unlike three parameters in previous cases, only one parameter was considered to judge each models performance: Overall Mean Square. The Overall Mean Square is similar to RMSE parameter utilized in sections 3.8.1 and 3.8.2. But it is in the squared form of S.E. Similar to the Retail Model developed in the last two sections, two parallel cross-validation analyses were performed: with release date and without release date. Model development without release date is shown in Table 3.14.

Table 3.15: Cross-validation for Retail Price (with release date)

With Release Date			
Performance Phones			
Model #	**Variables**	**Additional Variable(s)**	**RMSE**
1	Display Type	Release Date	140.49
2		Screen Size	135.89
3		Pixel Density	119.43
4		Colors	117.82
5		Cover Glass	120.55
6		Processor Brand	121.16
7		Cores	125.79
8		RAM Type	129.38
9		RAM Capacity	129.77
10		Rear Camera Capacity(MP)	133.03
11		Rear Camera Optical Size	131.43
12		Rear Camera Lens Elements	134.47
13		Front Camera Capacity(MP)	139.67
14		Log(Internal Memory)	145.49
15	-RAM	Battery Type	143.66
16	-RAM	Battery Pack Rating	145.54
17	-RAM	Gyro, Baro, Temp Sensors	159.95
18	-RAM	Headset	153.40
19	-RAM	USB Version	161.14
20	-RAM	- Rear Camera Optical Size	158.14
21	-RAM	-Cores	145.91
22	-RAM	- Processor Brand	130.69
23	-RAM	PoP	130.60
24	-RAM	-Gyro, Baro, Temp Sensors	123.49

On Table 3.14, the model with the lowest mean square error (Overall MS in column 4) is desired. Although model 4 results in the lowest overall MS, it was noticed that all display features were not covered at this point. In addition, complete definition of a smartphone would need to include variables more than that in model 4. Therefore, the analysis was continued to include as many variables as possible and still achieve a low mean square error. After model 4, model 24 resulted in the lowest mean square error possible. As a result, this model produces the best retail price predictions as shown in Table 6 of APPENDIX I. Thus, we choose model 24 to be the cross-validated model that includes variables that define and fit the best retail price for smartphones.

The same cross-validation analysis, including release dates, was performed on the same set of smartphones. This model development is shown in Table 3.15.

As expected from the addition of release date variable to the analysis, the mean square error value for each of the models above were different from the corresponding ones without release date in Table 3.14. It is interesting to note that, although the expectation of the error value by adding release date variable would be positive, the first few models showed higher errors. But the overall outcome of the cross-validation analysis with release date was similar to that of one without.

Model 4 was the first to have the least mean square error, whereas as lack of definition of smartphone using all variables at this stage eliminated this model. As a result, model 24 is selected with next best mean square error value. The prediction using this model is shown in Table 8 and Table 10 of APPENDIX I.

3.8.4 Summary

From the two models: Sample One and Sample Two, along with cross-validation between phones, two goals were accomplished. First, a methodology for streamlined selection of smartphone feature variables was established. Second, a model to predict retail price of smartphones with least error was created. One of the initial objectives of this research was to isolate the display features from the final retail price model and develop a model for display cost predictions. For this, it was necessary to separate the coefficients from the retail price regression model and build a model based on varying display features.

Although the coefficient for the variable display type was found to be correct, most other display variables coefficients in the retail price model were much higher than expected, as shown in Tables 5, 7 and 9 of APPENDIX I. These increased coefficient values were attributed to a few reasons evident from the model: 1) Correlation between display variables and other variables in the model, 2) Display variables being assigned some part of the coefficients from other variables, and 3) lack of more variables (both display and others) that could help explain the model better than its current state. As a result, it was identified that it was not possible to be separate display features from the analysis. Therefore, it was necessary to utilize the detailed teardown available for as many smartphones as possible.

The analysis performed in section 3.7 and 3.8 help validate the method in which the data is setup. Creation of a model and prediction of retail prices with low error confirmed that the data setup works well in its current format. It was noticed that at this stage of the analysis, the outcome would reject the hypothesis-1 based on the result. But we proceed to involve a sub-set of information available from this data for further display cost model development.

3.9 Display Model Development

After clear validation of data setup from section 3.8, it was found that there needed to be no other changes to be performed for display model setup. On the other hand, the amount of data available to perform display cost evaluation was different and smaller. From the data collected for 358 smartphones, due to segmenting, 161 phones were used in the retail price modeling. From this sample, detailed teardown reports that include data on display module costs are 55 across all brands of smartphones. Although a smaller subset of data, it can be assumed that this fairly represents the entire sample size due to its randomness in detailed teardown report availability.

3.9.1 Data and Model Setup

The subset of smartphones with detailed reports is separated from the non-detailed set of phones. All five display variables from the BOM breakdown are modeled, continuous or categorical, as in the retail price model. The five display variables used are shown in Table 2.1. A regression model is set up to regress display module cost on these five display variables. As construed from teardown reports and based on industry learnings, the display module constitutes display, touchscreen panel, and cover glass Figure 2.2. Since display cost prediction is the main objective of this research, it was necessary to ensure the sample size of data did not violate any assumptions of linear regression modeling. A sample size of 55 smartphone was sufficient to be used to examine using the residuals obtained. Executing a linear regression model in R-Studio resulted in the output shown in Table 9 of APPENDIX I. After performing the regression model it was noticed that, if release dates were taken into consideration, six phones distributed across seven quarters make an unsuitable sample size for display module cost prediction for certain quarters. Also, these six phones were older which would not be as relevant to the model to obtain precise price predictions. Therefore, these six smartphones were removed from the execution of the display model.

Table 3.16: Display Cost Model Parameters (without release date)

Model	R-Sq	Adj.R-Sq	S.E
Without Release Date	0.649	0.557	7.84

The linear model parameters are shown in Table 3.16 above. An Adjusted R-Squared of 0.557 and a Standard Error of $7.84 was seen. The display variables included in the model explain 55.7% of the variation in display module cost, as represented by adjusted r-squared.

Since variables in this regression model helps explain only about 55 % of the variation in display cost, additional variables available from the database were explored as a measure to improve adjusted r-squared. Technology maturity and newer technology introduction over a longer time range could lead to changes in cost of display components. Since data on smartphones is spread across a large period of time, date of release of a phone was considered. As modeled for retail price models, release dates are clustered into quarters. On the other hand, cost of display module varies based on different smartphone manufacturers. And since the data utilized in this research is spread across various smartphone brands, smartphone brand was chosen. Smartphone brands are modeled as 1 and 0 in the form of categorical variables. For example, an Apple brand phone is indicated 1 for the variable "Apple" and all other brands are indicated zero. Regression Models for display models with release date and smartphone brand are shown in Table 10 and Table 11 of APPENDIX I. The parameters of these models are shown in Table 3.17.

Table 3.17: Display Cost Model Parameters (with release date, and smartphone brand)

Model	R^2	Adj.R^2	S.E
With Release Date	0.745	0.579	7.65
With Release Date and Smartphone Brand	0.819	0.585	7.59

It was noticed that addition of smartphone brand and/or release did not drastically change either the Adjusted R-Squared or the Standard Error of the model. Hence, it was certainly difficult to choose one of the three models. Therefore, to pick one of these models it was necessary to check the display cost predictability of these regression outcomes using variables in each of these models. As a result, cross-validation of display price model was performed.

3.9.2 Cross-Validation of Display Price Model

After removing the six smartphones from the detailed teardown smartphone sample, the remaining 49 phones were utilized to perform cross-validation across 10 groups (also known as folds). Nine folds contained 5 samples each, whereas one fold contained 4 samples. Each of these folds predicted display module cost for their corresponding samples and generated a mean square error. All of these errors summed up to form the overall mean square error. This was performed using variables corresponding to all three regression models performed in the previous section 3.9.1. The overall mean square errors, along with other regression parameters for the three models are shown in Table 3.18.

Table 3.18: Cross-validation results for display cost model

Model	R^2	Adj.R^2	S.E	Overall MS	Predicted RMSE
Without Release Date	0.649	0.557	7.84	80.2	8.95
With Release Date	0.745	0.579	7.65	140	11.83
With Release Date and Smartphone Brand	0.819	0.585	7.59	190	13.78

Choosing a model based on results from the previous section was ambiguous. Whereas, by comparing the overall MS (from Table 3.18) which represents the overall mean square error for predicted smartphones, it is clear that the model with the lowest MS would be the most suitable. Taking a square root of overall MS in the first model provides the predicted root mean square error. This model results in $8.95 error which is relatively lesser compared to other models.

For all of the three models, the predicted cost is fitted against the actual cost for each fold in the model. The predicted display module cost is plotted on the x-axis and actual display module cost on y-axis. The line is most suitable when the line follows a 1:1 ratio (otherwise represented by the equation x = y) in its direction between predicted and actual cost. This would indicate that the predicted cost is very close to the actual display module cost.

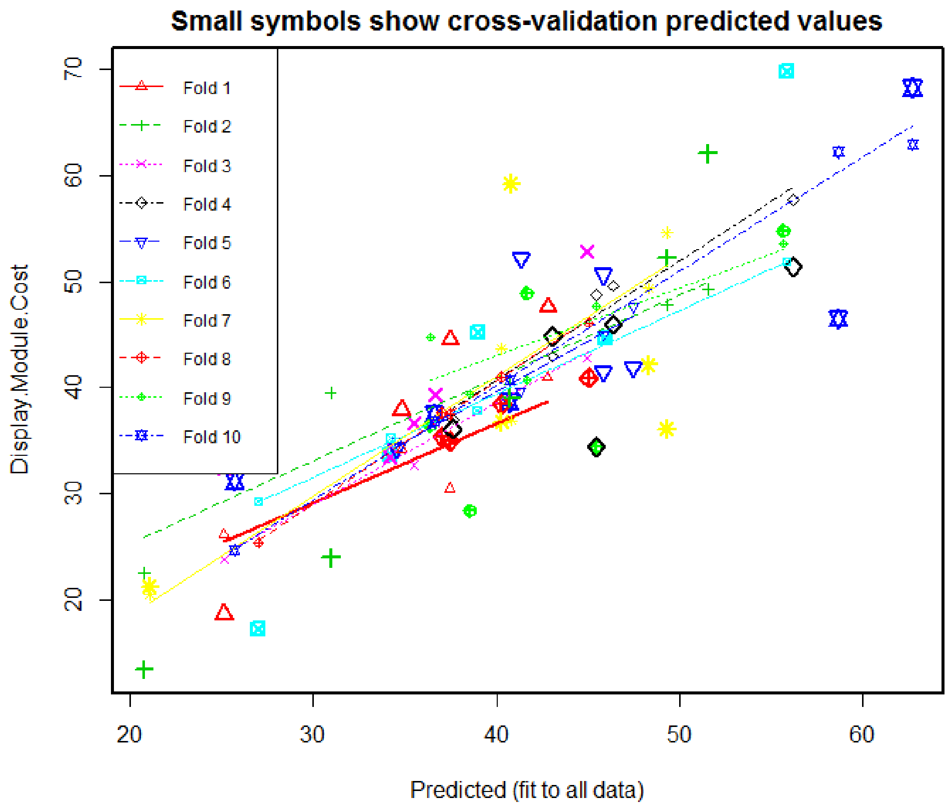

Figure 3.10: Cross-validated fit for display model (without release date)

The fitted lines for folds in the model without release date are shown in Figure 3.10. The fitted lines, although not perfectly forming 1:1 lines between x and y axis, were reasonably close in their fits. This can be explained by the mean square error in each fold. In addition, it was noted that no outliers in predictions far away from the fitted lines we found. Cross-validation for two other models with additional variables was performed to explore any further improvements.

The fitted lines for the folds in the other two models (with release date, and with release date and smartphone brand) are shown in Figure 3.11 and Figure 3.12 respectively. Visual inspection of the two figures revealed, although there seemed to exist no outliers, the fitted lines for most folds are skewed away from the 1:1 pattern that is deemed necessary for good prediction. This can be explained due to the mean square errors in each of these models shown in Table 3.18. Results from Table 3.18 above indicate that the overall mean square errors for both models are higher compared to the model without release dates.

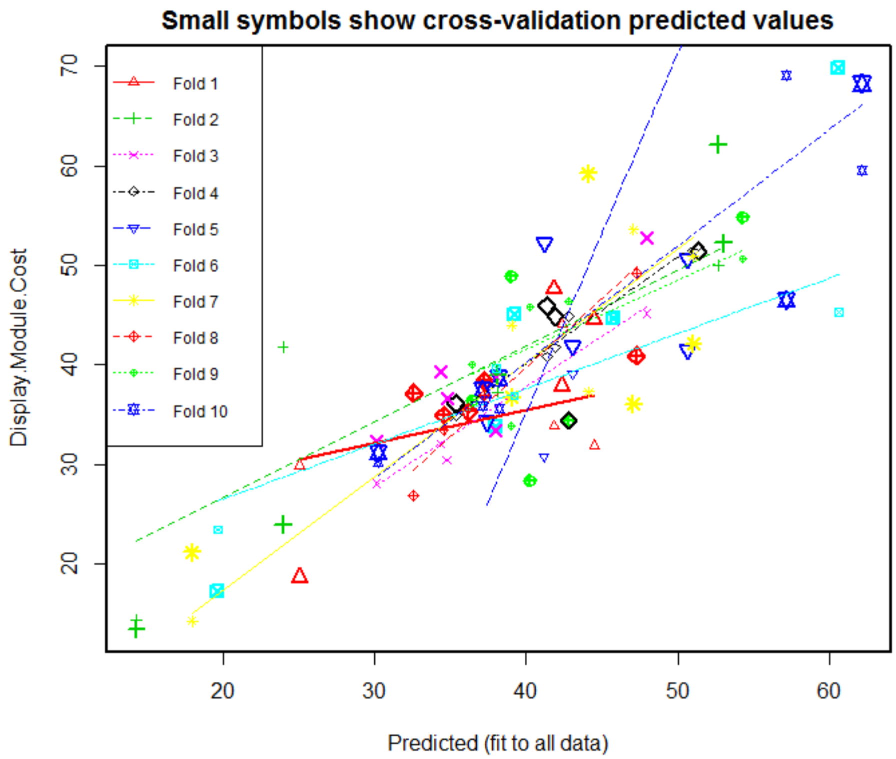

Figure 3.11: Cross-validated fit for display model (with release date)

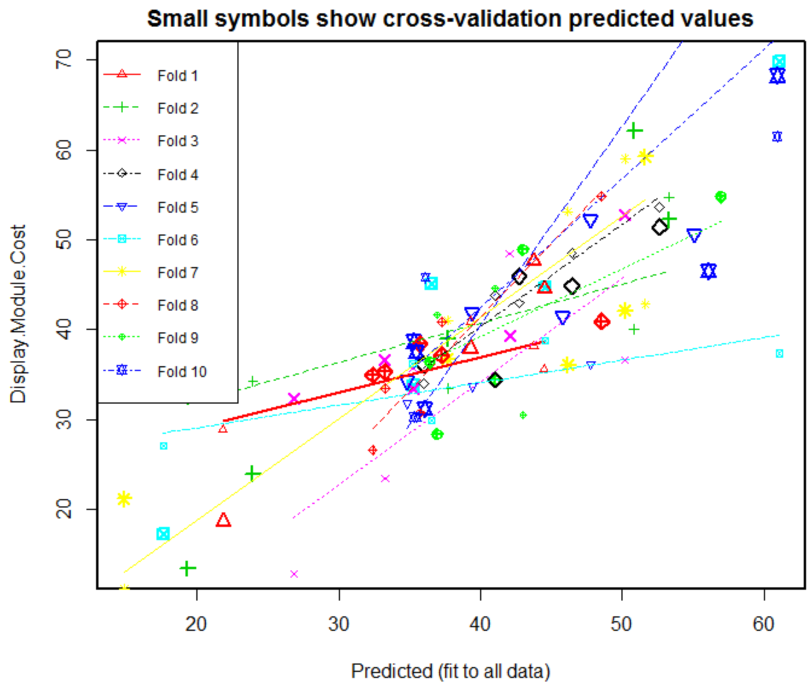

Figure 3.12: Cross-validated fit for display model (with release date and brand)

Comparing the outcome of the three models based on the different errors and cross-validation prediction charts, it was concluded the first model with the predicted root mean square error of $8.95 and better aligned prediction fits would be chosen to create the final display cost model. The transformation of this display cost model into the required Should-Cost Model interface for practical use is presented in Chapter 5. The usability and applicability of the predicted display cost are discussed in Chapter 6.

CHAPTER 4

4 A Should Cost Analysis through Significance Testing using Statistical Tools

4.1 Abstract

The market for technological products is highly competitive in terms of both technology and cost. Therefore, companies making these products are trying to adopt designs and methodologies that could help them stay competitive. An integral element of producing a product is strategically sourcing the components from various suppliers. The objective of this study is to compare the combinations of different components that go into a product and analyze the difference to build a Should Cost Analysis that helps during negotiation of pricing for sourcing components. The combinations are evaluated through significance testing using available statistical tools and methodologies. In certain cases, combinations with similar components/technology might drastically differ in cost. Such differences in cost are considered for further investigation at sub-component level of each of the combinations. Indication of relative increase in cost of a combination can assist in identifying factors affecting the cost of sourcing the particular combination. The resulting should-cost model can help analyze various causes that add to the cost of sourcing and hence serve as a good first hand basis for analyzing components/materials. As a result, this model would assist in effective negotiations ahead of sourcing.

4.2 Keywords

Cost Breakdown, Should Cost Analysis, Material Sourcing Cost.

4.3 Introduction

On reviewing the current pricing trends in the technological industry, it can be inferred that the Smartphone and Tablet industry has been experiencing unprecedented cost pressure. In such industries, competition is so high that even newer technologies cannot be sold at a very high premium. This facilitates the need for cost effective product development for ensuring success in the marketplace. About 60% of the cost of manufacturing a product is incurred from component purchases (Gencer & Gurpinar, 2007). Consequently, focusing on material cost should be instrumental in addressing a larger portion of the cost pressure in a smaller scope of work. Further, since an expensive portion of the smartphone cost coming from key component such as display (Anderson & Jonsson, 2006), a Should Cost analysis on displays would assist in cutting down a sizable portion of the overall production cost of phones.

The analysis proposed in this paper would help breakdown the price-component relationships and their significance. In order to address most recent trends, the analysis is performed on smartphones that are currently available in the market. As the development cycle of a smartphone seems to take about two years, the data for the research covers phones released in the last two years, giving us a range of about four years of display technologies to consider.

4.4 Current Knowledge and Practice

This section is divided into two sections, the first of which reviews the current practices available for cost estimating methodologies and the latter on current classifications in display technologies being considered in the research. The research includes focus on practical application of the resulting model in an industry setup, leading to the need for the most recent data pertaining to smartphone components.

4.4.1 Cost Estimation Techniques

Newnes et al (Newnes, et al., 2008) mention the availability of a number of cost estimation techniques, Generative Estimating and Parametric Estimating being the two basic types. Detailed data being gathered in the due course of a project is used in the generative approach, whereas estimation based on prior projects, past experiences and expected costs is utilized in the parametric approach. Each of these approaches possesses their own pros and cons. Although greater detail is demanded by the generative approach, estimation of cost per part is possible. On the other hand, applying relationship to cost evidence from previous products is used in the parametric approach.

Table 4.1: Cost estimating methodologies and lifecycle applicability

ANALOGY	PARAMETRIC	ENGINEERING (or) BOTTOM-UP	EXTRAPOLATION FROM ACTUALS
Compares new/proposed system with on homogenous system (i.e., similar) in which the form, fit and function are alike	Uses statistical regression analysis of a database of two or more similar systems	Reflects a detailed build-up of labor, material and overhead cost	Uses the actual (past or current) cost of an item to estimate future costs
Should include accurate cost/technical data from recent past	Develops cost estimating relationships (CERs) which estimate cost based on one of more system performance or design characteristics	Most detailed of all the techniques and the most costly to implement	Best suited for estimating follow-on units of the same item when there are actual data from current or past production efforts
Needs logical correlation between the proposed and past systems identified by the cost estimator	Performed in the initial phases of product description. CERs used to evaluate the cost effects of changes in design and performance and other characteristics	Data is available to populate the Work Breakdown Structure (WBS)	Essential to have accurate at the appropriate level of detail, and the cost estimator must ensure that the data is validated and normalized
Uses of additive and multiplicative factors	Based on statistical inferences about the relationship between cost and schedule	Estimate is based on standards, either company-specific or industry-wide	Reliance on historical costs to predict future costs

Application to low volume products and novel designs although proves less effective by this method (Watson, Curran, Murphy, & Cowan, 2006). These two techniques are included in the IMD Cost Methodology Book (IMD Cost Methodology Guidebook, 2013) by the Department of Defense, along with other such as Analogy and Expert Opinion. Their methodology and applicability presented in Table 4.1.

General classifications based on analysis are: analogous cost estimation (ACE) - otherwise known as 'top-down approach', 'bottom-up approach', and computing technology with artificial intelligence (Chou, Tai, & Chang, 2010). The top-down approach constitutes of the estimation of overall cost of the product and subsequent break down to sub-component level costs; the bottom-up approach is vice-versa (Watson, Curran, Murphy, & Cowan, 2006). Each of the estimating methods based on information available can be categorized into top-down and bottom-up approaches. The collection of cost data for each sub-component and the rolling up to the highest level in the bottom-up approach hold similarities with the generative estimation technique mentioned in the beginning of this section. Application of each of these techniques is also related to the stage of development of a product (Chou, Tai, & Chang, 2010).

Watson et al (Watson, Curran, Murphy, & Cowan, 2006) state that the estimation methods can be further divided into explicit (rule-based) cost estimating, rough order magnitude (ROM) (ratio) estimating, parametric cost estimating, and detailed estimating using activity-based costing (ABC) and/or resource costing; each of which are often based upon past experience. Approaches involving the use of artificial intelligence such as fuzzy logic and neural nets are rapidly developing which mimic the human thought process. Also, Variant (analogy) estimating (Watson, Curran, Murphy, & Cowan, 2006) involves identifying a similar part/ completed project cost and then using this actual cost as a basis for the estimate of the new part/project.

4.4.2 Overview on Display Technology

Displays used in smartphones broadly constitute three underlying structures: the Cover Glass, the Touchscreen panel (TSP) and the Display Module, in the respective order, from the outer end of the phone. A variety of differences in characteristics and functions have promoted use of different types of these components in current smartphones. Percentage of phones and smartbooks with touch technologies is projected to be 50% and 93%, respectively in 2014 (Lee, 2011). Eleven categories of touch technologies are listed by DisplaySearch (Colegrove, 2012): resistive (both analog and digital, surface capacitive, project capacitive, infrared (traditional infrared), optical imaging (camera-based), acoustic wave (both surface acoustic wave [SAW] and bending wave), digitizer, in-cell, on-cell, combination, and other touch technologies. Amongst these, the widely used Projected Capacitive (Pro-Cap) was first used in the iPhone in 2007 (Lee, 2011) and since then it has increasingly been used. It is expected that approximately 70% of the mobile phone market will use this technology (Lee, 2011). Variations in Pro-cap TSP are available based on the material (Glass Vs Film) on which the sensors are placed and also based on the patterning of the sensors themselves. Measures to reduce the thickness of smartphones have led to newer technologies integrating touch with the display module such as in-cell and on-cell touch technologies (Colegrove, 2012). Relative cost of adding touch technologies, as shown by Synaptics (Incorporated, 2012), seems to be decreasing from two layer discrete touch panel to single layer touch panel solutions to display integrated touch panel technology.

Liquid Crystal Display (LCD)

The electronics industry has been developing various kinds of display technologies for use in electronic products such as personal computers, smartphones, tablets and various other applications. The most prevailing for a few decades has been the LCD that consists of liquid crystals that are activated by electric current. Dramatic increase in manufacturing cost has led to significant a decrease in the cost of LCD based products (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). A number of suppliers exist, each providing displays in a various range of parameters, of which the major ones are: Kyocera, Sharp, Samsung, Optrex, Hitachi (Fujitsu Microelectronics America, 2006). The structure (Figure 4.1) of an LCD display module from top to bottom consists of a polarizer, glass, two layers of color filter enclosing the liquid crystals, a TFT glass substrate, another polarizer and finally a back light unit.

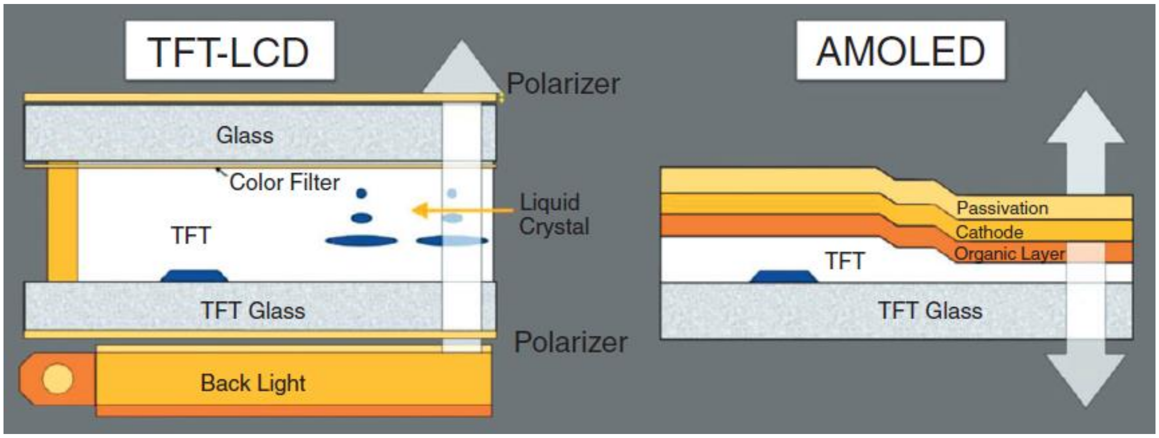

Figure 4.1: Structure of LCD and OLED Module

LCD modules can be categorized based on different characteristics, of which the two general types are: passive matrix (PMLCD's) and the newer and the most widely used active matrix (AMLCD's) (Fujitsu Microelectronics America, 2006), which uses individual TFT per pixel. The most widely used of the three LCD products based on liquid crystal alignment: Twisted Nematic (TN), Super Twisted Nematic (SN) and Thin film Transistor (TFT), is the TFT, which is otherwise known as Active Matrix LCD (Fujitsu Microelectronics America, 2006). The TFT industry has grown by a large extent since 2003 (Pan, Hsieh, Su, & Liu, 2008). The TFT-LCD contains three major manufacturing sectors: the array, cell and module processes (Wang & Su, 2006; Ukai, 2007). High performance of display has led to the growth of today's Amorphous Silicon (a-Si) TFT and Low Temperature Poly silicon (LTPS) TFT-LCDs. Active research is being done in developing metal-oxide TFT such as Indium-Gallium-Zinc-Oxide (IGZO) (Hausmann & Knowles, 2011). With circuitry, discrete driver IC are have been in use for the most part. Newer methods such as Chip-on-glass (COG) packaging directly connects the driver IC to the glass substrate with advantages such as easy producing, high through-put and weight minimization.

Organic Light Emitting Diode (OLED)

OLED is a relatively new superior display technology and regardless of the higher price and limited production volume (Colegrove, 2012), promising factors such as light weight, wider color gamut, better contrast, wide viewing angle and low bill of materials (Bardsley J. N., 2010) has led to the adoption of organic light emitting diode (OLED) display technology by various smartphone makers. Typically, OLED devices (Figure 4.1) are formed with either one or more layers of emissive organic layer located between a cathode and anode and deposited on a substrate (Kunic, 2012). Top-emitting, bottom-emitting and inverted top-emitting AMOLED structures are the different kinds. The substrate can be made of glass or flexible material or metal. Almost exclusive manufacturing of AMOLED is done on small glass substrates compared to LCD in which glass sheets are cut after TFT manufacture. Such process and equipment compatibility pose technical barriers to scaling up of OLED manufacturing (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Nevertheless, cost savings as much as 40% to 60% (although for 55” displays without TFTs), with reference to LCD, is seen as a result of lower material consumption, lower fixed dues to reduced maintenance and tooling (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Another advantage of AMOLED is that integrating circuitry with TFT substrates are also made possible (Bardsley J. N., 2004).

This literature survey suggests a few important points that lay the foundation for the proposed research in the paper. First, the various cost estimation techniques listed, although applied in different fields and contexts, could be modified to fit the basic evaluation of component weightage/relationships to cost. Second, decades of evolution in LCD technology seems to have comparative cost advantages to newer OLED displays with similar features. Finally, since cost competitiveness seems to be of high necessity in smartphone sales, this research aims at applying the suggested estimation techniques in this context. With this information, we proceed to propose a methodology to achieve our purpose.

4.5 Research Objectives and Methodology

In this paper, the authors propose a theoretical framework to quantify the factors affecting the cost of sourcing displays for smartphones and provide an analytical model involving these factors for component price negotiations. The following research questions/statements are listed as a guideline to understand the status quo of the technological and commercial aspects of components:

1. How many types of displays are available in the industry?
2. What sub-components are present in the various types of displays?
3. Understanding display data points used in its selection by smartphone companies
4. Evaluating trends in display technologies used in current smartphones and eliminating technologies that are fading out
5. Exploring availability of smartphone teardown reports from private research firms.

Literature review provides preliminary evidence to address research question 1 and 2. A comprehensive tree (Figure 4.2) of the sub-components at all levels was charted to help structure the analysis.

In order to perform a detailed analysis, pricing data for each sub-component will be obtained. In such a case, the bottom-up approach by rolling up the cost of each sub-component to the top most level could be done. But sensitive data (such as Intellectual Property) and high competition in the industry limits collectable data and hence makes this technique difficult to utilize. Given this restriction, we turn to product specifications (including components) and retail price information for smartphones made available by the respective smartphone companies, private smartphone teardown firms such as Techinsights, iSuppli, Display Search and other reputed electronics review firms such as CNET, GSM Arena. Using these retail prices and component information of smartphones, help set up Cost Estimating Relationships (CER) [4]. As a result, methods of parametric cost estimation [5, 19] using regression analysis could be performed.

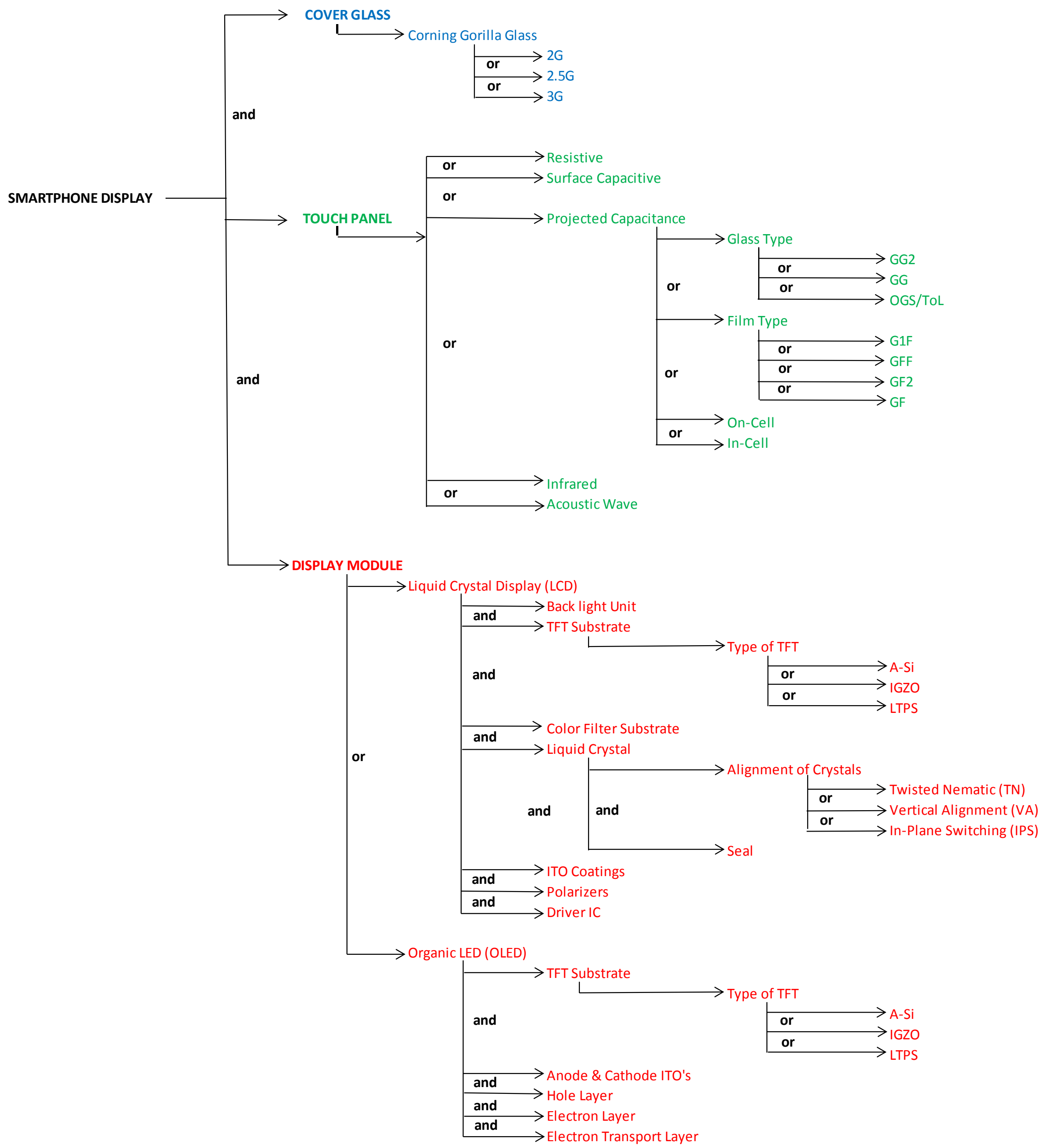

Figure 4.2: Smartphone Display breakdown

As mentioned in the introduction section of this paper, the ability of the application of this analysis to practical system demands the selection of technological data that are currently advancing in the market. Therefore, component specifications from smartphone companies and electronics reviewers for most smartphones released in the last two years are to be collected. A comprehensive detail of all sub-components of the display in each phone is formed. Lack of separating the pricing of display from rest of the components in the smartphone requires performing an analysis to help understand the effect of each of the other components on the total retail price. To record the variation of the retail price due to other components (other than display), specifications of these components would also be required.

The collected data could be grouped into similar technologies based on one particular component, i.e., using a table to combine smartphones on block (Table 4.2). Correlation between the retail prices of these phones and the specific technology in the block will be performed using regression. The analysis of this single variable regression of each factor with the retail price is suggested for relative comparison on the direction of cost due to a certain technology.

Table 4.2: Grouping blocks as per suggested combination of display technology

	TOUCHPANEL with 2G COVER GLASS								
DISPLAY MODULE	**Glass Type**			**Film type**				**On-Cell**	**In-Cell**
	GG2	**GG**	**OGS/ToL**	**G1F**	**GFF**	**GF2**	**GF**		
LCD									
OLED									

Since the analysis is focusing on display cost only, to isolate the cost or at least cost trends based on different display technology would be necessary. Other variables in the system of the smartphone are not of primary concern because accounting only for their effects on cost and not estimation of their cost is necessary. In order to account for the effect of each of these variables, a multivariate regression is proposed. Due to lack of sub-component details, the top-down approach seems to be appropriate in the context. As a result, primary variables of the display (Cover Glass, Touch Screen Panel (TSP), and the Display Module) known as independent variables are considered as a whole for the initial analysis. Each of these variables are set up as categorical variables to include each discrete sub-model in the analysis. The initial model with these variables as inputs is formed to measure the Retail

Price as the outcome, otherwise called the dependent variable of the basic analysis (Equation 1).

$$\mu = \{\text{Price} \mid \text{Cover Glass, Touch Screen Panel, Display Module}\} \quad (1)$$

After analysis of the basic regression in equation (1), the effects of other components (such as camera, memory, processor and others) are added to the analysis, one by one, at each stage to analyze their effects on the dependent variable. To look for effects of components only by themselves, any higher order interactions are excluded at first (Equation 2) and added later (Equation 3). The regression model is continued until all variables are exhausted.

$$\mu = \{\text{Price} \mid \text{Cover Glass, Touchscreen panel, Display Module, Camera Module}\} \quad (2)$$

$$\mu = \{\text{Price} \mid \text{Cover Glass, Touchscreen panel, Display Module, Camera Module, Memory}\} \quad (3)$$

Significant variations in outcomes of regressions with similar technologies are considered for further analysis. In such cases, the sub-component level of the component causing the variation is analyzed on similar lines. This process is continued to cover all component causes, if any, which affect the cost of sourcing. Other factors such as volume of production due to maturity of a technology, volume based pricing, yield rates, manufacturing complexity are incorporated through a buffer value in the outcome through expert opinion.

4.6 Limitations

The list of smartphones considered for this study is not intended to be exhaustive, but is as complete as possible, in order to provide as comprehensive an account of the system as possible. The collected data focuses on growing and most widely used technologies in smartphones that are the most prevalent and appealing from both the consumers and the producer’s perspective. To cover as many technological combination components in smartphones, all phones released only in the previous two years are considered in the analysis. Focus on component causality on price and not population inference, although not limited, is the desired first step as an outcome.

4.7 Conclusion and Future Work

The parameters in the regression analysis performed could be used to interpret linear relationships between price and components of different technologies. This forms a basis to establish a percentage value for the CER for a smartphone. As a result, validation of the analysis could involve applying the result to a random sample of smartphone from the collected data to breakdown its price using percentage composition. The resulting percentage compositions of the pricing could be recorded to establish a model in an excel format. The resulting model could be used to take in input values of quotes received from a display vendor to breakdown the pricing of a certain combination of components, in percentage terms.

The proposed conceptual Should Cost Model/Analysis would have the ability to understanding the key cost drivers and relative pricing for difference in technologies and assist smartphone producers in during vendor negotiations during display sourcing. The analysis could prove to be more favorable for companies in New Product Development Stage with limited information on display pricing. Further scope of this research could consist of checking the validity of the outcome of this analysis using data from an organization’s ‘New Product Development’ phase pricing. Further precision in the model could be achieved using bottom-up approach if detailed pricing data collection of sub-components is made available. A possible extension of the model to source other components could be pursued to check the application aspect of such cost estimating techniques.

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CHAPTER 5

5 Should-Cost Model Development for Component Price Prediction: Using an ad-hoc statistical model approach on Smartphone Displays

5.1 Introduction

Companies working on new product development of smartphones seek to adopt designs and methodologies to help them stay competitive. Due to its high cost contribution to a smartphone, optimizing display cost is an important part of a smartphone's cost reduction activity. Hence, strategically sourcing displays in the development of smartphones leads to a significant decrease in production costs. The objective of this study is to utilize data available from the smartphone industry and separate the display cost based on the technical features of a display. Reports containing data on three hundred and fifty eight smartphones were collected from smartphone research firms and similar sources. Based on available data and by reviewing the literature on the subject, features of sub-components of a smartphone were identified to build a Bill-of-Material (BOM). The BOM was utilized to filter the database of smartphones at each stage of the analysis. A step wise analysis was performed to identify components that help define the retail price of the smartphones. After performing analysis to predict retail prices, the analysis is narrowed down to a smaller subset of detailed data to separate display features. A regression model with only display features was created. Cross-validation of data was performed to include all smartphone samples collected in the testing of the analysis. The outcome of the regression analysis was used to build a Should-Cost Model to predict display pricing. The resulting should-cost model can help analyze various causes that add to the cost of sourcing and hence serve as a good first hand basis for analyzing components/materials. As a result, this model would assist in effective negotiations ahead of sourcing.

5.2 Literature Review

The literature review is divided into three sections describing the background with which the research was initiated. It contains an overview of the technological breakdown of smartphones and their components, existing analytical methods to build cost models and finally other tools and techniques used in the analytical section of this research.

In this section, numerous references to the term smartphone components are used to specify individual members that are combined to constitute a smartphone. These components can be broadly classified as Hardware and Software items. A high level classification of hardware components are Display, Camera, Battery, Memory, Sensors, etc. Software components include Operating system, Applications, etc. Different types of each of these components are used in the development of a smartphone.

5.2.1 Overview of Hardware Components

This section breaks down the components used in the construction of a smartphone. Two sections exist based on the detail of literature: Display Technology and Other Component Technology. Since the focus of this research is on Displays, a broader focus on display technology literature is provided. Comparatively, other components are explored only to an extent that is deemed necessary for the analysis. Each section provides a summary of the technology classification for the component, data points used in the measurement of its features and other important developments that are deemed relevant to this research.

Display Technology

Displays used in smartphones broadly constitute three underlying structures: the cover glass, the touchscreen panel (TSP) and the display module, in the respective order from the outer end of the phone. A variety of differences in characteristics and functions have promoted use of different types of these components in current smartphones. Percentage of phones and smartbooks with touch technologies is projected to be 50% and 93%, respectively in 2014 (Lee, 2011). Eleven categories of touch technologies are listed by DisplaySearch (Colegrove, 2012): resistive (both analog and digital, surface capacitive, project capacitive, infrared (traditional infrared), optical imaging (camera-based), acoustic wave (both surface acoustic wave [SAW] and bending wave), digitizer, in-cell, on-cell, combination, and other touch technologies. Amongst these, the widely used Projected

Capacitive (Pro-Cap) was first used in the iPhone in 2007 (Lee, 2011) and since then it has increasingly been used. It is expected that approximately 70% of the mobile phone market will use this technology (Lee, 2011). Variations in Pro-cap TSP are available based on the material (Glass Vs Film) on which the sensors are placed and also based on the patterning of the sensors themselves. Measures to reduce the thickness of smartphones have led to newer technologies, integrating touch with the display module, such as in-cell and on-cell touch technologies (Colegrove, 2012). Relative cost of adding touch technologies, as shown by Synaptics (Incorporated, 2012), seems to be decreasing from two layer discrete touch panel to single layer touch panel solutions to display integrated touch panel technology.

Liquid Crystal Display (LCD)

The electronics industry has been developing various kinds of display technologies for use in electronic products such as personal computers, smartphones, tablets and various other applications. The most prevailing for a few decades has been the LCD that consists of liquid crystals that are activated by electric current. Dramatic increase in manufacturing has led to significant decrease in the cost of LCD based products (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). A number of suppliers exist, each providing displays in a various range of parameters, of which the major ones are: Kyocera, Sharp, Samsung, Optrex, Hitachi (Fujitsu Microelectronics America, 2006). The structure of an LCD display module from top consists of a polarizer, glass, two layers of color filter enclosing the liquid crystals, a TFT glass substrate, another polarizer and finally a back light unit.

Organic Light Emitting Diode (OLED)

OLED is a relatively new superior display technology and regardless of the higher price and limited production volume (Colegrove, 2012), promising factors such as light weight, wider color gamut, better contrast, wide viewing angle and low bill of materials (Bardsley J. N., 2010) has led to the adoption of organic light emitting diode (OLED) display technology by various smartphone makers. Typically, OLED devices are formed with either one or more layers of emissive organic layer located between a cathode and anode and deposited on a substrate (Kunic, 2012). Top-emitting, bottom-emitting and inverted top-emitting AMOLED structures are the different kinds. The substrate can be made of glass or flexible material or metal. Almost exclusive manufacturing of AMOLED is done on small glass substrates compared to LCD in which glass sheets are cut after TFT manufacture. Such process and equipment compatibility pose technical barriers to scaling up of OLED manufacturing (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Nevertheless, cost savings as much as 40% to 60% (although for 55" displays without TFTs), with reference to LCD, is seen as a result of lower material consumption, lower fixed dues to reduced maintenance and tooling (Flattery, Fincher, LeCloux, O'Regan, & Richard, 2011). Another advantage of AMOLED is that integrating circuitry with TFT substrates are also made possible (Bardsley J. N., 2004).

Table 5.1: Display Features

Feature	Units of measurement	Feature Explained
Display Type	No units	Two broad types: LCD and OLED
Screen Size	Inches (“)	Diagonal length of the smartphones’ screen, measured in inches
Pixel Density	Pixel Per Inch (ppi)	Formula to calculate Pixel density utilizes resolution type and screen size (d_i). Resolution type provides total number of pixels present (represented as numbers in the form: a x b). The formula for Pixel Density is $\frac{\sqrt{a^2+b^2}}{d_i}$. Resolution of FHD (1080 x 1920) and Screen Size of 6” is calculated as $\frac{\sqrt{1080^2+1920^2}}{6}$ yielding 367 ppi.
Number of colors	Thousands (K) or Millions (M)	The color depth of the display module is represented by this feature. Standard color depths in smartphones include: 62K, 256K, 262K, 16M and 16.7M.
Cover Glass Type	Varies by strength of glass	The most widely known based on industry usage are from Corning named Gorilla Glass: CGG, CGG2 and CGG3, in increasing order of strength. Other types used by few smartphone developers are Scratch Resistant (SR) and Shatter-Proof (SP).

Based on technology review above, we identify five features that define the feature set of a display module: display type, screen size, pixel density, number of colors and cover glass type. Each of these features is detailed in the Table 5.1. It is to be noted that in this thesis, the terms display and display module are used interchangeably. Display can used to mention Display Module but not vice versa.

5.2.2 Other Smartphone Components

Processor

In the semiconductor industry, the building of Integrated Circuits (ICs) rolls back to the times of Personal Computer development. These ICs over the years have been cut down in size according to Moore's Law and are currently being used in Smartphones. Since the area available to place this circuit (also called a processor or a System-On-Chip (SoC)) is limited, there have been various developments in integrating other components with the SoC. The RAM which acts as a memory in the smartphone is packaged along with the SoC. These packages are of different types: Single-Package (SiP), Package-on-Package (PoP) and Package-in-Package (PiP). Of these three, the PoP type has been widely accepted and used in the development of smartphones (Apte, Bottoms, Chen, & Scalise, 2011). From the data available for this research, two features help define the characteristics of each; Processor and RAM. Clock Speed and Number of Cores for the processor, and RAM Type and RAM Capacity to define the RAM. Various smartphone developers have patented in-house PoP designs and others outsource this part.

Camera

As a functional addition to the smartphone, most phones in the market include cameras, called Rear Facing Camera. In the development of higher end smartphones there exist two cameras: the Rear Facing Camera and a Front Facing Camera. The available data points related to smartphone cameras are: type, camera capacity, optical size, number of lens elements and optical zoom.

Storage

The storage component of a smartphone is classified broadly based on their modularity: Internal and External. Internal memory is in-built and is part of the smartphone when manufactured. Whereas, external memory is optional and is part of the total storage via a memory card slot. The data points defining features of the two storage types are: Storage Capcity (in Gigabites) and Storage Type. In addition to these data points, the capacity extension of the external memory is defined by the term Extendability. Based on the data available from a wide range of smartphones used in this research, the storage capacities vary from 2GB to 128GB.

Battery

Batteries form the power source for all the components of the smartphones. Two types of widely utilized batteries are Lithium Ion and Lithium Polymer. They can be categorized similarly based on the type of packaging. Other data points that define the specification of batteries are battery voltage (in Volts) and battery pack rating (in milliamphere).

Connectivity

Features and components that help connect to external source for either data connectivity or other devices are broadly classified under this section. The components that are included in this section are Infrared (IR), Wifi, Bluetooth, GPS, FM Radio, USB and HDMI. Without breaking these features further down, based on available data, the presence of these components in each of the smartphone is checked.

Sensors

Most smartphones released consist of a package of sensors along with camera, wifi, Bluetooth and other additional features. A rich set of smartphone embedded sensors that are widely used include Accelerometer, Digital Compass, Gyroscope and GPS. Few other sensors used based off information from the smartphones used in this project include temperature sensor, ambient light sensor, proximity sensor, barometer, humidity sensor, magnetometer, and geomagnetic sensor (Lane, et al., 2010). The presence of each of these sensors has been considered without breaking them further by their sub-components.

Accessories

All elements that are provided along with smartphone but are not physically a part of the smartphone are considered accessories in this context. Common accessories include headset, adapter, charging cable, exterior packaging and any relevant documentation. Other accessories include docking station, external memory card and SIM tray pin. Common accessories mentioned here are the highly standardized across most smartphones and smartphone brands. Although this is the case, in a few cases accessory such as headset might not be included as a step of cost cut down.

5.2.3 Cost Estimation Techniques and Analytics

In this section, we review literature related to analysis/techniques used in cost estimation. Costing techniques relevant to both projects and products were important to be explored, since smartphone development could be considered as a project or product development. In regards to the tools used for cost estimation, four different methods have been identified: Analogy, Parametric, Bottom-up, and Extrapolation from actuals. These techniques have been utilized in different scenarios based on the type of data available.

Newnes et al (Newnes, et al., 2008) mention the availability of a number of cost estimation techniques, Generative Estimating and Parametric Estimating being the two basic types. Detailed data being gathered in the due course of a project is used in the generative approach, whereas estimation based on prior projects, past experiences and expected costs is utilized in the parametric approach. Each of these approaches possesses their own pros and cons. Although greater detail is demanded by the generative approach, estimation of cost per part is possible. On the other hand, applying relationship to cost evidence from previous products is used in the parametric approach. Application to low volume products and novel designs although proves less effective by this method (Watson, Curran, Murphy, & Cowan, 2006). These two techniques are included in the IMD Cost Methodology Book

(IMD Cost Methodology Guidebook, 2013) by the Department of Defense, along with other such as Analogy and Expert Opinion.

Analogy

This method helps compare similar form-fit-function of products and use accurate data from the past to develop a cost function for a new product. Variation of features in smartphones from different companies makes this method time taking and difficult to adapt. On the other hand, this model incorporates logical correlation between past and present systems. Similar logical correlation is derived from the analysis to help extrapolate the results of this research to be applied to display features being selected for future projects.

Parametric

Models using parametric techniques utilize statistical regression analysis. As mentioned in the earlier chapter, regression analysis establishes cost estimation relationships (CERs) on design characteristics of a system. These CERs are used to help evolve cost for an overall desired system. A major portion of the analysis involves this method, in addition to involving selective features from the other three methods.

Bottom-up

This method as its name reveals involves very detailed cost estimation by rolling up cost of each sub-component used to the top most level. As a result of its methodology, it is used when detailed data is available and also considered very expensive. As mentioned in the beginning of this section, the nature of electronics industry does not permit the use of this method for our purpose. Although we are unable to use this method in its entirety, there exists rolling up of cost factors to the top level to some extent in the analysis.

Extrapolate from Actuals

In this method, actual data is utilized to estimate the cost of the same/similar products being re-created in the future. Similar to Bottom-up method in terms of data, this methods demands accurate data for better results. Since various companies provide derivatives of phones, such as the most relevant Galaxy series from Samsung and iPhone series from Apple, a number of smartphone samples in our data are such. Also, since market is driven by competition between companies, the smartphones released at a particular instant in the market are mostly contemporary in their feature set. Therefore, the feature set of phones not only within a company but also across brand are possibly similar along time.

General classifications based on analysis are: analogous cost estimation (ACE) - otherwise known as ‘top-down approach’, ‘bottom-up approach’, and computing technology with artificial intelligence (Chou, Tai, & Chang, 2010). The top-down approach constitutes of the estimation of overall cost of the product and subsequent break down to sub-component level costs; the bottom-up approach is vice-versa (Watson, Curran, Murphy, & Cowan, 2006). Each of the estimating methods based on information available can be categorized into top-down and bottom-up approaches. The collection of cost data for each sub-component and the rolling up to the highest level in the bottom-up approach hold similarities with the generative estimation technique mentioned in the beginning of this section. Application of each of these techniques is also related to the stage of development of a product (IMD Cost Methodology Guidebook, 2013).

Watson et al (Watson, Curran, Murphy, & Cowan, 2006) state that the estimation methods can be further divided into explicit (rule-based) cost estimating, rough order magnitude (ROM) (ratio) estimating, parametric cost estimating, and detailed estimating using activity-based costing (ABC) and/or resource costing; each of which are often based upon past experience. Approaches involving the use of artificial intelligence such as fuzzy logic and neural nets are rapidly developing which mimic the human thought process. Also, Variant (analogy) estimating (Watson, Curran, Murphy, & Cowan, 2006) involves identifying a similar part/ completed project cost and then using this actual cost as a basis for the estimate of the new part/project.

5.2.4 Other Tools and Techniques Used

This section explains the concepts of tools and techniques that have been utilized in the analysis of the paper. Linear regression model, Pareto Chart, Pareto Efficiency, variable selection and software used are explained.

Linear Regression

A linear regression model is a type of analysis which can help model one particular variable as a function of one or more other variables. The variable being regressed is called the dependent/response variable and the variables used to explain the response variable is called the regressors or independent variables. The dependent variable in the model is regressed as a linear function of the regressors the sum of squared deviations of predictions (Wackerly, Mendenhall III, & Scheaffer, 2008). For representative purposes, a linear model consists of coefficients for each regressors. A general representation of a linear model is shown in Equation 5.1.

$$E(Y) = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k$$

Equation 5.1: Multiple linear regression equation (Wackerly, Mendenhall III, & Scheaffer, 2008)

In Equation 1 shown, the β's (except β_0) represent the coefficients and the x's represent the regressors. The β does not have a regressor and is referred to as the intercept of the model. The intercept is considered to be the baseline for the linear model. A model with only one regressor is known as simple regression, whereas a model with more than one regressor as is the case in this research is called a multiple regression. When a linear regression is performed, coefficients for each of the regressor are estimated and these coefficients also define the response variable. In addition, three parameters: R-squared (R^2), Adjusted R-squared (Adj-R^2), and Standard Error (S.E) are computed. These explain different aspect of the regression model and are considered important and are often used in this research. In addition, Mean Square Error or Root Mean Square Error is also used in the context of prediction analysis in the research.

The term R^2 measures the amount of variability in the response variable that is explained by the regressors included in the model. Larger R^2 is better, but this does not necessarily imply that higher R^2 is good. Addition of variables always increases the R^2 in a model regardless of whether the variable is significant or not (Montgomery, 2009). As a result, a model can have high R^2 and still yield poor predictions.

Since addition of variables could increase R^2 without yielding good predictions, the term adjusted R^2 is utilized. The adjusted R-squared is a modified R-squared that has been adjusted for the number of predictors in the model. The term Adj-R^2 does not always increase as variables are added to the model. Unnecessary terms included in the model in fact reduce the Adj-R^2 (Montgomery, 2009).

Standard Error of the estimate in a regression model refers to the measure of accuracy of predictions. It is represented as the square root of the average squared deviation. The lower the standard error, the more accurate the predictions are from the model. On the other hand, Root Mean Square Error (RMSE) is the measure of difference between the actual values and a predicted values based on a regression model used. It is derived by summing the square of these differences, dividing them by the number of test points and finally taking the square root. Similar to S.E, lower RMSE produces better prediction.

Pareto Chart

Pareto analysis is a technique used in various scenarios in Six Sigma. Roughly, pareto principle states that 80% of benefits can be addressed by focusing on efforts in 20% of key actions. For example, 80% of cost of quality is produced from 20% of the sources of error. This is named the 80/20 rule (Cano, Moguerza, & Redchuk, 2012). One of the tools available in pareto analysis is Pareto Chart that is used to help prioritize and focus on important factors from a collection of factors available. As seen in Figure 5.1, the pareto chart employs a bar chart in which the factors/causes are ordered in the descending order of their effects.

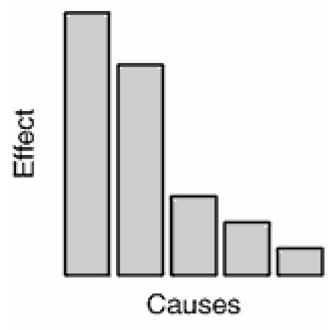

Figure 5.1: Pareto Chart Sample

Based on the 80/20 rule, the top 20% of the causes that can explain a major portion of the effects are prioritized for review. In the context of this research, the components used in smartphones are related to the cause, and cost of a smartphone is related to the effect in the pareto chart.

Pareto Frontier

Pareto efficiency is an economics concept which helps efficient allocation of resources. This concept is used in various fields for optimization purposes. A pareto efficient allocation is one for which there is no way to make all agents/resources better off. In the context of this research, pareto efficiency is used to optimize model selection based on different parameters. An example of a completely developed pareto frontier is shown in Figure 5.2.

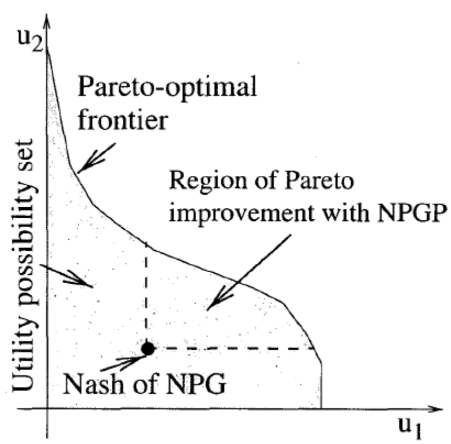

Figure 5.2: Pareto Frontier Chart

The model in Figure 2 analyzes the optimal point between resource u_1 and u_2. The point close to the utility frontier by optimality is chosen. The utility value of the two resources at this point is considered to be pareto efficient and optimal (Saraydar, Mandayam, & Goodman, 1999). Similar charts are produced between regression parameters to help assist model selection in the analysis.

Variable Selection

Since the objective of this research is to evaluate the features affecting retail and display price, the variables related to these features were to be taken in a selective manner. For this, existing methods such as forward selection, backward elimination and stepwise methods were used. In the forward selection method, during regression model creation in the context of this research, the model is started with no variables and at every step a variable is added. This is continued till all the regressors are exhausted. In backward elimination process the process of elimination begins after all variables are included in the model. At step of the process, regressors that do not contribute to the model are deleted. The stepwise selection process of variable selection is a combination of both forward selection and backward elimination. The model follows the forward-selection technique by starting with no variables. But it differs from forward selection such that at each step of variable selection, any variable that does not contribute to the model are eliminated. It is to be noted that for the variable selection methods used from here, the parameters R^2, Adj-R^2, S.E and RMSE are used to judge the contribution of the variable to the model.

Software Used

All regression models, cross-validations and price predictions for this research were performed in R. R-Studio which is an interface for R was used for this. R is an open source based statistical computing platform. The outputs to explain the methods is presented, whereas the code utilized to generate these outputs are no included in the paper APPENDIX I. Residual plots for data setup during initial analysis were created using statistical software JMP. The data collection for smartphones and model creation for cost modeling were performed on Microsoft Excel.

5.2.5 Literature Summary

The literature presented in this chapter show that work has been done to evaluate the various kinds of technologies, their specifications and their usage over years. It is also clear that there has been significant research done in modeling different cost estimation techniques based on types of data available to analyze. However, very few studies exist that have broken down components for a single study, compared different cost estimating techniques, and combined them to develop a model for an industry relevant situation.

Thus, although the main objective of this research is to develop a single model to predict display costs, various other sub-objectives have been setup to help assist in achieving the main objective. The literature reviewed in this chapter helps accomplish the different objectives presented in the beginning of the next chapter.

5.3 Data Collection

In order to establish an outcome that is relevant to current practices and improve usability, the data would need to be from smartphones released in recent past. In addition, reports on smartphones needed to contain as much detail on the phone's components as possible. Although this is a core necessity for the research, various intellectual property (IP) issues and competitive necessities of companies restrict the amount of detailed data available.

As a result, electronics teardown companies such as ABI, IDC, Techinsights, and recognized smartphone review companies such as CNET and GSM Arena are utilized to collect as much data on smartphone teardowns as possible for this research.

As a first step, all smartphones released mostly released in the last three years (2010 to 2014) were compiled from GSM Arena and CNET. This list enlisted seven hundred and fifty five smartphones released in the market by various companies. The complete list excluded from this paper. The next step was intended to obtain reports for each of these smartphones that could provide data on the components included in them.

Table 5.2: Teardown Report Sample

Product Description	
Product Type	Smartphone
Brand	
Product Name & Model	
Official Release Date	
Retail Price	
Product Features	
Operating System	
Connectivity	
Processor details	
Storage details	
Sensors	
Key Subsystems	
Battery details	
Main Display details	
Main Camera details	
Front Camera details	

Search through reports from research firms and review companies for these seven hundred and fifty five phones resulted with detailed and/or non-detailed teardown summary for three hundred and fifty eight phones. Irrespective of reports being detailed/non-detailed, each report included the items shown in Table 5.2.

Non-detailed reports provided broad breakdown of each component used in the assembly of the phone except the components of on the board. Detailed reports summarized part by part breakdown, manufacturing cost, electronic cost, cost of display subsystem, camera subsystem along with a few other subsystems in addition to the data shown in the non-detailed report represented in Table 5.3. These reports on smartphones were across twenty-three different smartphone brands.

Table 5.3: Additional Data from Detailed Teardown Report

Cost Metrics	
Manufacturing Cost	
Electronics Cost	
Manufacturing Cost Breakdown	
Battery Subsystem	
Display/Touch Subsystem	
Camera Subsystem	

5.4 Methodology

The main objective of the research was broken into three primary objectives (PO) and five secondary objectives (SO). The primary objectives are established to create and analyze a model that helps breakdown either retail price or display cost of the phone based on available data. The POs established are:

PO# 1 – Breakdown of the Bill-of-Material for a smartphone

PO# 2 – Identifying the primary factors those contributes to the retail price of the smartphone and hence develop a good retail price predicting model

PO# 3 – Evaluate the display only model to establish a model for display cost prediction

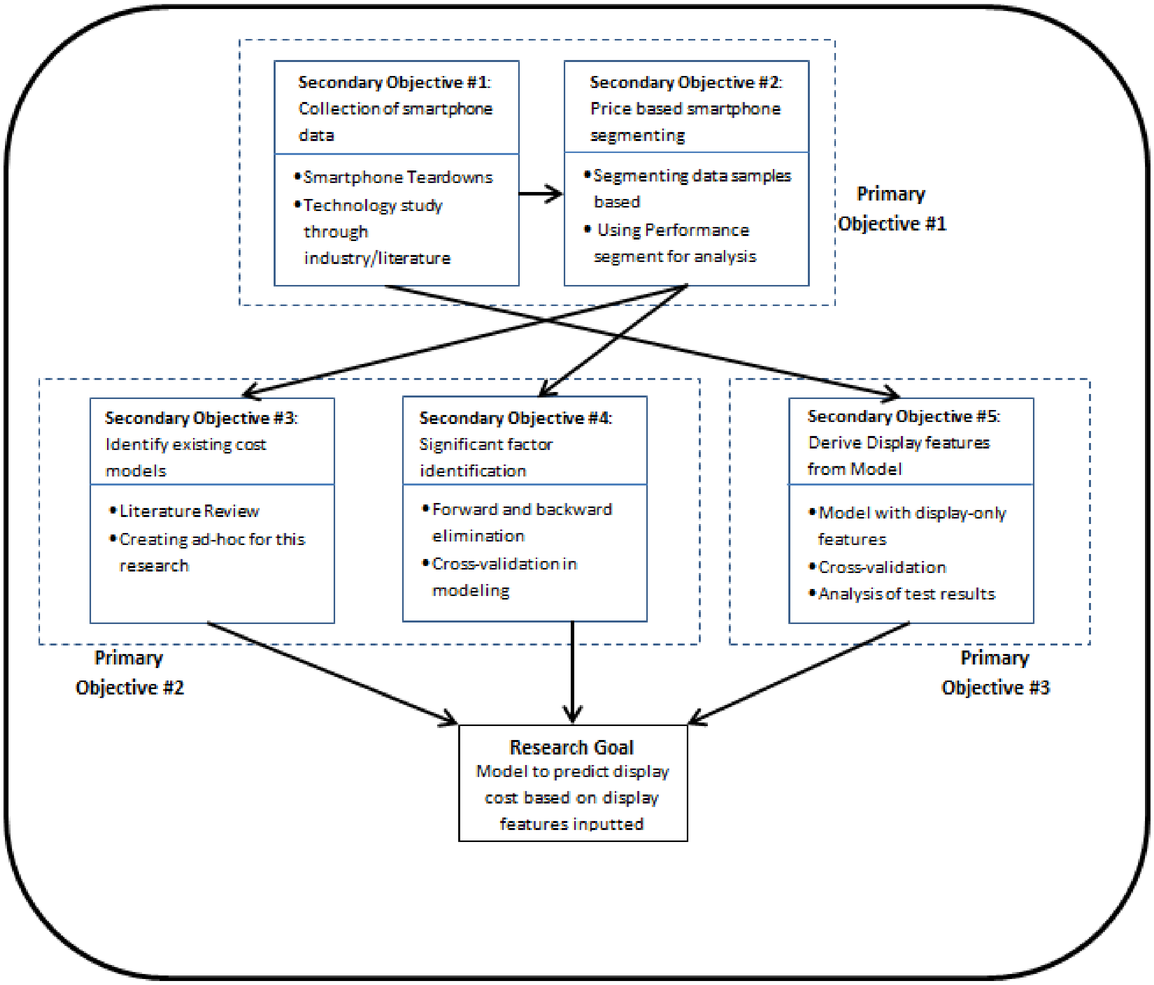

Figure 5.3: Research Scheme

The secondary objectives established to support the primary objectives are:

SO# 1 - Collection of data on smartphones mostly released in the last three years

SO# 2 – Identify existing cost estimating models that could be utilized in the analysis for costing these phones

SO# 3 – Eliminating irregularities in the properties of the smartphone characteristics used in the study, by segmenting smartphones

SO #4 - Screening data to help structure them for the analysis

SO #5 - Derive smaller sample set with detailed display features

Based on the secondary objectives established, multiple methods have been utilized in order to carry out the research. The relationship between different objectives and methods utilized is shown in Figure 5.3.

To meet primary objective #1, both SO#1 and SO#2 were deemed necessary. Although both these secondary objectives were needed, they were realized at different stages of the research. Identification of different cost models through literature review (SO#3) along with outcomes from the primary objective #1 formed the basis to begin the analysis. As a first step, the data obtained from the execution of primary objective #1 was used to eliminate features that are not required through SO#4. This formed the basis to accomplish PO#2. After identifying the elements defining the model predicting retail price, a subset of smartphones with detailed data are identified for the display cost prediction analysis (PO#3).

With all of the contributions from cost estimation methods presented in the literature review, we setup the base for a statistical regression method to begin analyzing the collected data based on the charted methodology.

5.4.1 Primary Objective#1: Bill-of-Material (BOM) Breakdown

Data obtained from three hundred and fifty eight non-detailed reports were extracted into an excel format. Based on technological details from the literature review and relevance to the data obtained from reports, each subsystem of the smartphone was broken down to four levels (Level 0 to Level 3) to form the bill-of-material for a generic smartphone. Before forming these levels, two basic categories of materials were defined: Mandatory and Optional. The mandatory portion consists of sub-system without which a generic smartphone cannot be constructed and the optional portion consists of features that could be added to a smartphone along with the mandatory parts. These two sections are listed in Table 5.4 below. It is to be noted that the each of these sub-systems are not disintegrated to their lowest component level.

Table 5.4: Mandatory versus Optional Sub-components

Smartphone sub-component systems	
Mandatory	Optional
Display	Camera
Battery	Sensors
PoP	Connectivity Parts
Storage	Accessories (except Adapter and Cable)
Operating System	Hard/Soft Keys
Note: Mandatory in this context refers to parts that are required to build a basic phone	

The bill-of-material framed from Level 0 to Level 3 include the mandatory section first and then the optional. Each of the levels breaks down either the material from the previous level or includes data points that further define the feature from the level above.

It was to be noted that although there are various features or components that help define a particular subsystem in the BOM, unavailability of data for some features/components makes them unusable. An example of such an instance is the display components. Although the kind of lamination of a cover glass contributes to the cost, unavailability of this data in the teardowns limits the analysis from using this feature. Therefore, the BOM is defined in accordance with all available characteristics obtained from the teardown reports. A partial BOM breakdown is shown in Table 5.5. The detailed BOM is not presented in this paper.

Table 5.5: Bill-of-Material (BOM) breakdown for smartphone (partial)

LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3
Smartphone	Display Type • LCD • OLED	Display Module • Screen Size • Resolution Type • Pixel Density • Number of Colors • Backlight	
		Touchscreen Panel • Resistive • Pro-Cap • Surface Cap	Lamination Type/ technology: • C/G/G

		• Infrared • Acoustic Wave	• ToG (touch on glass)/ SoL (Sensor on Lens) • In-cell • On-cell
		Cover Glass • CGG • CGG2 • CGG3 • SR • SP	

Data Setup

A comprehensive list of teardown data was included against smartphones added to APPENDIX II database. Both detailed and non-detailed data from teardowns were compiled in this sheet to form a reference database for this research. Since only three hundred and fifty eight teardowns were available out of the seven hundred and fifty five phones collected, these three hundred and fifty eight smartphone reports were usable for the research.

For employing regression analysis, the variables to be used in the model were to be defined into two groups based on how well they could be represented: continuous and non-continuous (otherwise known as categorical) variables. When a variable is considered continuous, it is included in the model with no changes and is modeled as numbers. On the other hand, non-continuous/categorical variables are categorized into two or more sections before being included in the analysis. A simple categorical variable is framed a binary digit with 1 and 0. One states that the feature exists and zero represents the absence of the feature. A more advance categorical variable helps breakdown variables that are continuous as per data, but are not correctly represented when added as such. In such cases, bins are created to categories them for better representation.

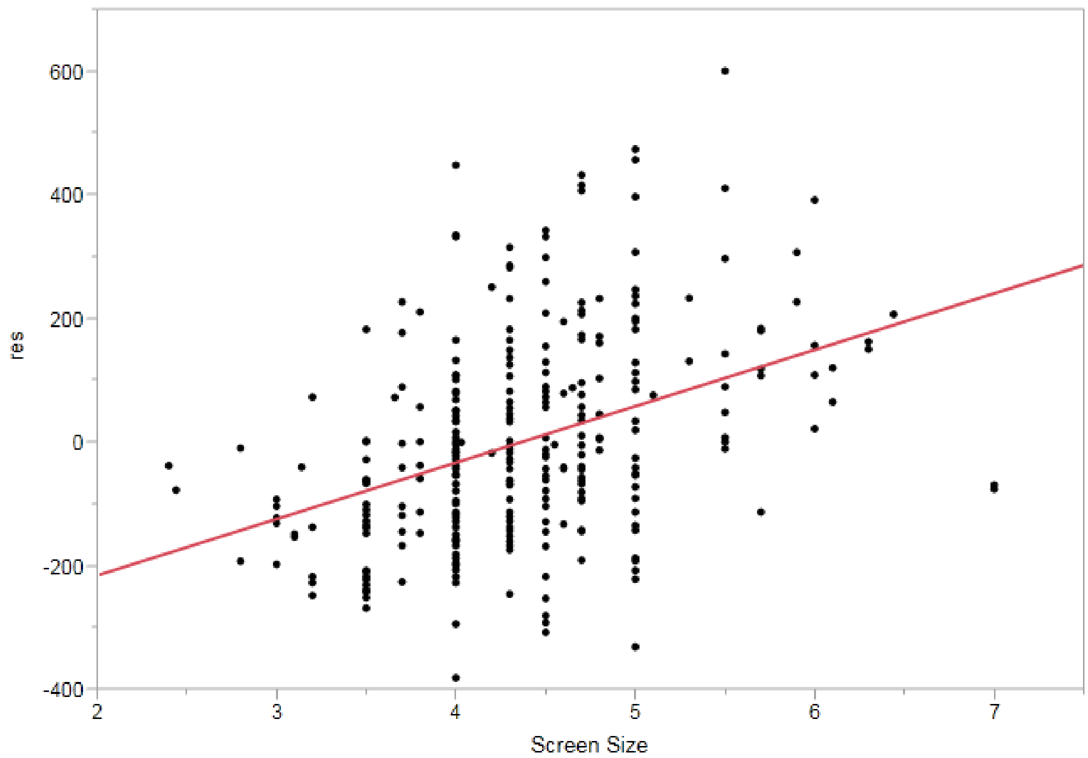

Figure 5.4: Residual Plot for Residual versus Screen Size

To setup the data in the input file for the analysis, initial screening of each factor in each subsystem was performed. In order to begin initial analysis setup, every variable from Level-1 and Level-2 was screened. For the 358 smartphones considered for the analysis, the residuals of retail price were plotted against each factor present in Level-1 and Level-2 of the BOM breakdown. These plots were used to determine the structuring of each factor into categorical or continuous variables for the analysis. The residuals are plotted in the y-axis and the specific variable is plotted on the x-axis. In addition, a line is fitted to determine if the points on the plot represent that specific variable well. An example of a residual plot showing residual versus screen size is shown in Figure 5.4. Other residual plots are not presented in the paper.

After analyzing the residual plot and defining continuous and non-continuous variables, all features are structured according to the input file to begin initial analysis.

Random Sample

Before beginning the first stage of the analysis, it was necessary to separate a set of phones that could serve as a working sample for predicting retail price. About ten percent of the entire sample set was removed from the complete sample set (three hundred and fifty eight smartphones) and kept out of the model creation. A random sample of thirty five numbers between one and three hundred and fifty eight was generated and the smartphones with the respective numbers allotted to them were removed. The random sample of smartphones is not shown in this paper. Since this sample was not included in the analysis, the result of the analysis was used to predict the retail price of these randomly sampled phones.

5.4.2 Primary Objective#2: Identify factors affecting Smartphone Retail Price

In this section, we elaborate on the initial steps of the analysis and provide directions for further analysis based on the results. The initial intention was to employ all factors, level by level (i.e., Level 1 through 3), in a forward selection manner. All variables from a particular level are included at step of the analysis. At every step, the prediction for the randomly sampled phones is performed.

Table 5.6: Prediction with Level-1 variables (partial)

#	Retail.Price	pred_price	error
1	490.00	415.74	74.25
2	450.00	363.48	86.51
3	449.99	498.01	-48.02
4	799.99	498.01	301.97
5	599.99	498.01	101.97
6	649.99	363.48	286.50
7	200.00	338.55	-138.55
8	387.93	497.27	-109.34

Using Level-1 variables, the outcome to predict the retail price for the thirty five randomly sampled phones resulted with prices with high variability between smartphones. A partial outcome of the prediction is shown in Table 5.6.

The table above lists the details for eight different phones from the random sample. There are three columns present: Retail Price, pred_price and error. The Retail Price is the actual price of the phone obtained from the teardown reports. The second column, pred_price, shows the predicted price that is calculated based on the variables included in the regression model. Finally, the last column showing error is the difference between retail price and predicted price (i.e., Column-1 minus Column-2). Visual inspection of the error term across all the eight phones reveals that there exists large variation in price prediction using variables only from Level-1 of the BOM breakdown. This is more apparent by looking at the prediction across the complete set of thirty five phones (not presented in the paper).

To follow the process of forward selection, and also due to high variability between price predictions using level-1 variables, it was anticipated that including Level-2 variables from the BOM along with Level-1 variables might help improve predictability for the same set of thirty five phones. As a result, the variables that better explain the Level-1 variables (i.e., Level-2 variables) from the BOM were added to the regression analysis. It is necessary to note that the variables of optional components such as camera, storage and connectivity discussed in Table 5.4, are included at this stage of the analysis. Similar to the analysis with Level-1 variables, prediction of retail price for the same partial set of eight phones is shown in Table 5.7.

Table 5.7: Prediction with Level-2 variables (partial)

#	Retail.Price	pred_price	error
1	490.00	671.72	-181.72
2	450.00	228.94	221.06
3	449.99	480.53	-30.54
4	799.99	836.56	-36.57
5	599.99	509.70	90.28
6	649.99	464.13	185.86
7	200.00	289.70	-89.70
8	387.93	421.61	-33.68

In comparison to Level-1 regression model, the intention of this step is to reduce both: the error in the prediction of retail price and the variability in prediction across the random sample. It can be noted that although there seems to be minor reduction in variability, the error still seem to be pretty high. Therefore, any further addition of variables might not improve either of these factors.

From the results obtained from the analysis of just level-1 and both level-1 & level-2 variables, a few points including high error and variability across price prediction were noted. First, irrespective of the retail price and other features, smartphones with similar level-1 variables yielded the same predicted price. This is because only few variables defining the smartphones were included in the regression model. Second, few smartphones that had smaller error in the first model had much higher error in the second model. This could be attributed to detailed features (added from Level-2) of the same variable that might be highly correlated and hence been double counted, thereby increasing the predicted price and hence the error. Finally, the sample set including the random sample consists of smartphones across a wide range of retail price in them. As a result, the feature set of these Smartphones would also vary widely. Hence it can be inferred that a regression model consisting this wide feature set would be unable to provide better prediction of retail price. With these findings, during the course of the analysis, changes to the data set and the analysis technique were employed.

Since the collection of 358 smartphones ranged from $70 to $968, the range of features included in these phones was identified to differ to a large extent. This difference to a large extent, accounts for variation in the prediction of retail price in the analysis above. In order to eliminate this variation, based on retail price segmenting followed in the industry, the database of phones were divided into four separate segments: Entry Level Phones, Value Phones, Mainstream Phones and Performance Phones. Retail price brackets for each of these segments are shown in Table 5.8. The table also includes the sample size available in each of the segments.

Table 5.8: Segmented Smartphone Data

Phone Segment	Retail Price ($)	Sample Size
Entry Level	(, 100]	6
Value	(100, 200]	56
Mainstream	(200, 400]	135
Performance	(400,)	161

Removal random samples of these smartphones from the working list resulted in reduced sample sizes shown in Table 5.9.

Table 5.9: Segmented Smartphone Data without Random Sample

Phone Segment	Retail Price ($)	Sample Size
Entry Level	(, 100]	6
Value	(100, 200]	49
Mainstream	(200, 400]	124
Performance	(400,)	144

Since the sample size and the number of detailed teardown reports in the Entry Level and Value segment were not sufficient, these two segments were filtered from the dataset at this stage. In addition, about 69% of the smartphones in the collected database were in the Mainstream and Performance segments. Of these, 130 performance smartphones and 117 mainstream smartphones were released in the last two years. Although this is the case, 45 of 55 detailed smartphone teardowns available for the 69% smartphones was constituted by Performance Phones.

Retail Price Model Development

Based on the finding from the initial analysis and segmenting of smartphones based on retail price, two actions were taken to improve predictions. First, for the purpose of this research, retail price model development was performed on smartphones only from the performance segment. This was for two reasons: 1) better data availability for smartphone reports collected for this research, 2) the purpose of segmenting was to perform the analysis segment by segment and improve the price predictions. Second, the hierarchy of adding variables to the regression has been setup from this stage of the analysis. Previously, during Level-1 and Level-2 of initial analysis, variables were assumed to be affecting price based on BOM levels. Therefore, all variables were added to Level-1 regression and all variables from Level-1 & 2 were added to Level-2 regression models.

The second action mentioned above refers to improving the method of adding variables to the model and hence setting a hierarchy. In addition, accounting for maximum amount of cost in the model with the least amount of explanatory variables was considered important. Therefore, subsystems (i.e., all variables explaining the subsystem shown in the detailed BOM breakdown) are added to the regression model in descending order of price contribution to the overall cost of the smartphone.

To identify the amount of cost contribution, smartphones with detailed teardowns were utilized. Since detailed teardown reports provide approximate subsystem costs, the averages of each of these subsystem costs were utilized to generate a Pareto chart. The averages of subsystem costs available from the reports are shown in Table 5.10. Since costs of all subsystems are not available from teardown, the sum of all available subsystem costs is considered to form 100% of the Pareto Chart Analysis in Figure 5.5.

Table 5.10: Average pricing of subsystems from detailed teardown reports

Components	Cost	Percentage of total	Cumulative Percentage
Display Module	$37.82	44.99%	45.0%
Processor/SoC	$27.5	32.71%	77.7%
Camera(s)	$14.2	16.89%	94.6%
Battery	$4.54	5.40%	100.0%

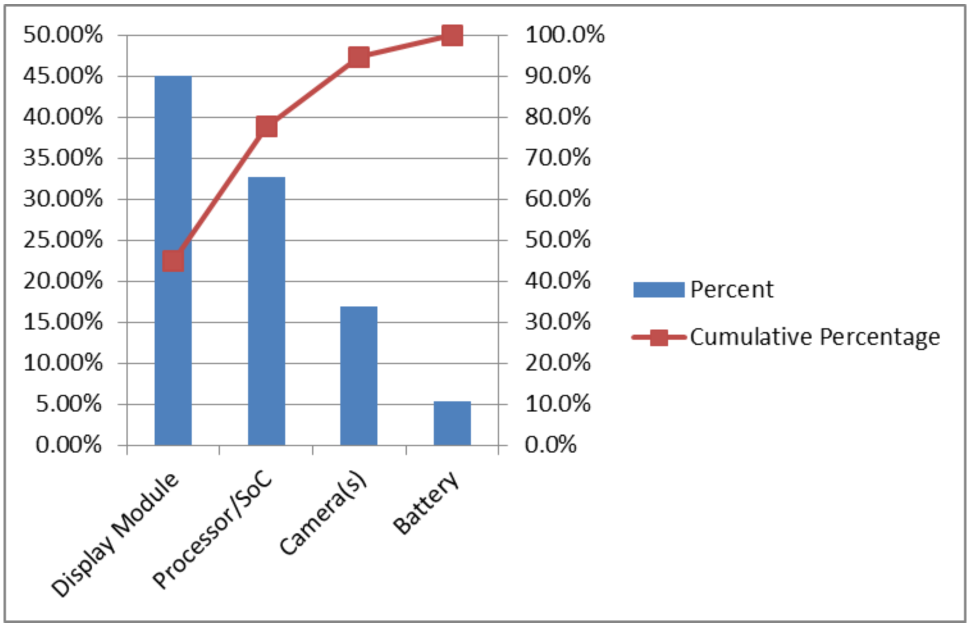

Figure 5.5: Pareto Chart for component subsystems

Based on the Pareto analysis above display module, processor, cameras and battery are initially added to the regression model, in the respective order. All other subsystems are subsequently added to the regression model based on industry trends and correlation with other variables in the analysis.

Regression analysis was performed on a sample of 146 performance segment smartphones. The remaining 15 of the randomly sampled smartphones from this segment were used for retail price prediction using the outcome of the regression analysis. In order to identify any time effects on retail price or on cost of other components, two parallel regression analyses was carried out. The first regression did not include release dates whereas the second model included release of smartphones from the beginning of the analysis.

Since the final objective of the model is to predict display cost, it is necessary to include all display feature variables in the analysis. As a result, at first, the retail price was regressed on all display variables, except lamination type, from the BOM breakdown. Although data on variable "lamination type" is unavailable from teardown reports or other sources, it is included in the detailed BOM breakdown only for representative purpose of display features.

At every step of variable addition, four parameters were noted in the regression analysis and in the prediction analysis: R-squared, Adjusted R-Squared, Standard Error in the regression model, and Root Mean Squared Error of predicted retail prices on from random sample.

Table 5.11: Regression Parameters (without Release Date) for Sample One Model

Without Release Date						
Performance Phones						
Model	**Variables**	**Additional Variable(s)**	**R-Sq**	**Adj. R-Sq**	**S.E**	**RMSE**
1	Display Type	NA	0.001797	-0.00523	133.8	131.78
2		Screen Size	0.06698	0.05374	129.8	124.21
3		Pixel Density	0.2502	0.2342	116.8	125.26
4		Colors	0.2834	0.252	115.4	120.08
5		Cover Glass	0.3107	0.2476	115.7	121.99
6		Processor Brand	0.3797	0.2482	115.7	115.65
7		Cores	0.3818	0.2245	117.5	111.93
8		RAM Type	0.4247	0.2383	116.5	113.96
9		RAM Capacity	0.4419	0.2471	115.8	113.58
10		Rear Camera Capacity(MP)	0.4607	0.2585	114.9	110.88
11		Rear Camera Optical Size	0.4714	0.2589	114.9	111.37
12		Rear Camera Lens Elements	0.476	0.2506	115.5	110.04
13		Front Camera	0.4987	0.2685	114.1	115.21
14		Front Camera Capacity(MP)	0.5029	0.2595	114.8	116.04
15		Log(Internal Memory)	0.5137	0.2602	114.8	115.01
16	-RAM	Battery Type	0.4934	0.2608	114.7	107.74
17	-RAM	Battery Pack Rating	0.4958	0.2567	115	109.38
18	-RAM	Gyro, Baro, Temp Sensors	0.5347	0.2688	114.1	123.21
19	-RAM	Headset	0.5584	0.2905	112.4	114.80
20	-RAM	USB Version	0.5675	0.2891	112.5	114.07
21	-RAM	- Rear Camera Optical Size	0.5658	0.3023	111.5	115.21

The model began with Display Type and then adding all display feature variables. The order between display variables is random since all of the features are necessary in the model to define display cost. Subsequently, based on Pareto analysis, processor, RAM, cameras – both rear camera and front camera, storage, battery, and other features of sensors, accessories and connectivity were included. Each line in Table 5.11 refers to a model. And each of the models includes all variables from prior models including the variables in the corresponding line. After exhausting all variables, backward elimination of specific variables based on the four parameters is performed. Variables that induce high error when added to the regression model are immediately removed and are not shown in the Table 5.11. Variables that cause minute increase in error are continued to be retained in the regression model for evaluation later in the analysis. Elimination of variables in Table 5.11 is indicated by a negative sign in front of the variable.

Of the four parameters considered above, three are considered essential in selection of a model with the right combination of parameters. They are Adjusted R-Squared, Standard Error, and Root Mean Squared Error. To select a model out of the 21 models listed in Table 5.11 above, analysis similar to Pareto efficiency is performed. All three parameters are plotted against each other to identify the best possible points on each chart. Each point in the chart represents one of 21 models presented in Table 5.11.

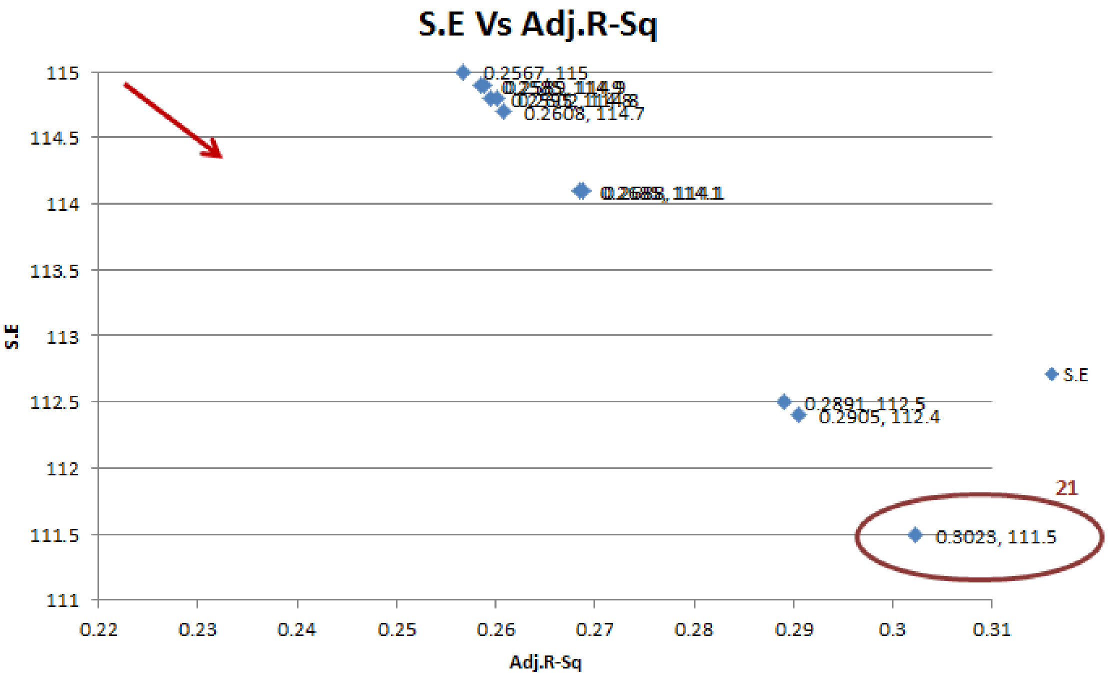

Figure 5.6: Sample One (without release) - S.E Versus Adj.R-Sq

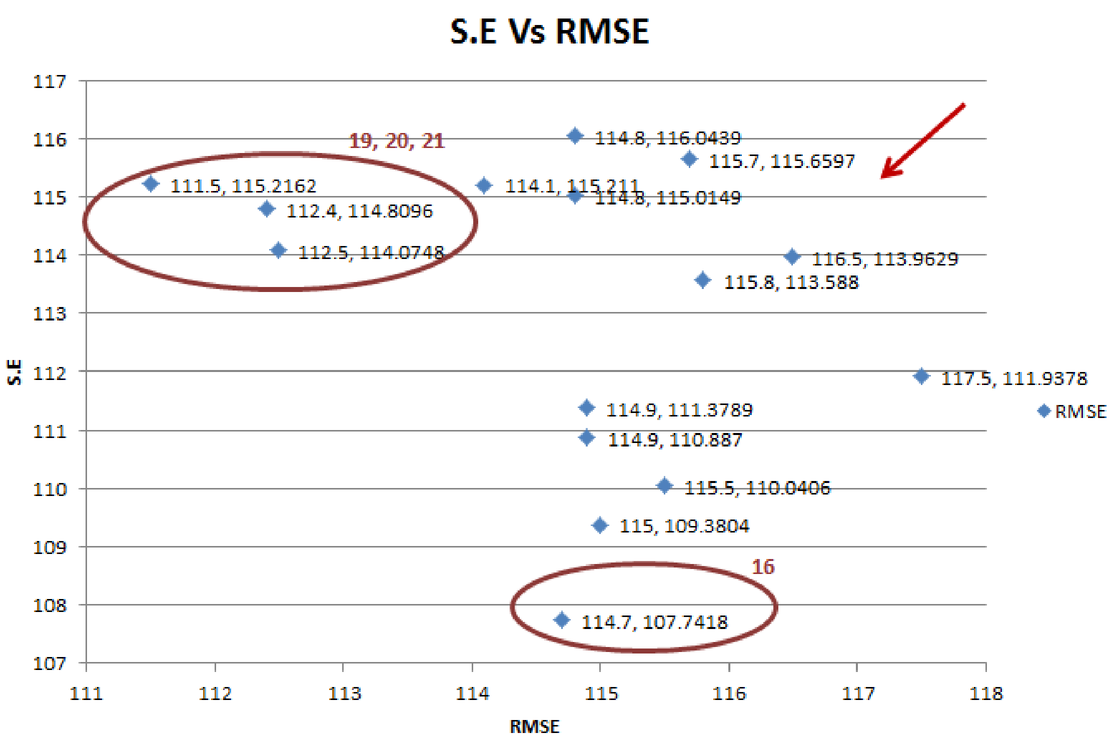

Figure 5.7: Sample One (without release) - S.E Versus RMSE

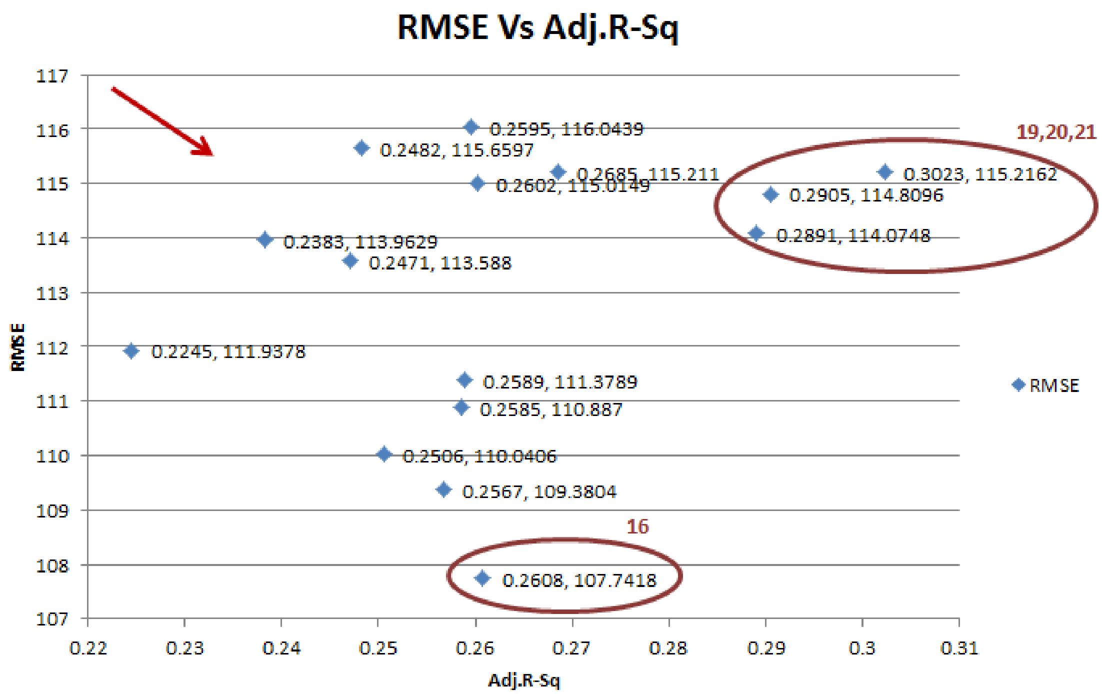

Figure 5.8: Sample One (without release) – RMSE Versus Adj.R-Sq

The points that have the best of values of both parameters in each chart are identified. Arrows in each chart points the desired direction in which both parameters in the plot would produce best results. Common points from all the three charts were picked. From the Pareto efficiency charts above, although other models are highlighted, only model 21 was present in all three charts. As a result, it was summarized that variables in model 21 are found to produce, not only the lowest errors but also, the best possible retail price prediction compared to all other models.

Similar analysis of the second regression model including the release dates resulted in the presenting points 19 and 21 are found common. This was unlike one single point being chosen in Sample One Model. Selection of either model in this case would not lead to drastically different results. But prediction error and selection of Model 21 from the first model favored the selection of the same from this analysis as well.

Cross-Validation of Retail Price Model

In order to improve the testing outcome of this analysis, cross-validation was performed. In cross-validation, the complete sample of smartphones was broken down into various groups. To maintain consistency, the sample was broken down into 10 distinct groups named folds. This ensured similarity with 10% of phone randomly sampled for Sample One and Sample Two Models.

Table 5.12: Cross-validation for Retail Price (without release date)

Without Release Date			
Performance Phones			
Model #	**Variables**	**Additional Variable(s)**	**RMSE**
1	Display Type	-	131.78
2		Screen Size	124.21
3		Pixel Density	125.26
4		Colors	120.08
5		Cover Glass	121.99
6		Processor Brand	115.65
7		Cores	111.93
8		RAM Type	113.96
9		RAM Capacity	113.58
10		Rear Camera Capacity(MP)	110.88
11		Rear Camera Optical Size	111.37
12		Rear Camera Lens Elements	110.04
13		Front Camera Capacity(MP)	115.21
14		Log(Internal Memory)	116.04
15	-RAM	Battery Type	115.01
16	-RAM	Battery Pack Rating	107.74
17	-RAM	Gyro, Baro, Temp Sensors	109.38
18	-RAM	Headset	123.21
19	-RAM	USB Version	114.80
20	-RAM	- Rear Camera Optical Size	114.07
21	-RAM	- Cores	115.21
22	-RAM	- Processor Brand	131.78
23	-RAM	PoP	124.21
24	-RAM	- Gyro, Baro, Temp Sensors	125.26

Each fold from the 10 folds was eliminated once to be used as a random sample for retail price prediction. The other 9 folds were used in the analysis used for prediction. As a result, ten separate groups of phones predict retail price and validate the analysis performed.

As seen in Sample One and Sample Two models, forward selection and backward elimination of variables created various models to consider. To check all of the models, the cross-validation technique explained above was to be performed on every model. As a result, at least 21 separate models were to be cross-validated. Unlike three parameters in previous cases, only one parameter was considered to judge each models performance: Overall Mean Square. The Overall Mean Square is similar to RMSE parameter used earlier. But it is in the squared form of S.E. Similar to the Retail Model developed in the last two sections, two parallel cross-validation analyses were performed: with release date and without release date. Model development without release date is shown in Table 5.12.

On the table above, the model with the lowest mean square error (Overall MS in column 4) is desired. Although model 4 results in the lowest overall MS, it was noticed that all display features were not covered at this point. In addition, complete definition of a smartphone would need to include variables more than that in model 4. Therefore, the analysis was continued to include as many variables as possible and still achieve a low mean square error. After model 4, model 24 resulted in the lowest mean square error possible. As a result, this model produces the best retail price predictions (not presented in the paper). Thus, we choose model 24 to be the cross-validated model that includes variables that define and fit the best retail price for smartphones.

Cross-validation including release dates, was performed on the same set of smartphones (results not presented). As expected from the addition of release date variable to the analysis, the mean square error value for each of the models above were different from the corresponding ones without release date in Table 12. It is interesting to note that, although the expectation of the error value by adding release date variable would be positive, the first few models showed higher errors. But the overall outcome of the cross-validation analysis with release date was similar to that of one without. Model 4 was the first to have the least mean square error, whereas as lack of definition of smartphone using all variables at this stage eliminated this model. As a result, model 24 is selected with next best mean square error value.

From the two models, along with the cross-validation results, two goals were accomplished. First, a methodology for streamlined selection of smartphone feature variables was established. Second, a model to predict retail price of smartphones with least error was created. One of the initial objectives of this research was to isolate the display features from the final retail price model and develop a model for display cost predictions. For this, it was necessary to separate the coefficients from the retail price regression model and build a model based on varying display features.

Although the coefficient for the variable display type was found to be correct, most other display variables coefficients in the retail price model were much higher than expected (result not resented). These increased coefficient values were attributed to a few reasons evident from the model: 1) Correlation between display variables and other variables in the model, 2) Display variables being assigned some part of the coefficients from other variables, and 3) lack of more variables (both display and others) that could help explain the model better than its current state. As a result, it was identified that it was not possible to be separate display features from the analysis. Therefore, it was necessary to utilize the detailed teardown available for as many smartphones as possible.

The analysis performed in this section helped validate the method in which the data is setup for further use. Creation of a model and prediction of retail prices with low error confirmed that the data setup works well in its current format.

5.4.3 Primary Objective#3: Display Model Development

After clear validation of data setup from section 3.8, it was found that there needed to be no other changes to be performed for display model setup. On the other hand, the amount of data available to perform display cost evaluation was different and smaller. From the data collected for 358 smartphones, due to segmenting, 161 phones were used in the retail price modeling. From this sample, detailed teardown reports that include data on display module costs are 55 across all brands of smartphones. Although a smaller subset of data, it can be assumed that this fairly represents the entire sample size due to its randomness in detailed teardown report availability.

Data and Model Setup

The subset of smartphones with detailed reports is separated from the non-detailed set of phones. All five display variables from the BOM breakdown are modeled, continuous or categorical, as in the retail price model. The five display variables used are shown in Table 5.1. A regression model is set up to regress display module cost on these five display variables. As construed from teardown reports and based on industry learnings, the display module constitutes display, touchscreen panel, and cover glass. Since display cost prediction is the main objective of this research, it was necessary to ensure the sample size of data did not violate any assumptions of linear regression modeling. A sample size of 55 smartphone was sufficient to be used to examine using the residuals obtained. After performing the regression model it was noticed that, if release dates were taken into consideration, six phones distributed across seven quarters make an unsuitable sample size for display module cost prediction for certain quarters. Also, these six phones were older which would not be as relevant to the model to obtain precise price predictions. Therefore, these six smartphones were removed from the execution of the display model.

Table 5.13: Linear Regression Model Parameters

Model	R-Sq	Adj.R-Sq	S.E
Without Release Date	0.649	0.557	7.84
With Release Date	0.745	0.579	7.65
With Release Date and Smartphone Brand	0.819	0.585	7.59

The linear model parameters are shown in Table 5.13 above. An Adjusted R-Squared of 0.557 and a Standard Error of $7.84 was seen. The display variables included in the model explain 55.7% of the variation in display module cost, as represented by adjusted r-squared. Since variables in this regression model helps explain only about 55 % of the variation in display cost, additional variables available from the database were explored as a measure to improve adjusted r-squared. Technology maturity and newer technology introduction over a longer time range could lead to changes in cost of display components. Since data on smartphones is spread across a large period of time, date of release of a phone was considered. As modeled for retail price models, release dates are clustered into quarters. On the other hand, cost of display module varies based on different smartphone manufacturers. And since the data utilized in this research is spread across various smartphone brands, smartphone brand was chosen. Smartphone brands are modeled as 1 and 0 in the form of categorical variables. For example, an Apple brand phone is indicated 1 for the variable “Apple” and all other brands are indicated zero. Regression Models for display models with release date and smartphone brand are presented in the paper. The parameters of these models are shown in Table 5.13 as well.

It was noticed that addition of smartphone brand and/or release did not drastically change either the Adjusted R-Squared or the Standard Error of the model. Hence, it was certainly difficult to choose one of the three models. Therefore, to pick one of these models it was necessary to check the display cost predictability of these regression outcomes using variables in each of these models. As a result, cross-validation of display price model was performed.

Cross-validation of Display Price model

After removing the six smartphones from the detailed teardown smartphone sample, the remaining 49 phones were utilized to perform cross-validation across 10 groups (also known as folds). Nine folds contained 5 samples each, whereas one fold contained 4 samples. Each of these folds predicted display module cost for their corresponding samples and generated a mean square error. All of these errors summed up to form the overall mean square error. This was performed using variables corresponding to all three regression models performed in the previous section. The overall mean square errors, along with Predicted RMSE for the three models are shown in Table 5.14.

Table 5.14: Cross-validation results for display cost model

Model	Overall MS	Predicted RMSE
Without Release Date	80.2	8.955445271
With Release Date	140	11.83215957
With Release Date and Smartphone Brand	190	13.78404875

Choosing a model based on results from the previous section was ambiguous. Whereas, by comparing the overall MS (from Table 5.14) which represents the overall mean square error for predicted smartphones, it is clear that the model with the lowest MS would be the most suitable. Taking a square root of overall MS in the first model provides the predicted root mean square error. This model results in $8.95 error which is relatively lesser compared to other models.

For all of the three models, the predicted cost is fitted against the actual cost for each fold in the model. The predicted display module cost is plotted on the x-axis and actual display module cost on y-axis. The line is most suitable when the line follows a 1:1 ratio (otherwise represented by the equation x = y) in its direction between predicted and actual cost. This would indicate that the predicted cost is very close to the actual display module cost. The fitted lines for folds in the model without release date are shown in Figure 5.9. The fitted lines, although not perfectly forming 1:1 lines between x and y axis, were reasonably close in their fits. This can be explained by the mean square error in each fold. In addition, it was noted that no outliers in predictions far away from the fitted lines we found. Cross-validation for two other models with additional variables was performed to explore any further improvements.

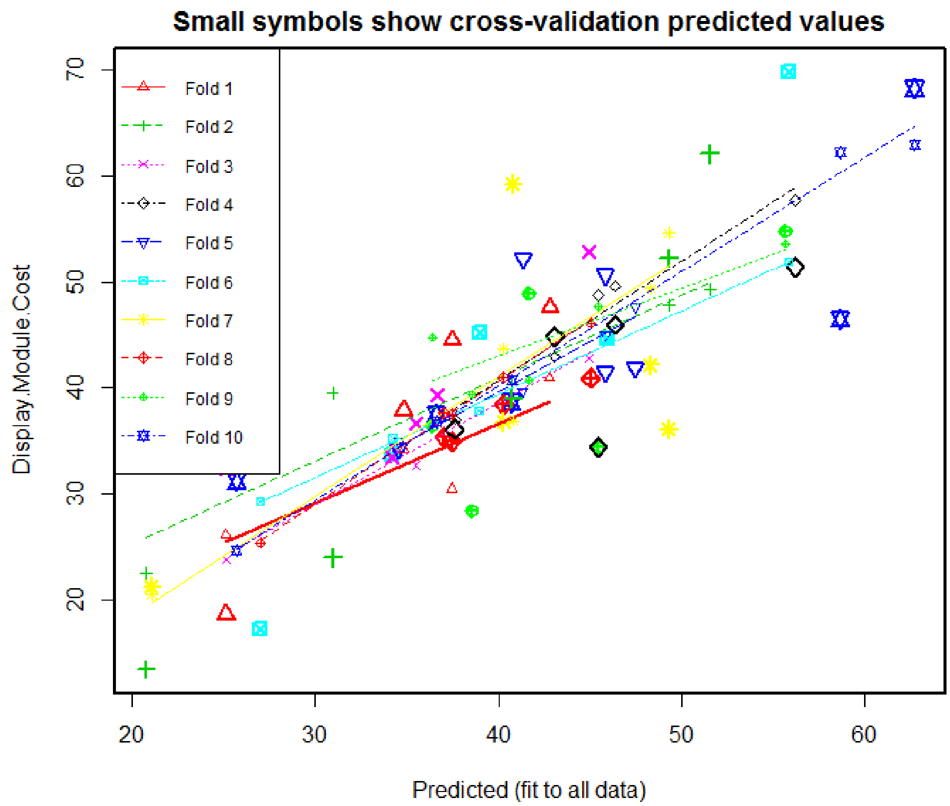

Figure 5.9: Cross-validated fit for display model (without release date)

The fitted lines for the folds in the other two models (with release date, and with release date and smartphone brand) are shown in Figure 5.10 and Figure 5.11 respectively. Visual inspection of the two figures revealed, although there seemed to exist no outliers, the fitted lines for most folds are skewed away from the 1:1 pattern that is deemed necessary for good prediction. This can be explained due to the mean square errors in each of these models shown in Table 5.14. Results from Table 5.14 above indicate that the overall mean square errors for both models are higher compared to the model without release dates.

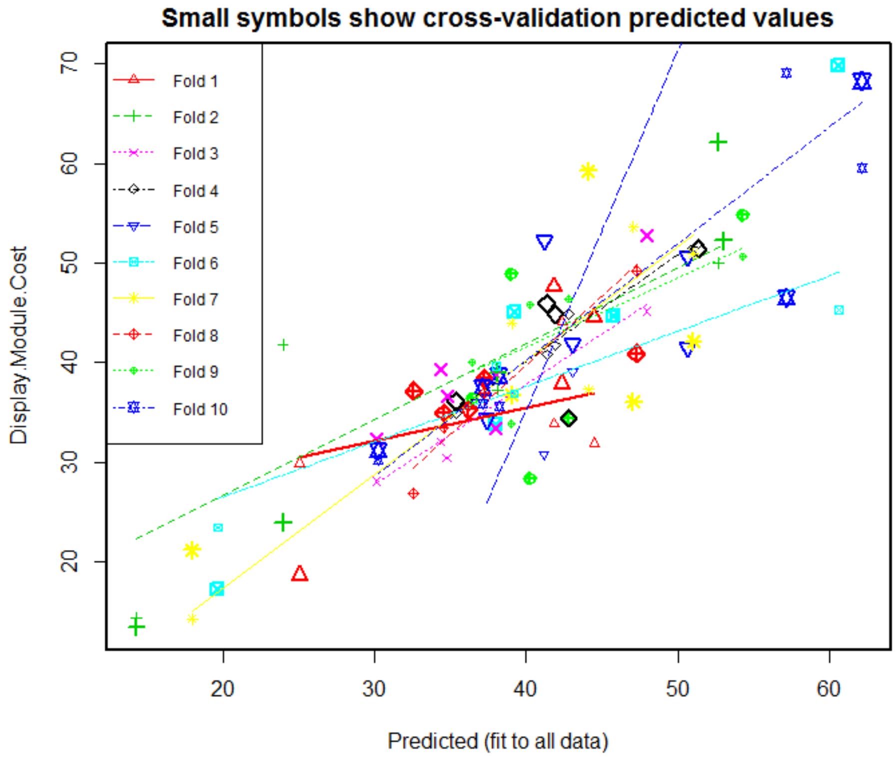

Figure 5.10: Cross-validated fit for display model (with release date)

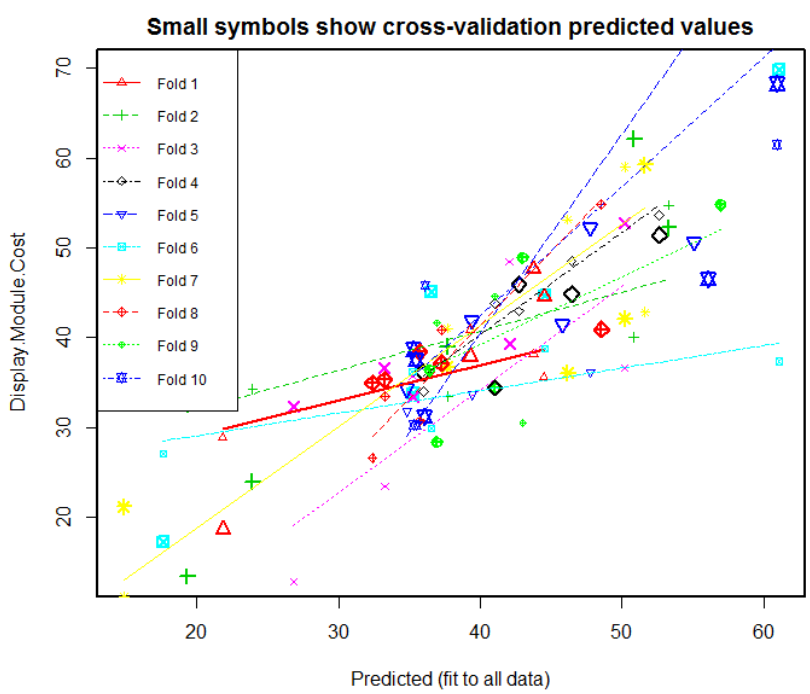

Figure 5.11: Cross-validated fit for display model (with release date and brand)

Comparing the outcome of the three models based on the different errors and cross-validation prediction charts, it was concluded the first model with the predicted root mean square error of $8.95 and better aligned prediction fits would be chosen to create the final display cost model.

Display Feature Testing

Based on results from retail model creation, the model with no release date was chosen for display model creation. The model, although during cross-validation performed well in predicting display module cost, included phones only from the sample that were present in the database. Since the objective of this research is to develop a model for practical scenario utilization, it was necessary to test the outcome of the model on display features outside the sampled data.

Research Hypothesis-2 restated

One of the general hypotheses stated is to validate the applicability of the model. This is to test the hypothesis for $8.9 margin of error in the display model created. By this, we construct the limits within which the display prediction model would need to operate. Therefore, the null hypothesis is set with limits of $8.9 and beyond which would not be suitable and the alternate hypothesis is set up to prove that the model perform within this limit.

Null Hypothesis:

H_0: Display Cost Error = ± $10

Alternate Hypothesis:

H_a: Display Cost Error < ± $10

Three different display feature set were randomly picked to be tested for display module cost. For each of the feature set, the five display feature variables in the model were defined as in Table 5.15. Each display specification was names A, B and C for the purpose of reference.

Table 5.15: Display Model Test Phone Specification

Display Variables	Spec 1 (A)	Spec 2 (B)	Spec 3 (C)
Display Type	LCD	OLED	OLED
Screen Size	4.7	8	6
Pixel Density	468	189	245
Colors	16.7M	16.7M	16.7M
Cover Glass	CGG2	CGG3	CGG3

Testing each of these specifications by the outcome of the display model without release date produced results shown in Table 5.16.

Table 5.16: Display model test results

	Spec 1 (A)	Spec 2 (B)	Spec 3 (C)
Display Module Cost ($)	40.28	73.50	54.80

The costs of three specifications represent the display cost results from the final display model. It was noticed that the display cost predicted represented to a reasonable extent the specifications of the display. This provides evidence for rejection of the null hypothesis in hypothesis-2 and proves that the model performs within the desired error limit in predicting display costs. Considering the range of error in the final model, the cost of the three predicted displays were in line with similar ones in the actual data set used in the analysis.

Adjusted Display Model

After testing the prediction ability of the model, it was found that the variables (i.e., Screen Size and Pixel Density) that are modeled as continuous variables are set to zero. Keeping continuous variables zero in the model made it difficult to translate the coefficients from the regression output. Hence, it was necessary to adjust the regression model to improve its comprehension. To do this, the model was adjusted to reference the screen size to 3 inches and the pixel density to 250 ppi. The intercept of the adjusted regression model is then referred to as the base display. This base display consists of features that serve as an absolute reference for any other feature combination in displays. The features of the intercept are shown in Table 5.17.

Table 5.17: Base Display features in Adjusted Display Regression Model

Display Feature	Base Specification
Display Type	OLED
Screen Size	3 inches
Pixel Density	250 ppi
Number of Colors	Unknown.NumberofColors
Cover Glass	Unknown.CoverGlass

5.5 Result

This section elaborates the usage of the conclusion obtained from the final display model testing results and the adjusted model. From the results above, display cost model with no release dates was chosen to build a Should-Cost Model (SCM). A SCM in the context of this research is defined as an interface which allows inputs of display features and outputs a predicted cost based on the inputted features. The SCM interface to input display features and produce the corresponding display cost was created using Microsoft Excel.

$$\begin{aligned} Cost\ of\ Base\ Display - 8.001246 * LCD + 0 * OLED + 9.318218 * (Screen\ Size - 3) \\ - 0.000196 * (Pixel\ Density - 250) - 5.098502 * 16MColors + 8.643324 \\ * 16.7M\ Colors + 2.199954 * CGG + 1.762882 * CGG2 - 3.872993 * CGG3 \\ + 9.884885 * SR + 7.982813 * SP \end{aligned}$$

Equation 5.2: Display Cost Equation

Since the Adjusted model is a variation of the selected model from the analysis - Display model with no release dates, the coefficient values of all regressors are collected. A table of all the display feature variables are created and the coefficients from the Adjusted display model are assigned to the corresponding variable names in the excel tool as shown in Figure 12. The inputs cell for each variable is multiplied to the corresponding coefficient and summed to assess predicted display cost, as shown in Equation 5.2. An input for one variable in each of the five display feature selects those features. As a result, it was seen that the display cost computed is described for the variables inputted. The final model of the Should-Cost Model interface is shown in Figure 5.12. The usability and applicability of the predicted display cost and the SCM interface are discussed in the next section.

						Display Cost Model							
Base* smartphone display cost =			[redacted]										
							Note: Enter 1 to select type in each display feature, unless specified otherwise						
Display Type		Screen Size		Pixel Density		Number of Colors		Cover Glass Type					
LCD		Screen Size		Input Density		16M Colors		CGG		CGG3		Scratch resistant	
OLED		(in inches)	[redacted]	(ppi)	[redacted]	16.7M Colors		CGG2		[redacted]		Shatter-Proof	
	Display with:												
		Display Type	0	0									
		Screen Size(")	0										
		Pixel Density(ppi)	0										
		Colors	0	0									
		Cover Glass	0	0	0	0	0						
												Display Cost =	[redacted]
*Base Phone:	OLED Display, 3" Screen Size, 250ppi Pixel Density												

Figure 5.12: Should-Cost Model

5.6 Conclusion

The conclusions drawn from the obtained results and discussion, and the extent to which the primary objectives set forth in section 5.4 have been achieved are presented in this section.

Primary objective #1 was to breakdown the components of a smartphone and build Bill-of-Material (BOM). This was achieved by collecting data on smartphones released in the market, and documenting the details available from teardowns and other sources accessed. A clearer picture of building the variables in BOM was also achieved based on literature collected on technologies, trends and data points each subsystem in smartphones. Although the secondary objective of segmenting smartphones did not directly impact the initial creation of the BOM, it can be seen that the purpose of this step was to group smartphones with similar pricing and feature set. Therefore, the features on the BOM vary based on the segment considered and hence secondary objective #2 formed a part of primary objective #1.

Primary objective #2 was to identify primary factors those contribute to the retail price of the smartphone and hence develop a good retail price predicting model. The analytical setup for this step was identified from reviewing existing cost estimating methods and identifying the regression analysis, along with few analogies identified from other methods. This helped form the outline for the analysis. The theoretical framework presented in the conference paper presented in Chapter 4 also helped outline the analysis. The identification of factors affecting cost was developed based on: analysis outlined, tools and techniques such as pareto analysis and variable selection, and cross-validation of smartphone costs.

Primary objective #3 was to identify display features and derive a model to predict display cost with the least error. The preliminary linear regression model creation shown in Chapter 3 reveals that the model with the least amount of error is to be selected. Cross-validation and random specification testing of the model also confirms the selection of this model.

The ultimate goal of this research was to create a model that can be used to predict smartphone display cost based on the display features. The numerical outputs of this final model/analysis were linked to a working interface named the Should-Cost Model in which display feature inputs are provided. The inputs in the SCM as shown in Chapter 3 create a value for the display cost in US Dollars ($).

5.7 Applicability of the Model

The Should-Cost Model interface developed in Chapter 3 allows predicting cost for various display feature combinations. As a result, the main objective of creating a model to use as a first hand basis for display cost negotiation is achieved.

The SCM not only provides a single point solution to cost prediction, but also acts as a cost comparison tool. The model calculates a display cost when variable inputs are provided. Changing one feature at a time helps compute change in display cost due to that variable change. Comparing this change in cost provides an idea of percentage change in cost due to one or more particular changes in feature. Similar changes can be made for more than one display feature. This would help assist engineering decisions for display feature selection based on cost. In addition to this, decision to change display features based on material availability can be assessed using this model.

5.8 Future Scope

This research can be viewed as a preliminary framework, aimed towards understanding and quantifying the product sub-system contributions to overall cost of a system. The following recommendations for further scope/investigation are proposed on the conclusion and limitations of the research:

i. Data on features identified in the limitations can possibly be collected to create a Should-Cost Model with additional features and predict better cost.

ii. Validation of the research by sampling over a wider range of data will increase the applicability to a wider market of phones.

iii. The analysis could prove to be more favorable for companies in New Product Development Stage with limited information on display pricing. Therefore, checking the validity of the outcome of this analysis using data from an organization's 'New Product Development' phase pricing would explain the applicability of this model better.

iv. Further precision in the model could be achieved using bottom-up approach if detailed pricing data collection of sub-components is made available.

v. A possible extension of the model to source other components could be pursued to check the application aspect of such cost estimating techniques.

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CHAPTER 6

6 CONCLUSION

6.1 Conclusion

The conclusions drawn from the obtained results and discussion in Chapter 5, and the extent to which the primary objectives set forth in Chapter 3 have been achieved are presented in this section.

Primary objective #1 was to breakdown the components of a smartphone and build Bill-of-Material (BOM). This was achieved by collecting data on smartphones released in the market, and documenting the details available from teardowns and other sources accessed. A clearer picture of building the variables in BOM was also achieved based on literature collected on technologies, trends and data points each subsystem in smartphones. Although the secondary objective of segmenting smartphones did not directly impact the initial creation of the BOM, it can be seen that the purpose of this step was to group smartphones with similar pricing and feature set. Therefore, the features on the BOM vary based on the segment considered and hence secondary objective #2 formed a part of primary objective #1.

Primary objective #2 was to identify primary factors those contribute to the retail price of the smartphone and hence develop a good retail price predicting model. The analytical setup for this step was identified from reviewing existing cost estimating methods and identifying the regression analysis, along with few analogies identified from other methods. This helped form the outline for the analysis. The theoretical framework presented in the conference paper presented in Chapter 4 also helped outline the analysis. The identification of factors affecting cost was developed based on: analysis outlined, tools and techniques such as pareto analysis and variable selection, and cross-validation of smartphone costs.

Primary objective #3 was to identify display features and derive a model to predict display cost with the least error. The preliminary linear regression model creation shown in Chapter 3 reveals that the model with the least amount of error is to be selected. Cross-validation and random specification testing of the model also confirms the selection of this model.

The ultimate goal of this research was to create a model that can be used to predict smartphone display cost based on the display features. The numerical outputs of this final model/analysis were linked to a working interface named the Should-Cost Model in which display feature inputs are provided. The inputs in the SCM as shown in Chapter 3 create a value for the display cost in US Dollars ($).

6.2 Findings of the Research

It is possible to utilize the complete set of data available and predict a retail price. Although this is the case, isolation of display variables is not deemed possible for reasons explained in Chapter 3.

The subset of data on display from the information collected can be utilized to construct a display cost model within the hypothesized error obtained using the data in Chapter 3. The results from testing various display features indicate suitable information to build the Should-Cost Model for practical purposes.

6.3 Applicability of Model

The Should-Cost Model interface developed in Chapter 3 and tested in Chapter 5 allows cost predicting for various display feature combinations. As a result, the main objective of creating a model to use as a first hand basis for display cost negotiation is achieved.

The SCM not only provides a single point solution to cost prediction, but also acts as a cost comparison tool. The model calculates a display cost when variable inputs are provided.

Changing one feature at a time helps compute change in display cost due to that variable change. Comparing this change in cost provides an idea of percentage change in cost due to one or more particular changes in feature. Similar changes can be made for more than one display feature. This would help assist engineering decisions for display feature selection based on cost. In addition to this, decision to change display features based on material availability can be assessed using this model.

6.4 Future Scope

This research can be viewed as a preliminary framework, aimed towards understanding and quantifying the product sub-system contributions to overall cost of a system. The following recommendations for further scope/investigation are proposed on the conclusion and limitations of the research:

vi. Data on features identified in the limitations can possibly be collected to create a Should-Cost Model with additional features and predict better cost.

vii. Validation of the research by sampling over a wider range of data will increase the applicability to a wider market of phones.

viii. The analysis could prove to be more favorable for companies in New Product Development Stage with limited information on display pricing. Therefore, checking the validity of the outcome of this analysis using data from an organization's 'New Product Development' phase pricing would explain the applicability of this model better.

ix. Further precision in the model could be achieved using bottom-up approach if detailed pricing data collection of sub-components is made available.

x. A possible extension of the model to source other components could be pursued to check the application aspect of such cost estimating techniques.

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8 APPENDIX

APPENDIX I: CODES AND OUTPUT FROM R-STUDIO

CODE IN R-STUDIO

Initial Analysis for Retail Price Model

```
Level1.1_PerformancePhone<- read.csv("C:/Users/vparame1/Downloads/Teardown PDFs/Data Files/Excel Files/Phone Segment/PerformancePhoneWithBrand1.csv")
View(Level1.1_PerformancePhone)
Level1.1_PerformancePhoneRandom<- read.csv("C:/Users/vparame1/Downloads/Teardown PDFs/Data Files/Excel Files/Phone Segment/PerformancePhoneRandomWithBrand1.csv")
View(Level1.1_PerformancePhoneRandom)

***********************Model 21****************************
  *Without Release
fit1_PerformancePhone <- lm(formula = Retail.Price ~ LCD + OLED +
Unknown.DisplayType + Screen.Size + Pixel.Density + Unknown.PixelDensity +
X65K.Colors + X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors +
Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass +
RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity +
Unknown.RearCameraCapacity + X4.and.Below.RearLensElements +
X5.and.above.RearLensElements + Unknown.RearLensElements + With.Front.Camera +
No.Front.Camera + Unknown.FrontCamera + X0.3.to.1.3.FrontCameraCapacity +
X1.6.to.5.FrontCameraCapacity + VGA.FrontCameraCapacity +
Unknown.FrontCameraCapacity + Log.InternalMemory + Unknown.InternalMemory +
Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Battery.Pack.Rating +
Unknown.BatteryPackRating + Headset + Unknown.Headset + USB2.0 + USB3.0 +
Unknown.USB.Version, data = subset(Level1.1_PerformancePhone, select= c( -X,-SI.NO,-
Phone,-Brand,-Mfg.Cost,-Unknown.Mfg.Cost,-Elec.Cost,-Unknown.Elec.Cost,-Retina,-
DVGA,-FHD,-FWVGA,-HVGA,-nHD,-qHD,-QVGA,-SVGA,-WQVGA,-WSVGA,-WVGA,-
WXGA,-XGA,-Unknown,-X3.7V.Battery.Voltage.and.Below,-
X3.75V.Battery.Voltage.and.Above,-Unknown.BatteryVoltage,-Soft.Pack,-Hard.Pack,-
```

```
Unknown.BatteryPackaging,-PoP,-Unknown.PoP,-Clock.Speed,-Unknown.ClockSpeed,-iOS,-
Android,-Windows,-Blackberry,-Symbian,-Unknown.OS,-BB.7,-BB.7.1,-BB.10,-BB.10.2,-
Froyo,-Gingerbread,-IceCream.Sandwich,-JellyBean,-KitKat,-Mango,-iOS.4,-iOS.6,-iOS.7,-
Win.7,-Win.8,-Win.8S,-Unknown.OSName,-With.External.Included.Memory,-
No.External.Included.Memory,-Unknown.ExternalIncludedMemory,-Cloud,-MicroSD,-
Unknown.ExternalMemoryType,-Zero.Extendability,-X7.to.32.Extendability,-
X64.to.128.Extendability,-Unknown.External.Extendability,-Rear.Camera,-FrontOpticalSize,-
Unknown.FrontOpticalSize,-X1.to.3.FrontCameraLensElements,-
X4.to.5.FrontCameraLensElements,-Unknown.FrontCameraLensElements,-
Bluetooth.Version,-Cable,-Unknown.Cable,-Adapter,-Unknown.Adapter,-Exterior.Packaging,-
Unknown.Packaging,-Documentation,-Unknown.Documentation,-Q1.14,-Q2.14,-Q1.13,-
Q2.13,-Q3.13,-Q4.13,-Q1.12,-Q2.12,-Q3.12,-Q4.12,-Q1.11,-Q2.11,-Q3.11,-Q4.11,-Q1.10,-
Q2.10,-Q3.10,-Q4.10,-Q2.09,-Unknown.Release.Date)))

summary(fit1_PerformancePhone)

predict(fit1_PerformancePhone, newdata = Level1.1_PerformancePhoneRandom)
Level1.1_PerformancePhoneRandom$pred_price <- predict(fit1_PerformancePhone, newdata
= Level1.1_PerformancePhoneRandom)
with(Level1.1_PerformancePhoneRandom, data.frame(Retail.Price, pred_price, error =
Retail.Price-pred_price))
Level1.1_PerformancePhone_Predictions <- with(Level1.1_PerformancePhoneRandom,
data.frame(Retail.Price, pred_price, error = Retail.Price-pred_price))

sqrt(mean(Level1.1_PerformancePhone_Predictions$error^2))
```

***With Release Date**

```
fit1_PerformancePhoneWithRelease <- lm(formula = Retail.Price ~ LCD + OLED +
Unknown.DisplayType + Screen.Size + Pixel.Density + Unknown.PixelDensity +
X65K.Colors + X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors +
Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass +
RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity +
```

```
Unknown.RearCameraCapacity + X4.and.Below.RearLensElements +
X5.and.above.RearLensElements + Unknown.RearLensElements + With.Front.Camera +
No.Front.Camera + Unknown.FrontCamera + X0.3.to.1.3.FrontCameraCapacity +
X1.6.to.5.FrontCameraCapacity + VGA.FrontCameraCapacity +
Unknown.FrontCameraCapacity + Log.InternalMemory + Unknown.InternalMemory +
Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Battery.Pack.Rating +
Unknown.BatteryPackRating + USB2.0 + USB3.0 + Unknown.USB.Version + Headset +
Unknown.Headset + Q1.14 + Q2.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 +
Q3.12 + Q4.12 + Q1.11 + Q2.11 + Q3.11 + Q4.11 + Q1.10 + Q2.10 + Q3.10 + Q4.10 + Q2.09
+ Unknown.Release.Date, data = subset(Level1.1_PerformancePhone, select= c( -X,-SI.NO,-
Phone,-Brand,-Mfg.Cost,-Unknown.Mfg.Cost,-Elec.Cost,-Unknown.Elec.Cost,-Retina,-
DVGA,-FHD,-FWVGA,-HVGA,-nHD,-qHD,-QVGA,-SVGA,-WQVGA,-WSVGA,-WVGA,-
WXGA,-XGA,-Unknown,-X3.7V.Battery.Voltage.and.Below,-
X3.75V.Battery.Voltage.and.Above,-Unknown.BatteryVoltage,-Soft.Pack,-Hard.Pack,-
Unknown.BatteryPackaging,-PoP,-Unknown.PoP,-Clock.Speed,-Unknown.ClockSpeed,-iOS,-
Android,-Windows,-Blackberry,-Symbian,-Unknown.OS,-BB.7,-BB.7.1,-BB.10,-BB.10.2,-
Froyo,-Gingerbread,-IceCream.Sandwich,-JellyBean,-KitKat,-Mango,-iOS.4,-iOS.6,-iOS.7,-
Win.7,-Win.8,-Win.8S,-Unknown.OSName,-With.External.Included.Memory,-
No.External.Included.Memory,-Unknown.ExternalIncludedMemory,-Cloud,-MicroSD,-
Unknown.ExternalMemoryType,-Zero.Extendability,-X7.to.32.Extendability,-
X64.to.128.Extendability,-Unknown.External.Extendability,-Rear.Camera,-FrontOpticalSize,-
Unknown.FrontOpticalSize,-X1.to.3.FrontCameraLensElements,-
X4.to.5.FrontCameraLensElements,-Unknown.FrontCameraLensElements,-
Bluetooth.Version,-Documentation,-Unknown.Documentation)))

summary(fit1_PerformancePhoneWithRelease)

predict(fit1_PerformancePhoneWithRelease, newdata = Level1.1_PerformancePhoneRandom)
Level1.1_PerformancePhoneRandom$pred_price <-
predict(fit1_PerformancePhoneWithRelease, newdata = Level1.1_PerformancePhoneRandom)
with(Level1.1_PerformancePhoneRandom, data.frame(Retail.Price, pred_price, error =
Retail.Price-pred_price))
```

```
Level1.1_PerformancePhone_Predictions <- with(Level1.1_PerformancePhoneRandom,
data.frame(Retail.Price, pred_price, error = Retail.Price-pred_price))

sqrt(mean(Level1.1_PerformancePhone_Predictions$error^2))
```

Retail Price Model Cross-Validation

********************Model 21****************************

```
Level1.1_PerformancePhone<- read.csv("C:/Users/vparame1/Downloads/Teardown
PDFs/Data Files/Excel Files/Phone Segment/For cvlm/PerformancePhone.csv")
View(Level1.1_PerformancePhone)
```

***Without Release Date**

```
fit1_PerformancePhone <- lm(formula = Retail.Price ~ LCD + OLED +
Unknown.DisplayType + Screen.Size + Pixel.Density + X262K.Colors +
X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 +
CGG3 + SR + SP + Unknown.CoverGlass + PoP + Unknown.PoP + RAM.Capacity +
Unknown.RAMCapacity + Rear.Camera.Capacity + Unknown.RearCameraCapacity +
X4.and.Below.RearLensElements + X5.and.above.RearLensElements +
Unknown.RearLensElements + X0.3.to.1.3.FrontCameraCapacity +
X1.6.to.5.FrontCameraCapacity + VGA.FrontCameraCapacity +
Unknown.FrontCameraCapacity + Log.InternalMemory + Unknown.InternalMemory
+ Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Battery.Pack.Rating +
Unknown.BatteryPackRating + Headset + Unknown.Headset + USB2.0 + USB3.0 +
Unknown.USB.Version, data = subset(Level1.1_PerformancePhone, select= c( -X,-
SI.NO,-Phone,-Brand,-Mfg.Cost,-Unknown.Mfg.Cost,-Elec.Cost,-
Unknown.Elec.Cost,-Retina,-DVGA,-FHD,-FWVGA,-HVGA,-nHD,-qHD,-QVGA,-
SVGA,-WQVGA,-WSVGA,-WVGA,-WXGA,-XGA,-Unknown,-X65K.Colors,-
X256K.Colors,-X3.7V.Battery.Voltage.and.Below,-
X3.75V.Battery.Voltage.and.Above,-Unknown.BatteryVoltage,-Soft.Pack,-
Hard.Pack,-Unknown.BatteryPackaging,-Clock.Speed,-Unknown.ClockSpeed,-iOS,-
```

```
Android,-Windows,-Blackberry,-Symbian,-Unknown.OS,-BB.7,-BB.7.1,-BB.10,-
BB.10.2,-Froyo,-Gingerbread,-IceCream.Sandwich,-JellyBean,-KitKat,-Mango,-
iOS.4,-iOS.6,-iOS.7,-Win.7,-Win.8,-Win.8S,-Unknown.OSName,-
With.External.Included.Memory,-No.External.Included.Memory,-
Unknown.ExternalIncludedMemory,-Cloud,-MicroSD,-
Unknown.ExternalMemoryType,-Zero.Extendability,-X7.to.32.Extendability,-
X64.to.128.Extendability,-Unknown.External.Extendability,-Rear.Camera,-
With.Front.Camera,-No.Front.Camera,-Unknown.FrontCamera,-FrontOpticalSize,-
Unknown.FrontOpticalSize,-X1.to.3.FrontCameraLensElements,-
X4.to.5.FrontCameraLensElements,-Unknown.FrontCameraLensElements,-IR,-
Unknown.IR,-Wifi,-Unknown.Wifi,-Bluetooth,-Unknown.Bluetooth,-
GPS.GLONASS,-Unknown.GPS.GLONASS,-FM.Radio,-Unknown.FMRadio,-USB,-
Unknown.USB,-HDMI,-Unknown.HDMI,-NFC,-Unknown.NFC,-DLNA,-
Unknown.DLNA,-Bluetooth.Version,-BluetoothVersion2,-BluetoothVersion2.1,-
BluetoothVersion3,-BluetoothVersion3.1,-BluetoothVersion4,-
Unknown.BluetoothVersion,-Micro.USB.Version,-Accelerometer,-
Unknown.Accelerometer,-Al,-Unknown.Al,-PS,-Unknown.PS,-Electronic.Compass,-
Unknown.ElectronicCompass,-Magnetometer,-Unknown.Magnetometer,-
Geomagnetic.Sensor,-Unknown.GeomagneticSensor,-Magnetic,-Unknown.Magnetic,-
Cable,-Unknown.Cable,-Adapter,-Unknown.Adapter,-Exterior.Packaging,-
Unknown.Packaging,-Documentation,-Unknown.Documentation,-Q1.14,-Q2.14,-
Q1.13,-Q2.13,-Q3.13,-Q4.13,-Q1.12,-Q2.12,-Q3.12,-Q4.12,-Q1.11,-Q2.11,-Q3.11,-
Q4.11,-Q1.10,-Q2.10,-Q3.10,-Q4.10,-Q2.09,-Unknown.Release.Date)))
cv.lm(df = Level1.1_PerformancePhone, fit1_PerformancePhone, m = 10)
```

***With Release Date**

```
fit1_PerformancePhoneWithRelease <- lm(formula = Retail.Price ~ LCD + OLED +
Unknown.DisplayType + Screen.Size + Pixel.Density + X262K.Colors +
X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 +
CGG3 + SR + SP + Unknown.CoverGlass + PoP + Unknown.PoP + RAM.Capacity +
```

```
Unknown.RAMCapacity + Rear.Camera.Capacity + Unknown.RearCameraCapacity +
X4.and.Below.RearLensElements + X5.and.above.RearLensElements +
Unknown.RearLensElements + X0.3.to.1.3.FrontCameraCapacity +
X1.6.to.5.FrontCameraCapacity + VGA.FrontCameraCapacity +
Unknown.FrontCameraCapacity + Log.InternalMemory + Unknown.InternalMemory
+ Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Battery.Pack.Rating +
Unknown.BatteryPackRating + Headset + Unknown.Headset + USB2.0 + USB3.0 +
Unknown.USB.Version + Q1.14 + Q2.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12
+ Q2.12 + Q3.12 + Q4.12 + Q1.11 + Q2.11 + Q3.11 + Q4.11 + Q1.10 + Q2.10 +
Q3.10 + Q4.10 + Q2.09 + Unknown.Release.Date, data =
subset(Level1.1_PerformancePhone, select= c( -X,-SI.NO,-Phone,-Brand,-Mfg.Cost,-
Unknown.Mfg.Cost,-Elec.Cost,-Unknown.Elec.Cost,-Retina,-DVGA,-FHD,-
FWVGA,-HVGA,-nHD,-qHD,-QVGA,-SVGA,-WQVGA,-WSVGA,-WVGA,-
WXGA,-XGA,-Unknown,-X65K.Colors,-X256K.Colors,-
X3.7V.Battery.Voltage.and.Below,-X3.75V.Battery.Voltage.and.Above,-
Unknown.BatteryVoltage,-Soft.Pack,-Hard.Pack,-Unknown.BatteryPackaging,-
Clock.Speed,-Unknown.ClockSpeed,-iOS,-Android,-Windows,-Blackberry,-Symbian,-
Unknown.OS,-BB.7,-BB.7.1,-BB.10,-BB.10.2,-Froyo,-Gingerbread,-
IceCream.Sandwich,-JellyBean,-KitKat,-Mango,-iOS.4,-iOS.6,-iOS.7,-Win.7,-Win.8,-
Win.8S,-Unknown.OSName,-With.External.Included.Memory,-
No.External.Included.Memory,-Unknown.ExternalIncludedMemory,-Cloud,-
MicroSD,-Unknown.ExternalMemoryType,-Zero.Extendability,-
X7.to.32.Extendability,-X64.to.128.Extendability,-Unknown.External.Extendability,-
Rear.Camera,-With.Front.Camera,-No.Front.Camera,-Unknown.FrontCamera,-
FrontOpticalSize,-Unknown.FrontOpticalSize,-X1.to.3.FrontCameraLensElements,-
X4.to.5.FrontCameraLensElements,-Unknown.FrontCameraLensElements,-IR,-
Unknown.IR,-Wifi,-Unknown.Wifi,-Bluetooth,-Unknown.Bluetooth,-
GPS.GLONASS,-Unknown.GPS.GLONASS,-FM.Radio,-Unknown.FMRadio,-USB,-
Unknown.USB,-HDMI,-Unknown.HDMI,-NFC,-Unknown.NFC,-DLNA,-
Unknown.DLNA,-Bluetooth.Version,-BluetoothVersion2,-BluetoothVersion2.1,-
```

```
BluetoothVersion3,-BluetoothVersion3.1,-BluetoothVersion4,-
Unknown.BluetoothVersion,-Micro.USB.Version,-Accelerometer,-
Unknown.Accelerometer,-Al,-Unknown.Al,-PS,-Unknown.PS,-Electronic.Compass,-
Unknown.ElectronicCompass,-Magnetometer,-Unknown.Magnetometer,-
Geomagnetic.Sensor,-Unknown.GeomagneticSensor,-Magnetic,-Unknown.Magnetic,-
Cable,-Unknown.Cable,-Adapter,-Unknown.Adapter,-Exterior.Packaging,-
Unknown.Packaging,-Documentation,-Unknown.Documentation)))
cv.lm(df = Level1.1_PerformancePhone, fit1_PerformancePhoneWithRelease, m = 10)
```

Display Cost Model

```
Level1_PerformancePhoneDisplay<-
read.csv("C:/Users/vparame1/Downloads/Teardown PDFs/Data Files/Excel
Files/Phone Segment/For cvlm/PerformancePhoneDisplay.csv")
View(Level1_PerformancePhoneDisplay)

**Without Release Date
fit <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + Pixel.Density +
X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3
+ SR + SP + Unknown.CoverGlass, data = Level1_PerformancePhoneDisplay)
summary(fit)

**With Release Date
fit1 <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + Pixel.Density +
X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3
+ SR + SP + Unknown.CoverGlass + Q1.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12
+ Q2.12 + Q3.12 + Q4.12 + Q4.11, data = Level1_PerformancePhoneDisplay)
summary(fit1)
```

Display Cost Model Cross-Validation

```
install.packages("DAAG")
library(DAAG)

Level1_PerformancePhoneDisplay<-
read.csv("C:/Users/vparame1/Downloads/Teardown PDFs/Data Files/Excel Files/Phone Segment/For cvlm/PerformancePhoneDisplayfromQ4'11.csv")
View(Level1_PerformancePhoneDisplay)

**Without Release Date
fit <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass, data = Level1_PerformancePhoneDisplay)
cv.lm(df = Level1_PerformancePhoneDisplay, fit, m = 10)

**With Release Date
fit1 <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Q1.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q3.12 + Q4.12 + Q4.11, data = Level1_PerformancePhoneDisplay)
cv.lm(df = Level1_PerformancePhoneDisplay, fit1, m = 10)
```

Adjusted Display Cost Model

```
**Without Release Date
fit <- lm(Display.Module.Cost ~ LCD + OLED + I(Screen.Size-3)+ I(Pixel.Density-250) + X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass, data = Level1_PerformancePhoneDisplay)
summary(fit)
```

OUTPUTS

Table 1: Level One Regression Output

```
> fit1_no.missing<- lm(formula= Retail.Price ~ LCD + OLED + Unknown.Dis
playType + Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Apple.
Processor + Broadcom.Processor + Hexa.Core.Processor + HiSilicon.Proces
sor + Intel.Processor + Marvell.Processor + MediaTek.Processor + Nokia.
Processor + NVIDIA.Processor + Qualcomm.Processor + Samsung.Processor +
 Spreadtrum.Processor + STMicro.Processor + ST.Ericsson.Processor + TI.
Processor + Unknown.ProcessorBrand + iOS + Android + Windows + Blackber
ry + Symbian + Unknown.OS, data = LevelOnenomissing)
> summary(fit1_no.missing)

Call:
lm(formula = Retail.Price ~ LCD + OLED + Unknown.DisplayType +
    Li.P.Battery + Li.Ion.Battery + Unknown.BatteryType + Apple.Process
or +
    Broadcom.Processor + Hexa.Core.Processor + HiSilicon.Processor +
    Intel.Processor + Marvell.Processor + MediaTek.Processor +
    Nokia.Processor + NVIDIA.Processor + Qualcomm.Processor +
    Samsung.Processor + Spreadtrum.Processor + STMicro.Processor +
    ST.Ericsson.Processor + TI.Processor + Unknown.ProcessorBrand +
    iOS + Android + Windows + Blackberry + Symbian + Unknown.OS,
    data = LevelOnenomissing)

Residuals:
    Min      1Q  Median      3Q     Max
-400.12 -115.87  -30.82   97.47  604.76

Coefficients: (5 not defined because of singularities)
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)             92.0612   171.0656   0.538   0.5909
LCD                    126.8083   122.1287   1.038   0.3000
OLED                   312.5563   125.5366   2.490   0.0133 *
Unknown.DisplayType          NA         NA      NA       NA
Li.P.Battery            67.8316    69.7668   0.972   0.3317
Li.Ion.Battery         -66.6905    68.6690  -0.971   0.3322
Unknown.BatteryType          NA         NA      NA       NA
Apple.Processor         12.2989   196.7043   0.063   0.9502
Broadcom.Processor      -0.1675   102.6327  -0.002   0.9987
Hexa.Core.Processor    223.4198   195.0012   1.146   0.2528
HiSilicon.Processor    131.9328   114.6079   1.151   0.2506
Intel.Processor         50.3983   106.5080   0.473   0.6364
Marvell.Processor       37.0060   109.7493   0.337   0.7362
MediaTek.Processor       7.0645    95.1054   0.074   0.9408
Nokia.Processor              NA         NA      NA       NA
```

```
NVIDIA.Processor        260.5373   101.5680   2.565   0.0108 *
Qualcomm.Processor      132.6677    91.0806   1.457   0.1463
Samsung.Processor       179.7016   102.5208   1.753   0.0807 .
Spreadtrum.Processor     -1.8888   134.2273  -0.014   0.9888
STMicro.Processor       144.5678   193.5822   0.747   0.4558
ST.Ericsson.Processor    99.6886   101.8416   0.979   0.3284
TI.Processor            163.7711   101.6762   1.611   0.1083
Unknown.ProcessorBrand        NA         NA      NA       NA
iOS                     400.2500   191.0028   2.096   0.0370 *
Android                  78.6431    49.4822   1.589   0.1130
Windows                  53.7095    59.1576   0.908   0.3647
Blackberry              141.1251    86.7156   1.627   0.1047
Symbian                 171.9478   118.0956   1.456   0.1464
Unknown.OS                    NA         NA      NA       NA
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 170.8 on 299 degrees of freedom
Multiple R-squared: 0.3655,     Adjusted R-squared: 0.3167
F-statistic:  7.49 on 23 and 299 DF,  p-value: < 2.2e-16
```

Table 2: Level One Prediction Results

```
> with(LevelOnenomissingRandom, data.frame(Retail.Price, pred_price
, error = Retail.Price-pred_price))
   Retail.Price pred_price        error
1        490.00   415.7425   74.2575366
2        450.00   363.4899   86.5101382
3        449.99   498.0119  -48.0218997
4        799.99   498.0119  301.9781003
5        599.99   498.0119  101.9781003
6        649.99   363.4899  286.5001382
7        200.00   338.5563 -138.5562576
8        387.93   497.2770 -109.3470063
9        379.99   498.0119 -118.0218997
10       219.99   363.4899 -143.4998618
11       175.00   363.4899 -188.4898618
12       161.76   498.0119 -336.2518997
13       790.00   498.0119  291.9881003
14       149.00   363.4899 -214.4898618
15       180.00   237.8867  -57.8866804
16       400.00   372.4087   27.5912816
17       684.99   337.9271  347.0628982
18       449.99   658.8264 -208.8363591
19       399.99   549.2379 -149.2479253
20       355.00   230.6546  124.3453846
21       474.00   416.4027   57.5973210
22       699.99   549.2379  150.7520747
23       399.99   596.2718 -196.2818326
24       629.99   498.0119  131.9781003
25       361.48   465.0328 -103.5527679
26       383.21   363.4899   19.7201382
27       380.00   498.0119 -118.0118997
28       403.78   491.3594  -87.5794402
29       180.00   363.4899 -183.4898618
30       549.99   363.4899  186.5001382
31       194.37   267.8281  -73.4581230
32       599.00   419.3688  179.6312161
33       408.42   372.4087   36.0112816
34       371.64   372.4087   -0.7687184
35       742.82   491.3594  251.4605598
```

Table 3: Level Two Regression Output

```
> fit2_no.missing <- lm(formula = Retail.Price ~ LCD + OLED + Unknown.DisplayTyp
e + Screen.Size + Retina+ DVGA + FHD + FWVGA + HVGA + nHD + qHD + QVGA + SVGA + 
WQVGA + WSVGA + WVGA + WXGA + XGA + Unknown + Pixel.Density + Unknown.PixelDensi
ty + X65K.Colors + X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors + U
nknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Li.P.
Battery + Li.Ion.Battery + Unknown.BatteryType + X3.7V.Battery.Voltage.and.Below
 + X3.75V.Battery.Voltage.and.and.Above + Unknown.BatteryVoltage + Battery.Pack.
Rating + Unknown.BatteryPackRating + Soft.Pack + Hard.Pack + Unknown.BatteryPack
aging + PoP + Unknown.PoP + Apple.Processor + Broadcom.Processor + Hexa.Core.Pro
cessor + HiSilicon.Processor + Intel.Processor + Marvell.Processor + MediaTek.Pr
ocessor + Nokia.Processor + NVIDIA.Processor + Qualcomm.Processor + Samsung.Proc
essor + Spreadtrum.Processor + STMicro.Processor + ST.Ericsson.Processor + TI.Pr
ocessor + Unknown.ProcessorBrand + Clock.Speed + Unknown.ClockSpeed + Single.Cor
e + Dual.Core + Quad.Core + Hexa.Core + Octa.Core + Unknown.Cores + DDR + DDR2 +
 DDR2.S4 + DDR3 + DDR3.S4 + LPDDR2 + LPDDR3 + Unknown.RAMType + RAM.Capacity + U
nknown.RAMCapacity + iOS + Android + Windows + Blackberry + Symbian + Unknown.OS
 + BB.7 + BB.7.1 + BB.10 + BB.10.2 + Froyo + Gingerbread + IceCream.Sandwich + J
ellyBean + KitKat + Mango + iOS4 + iOS6 + iOS7 + Win7 + Win8 + Win8S + Unknown.O
SName + With.External.Included.Memory + No.External.Included.Memory + Unknown.Ex
ternalIncludedMemory + Rear.Camera + With.Front.Camera + No.Front.Camera + Unkno
wn.FrontCamera + IR + Unknown.IR + Wifi + Unknown.Wifi + Bluetooth + Unknown.Blu
etooth + GPS.GLONASS + Unknown.GPS.GLONASS + FM.Radio + Unknown.FMRadio + USB + 
Unknown.USB + HDMI + Unknown.HDMI + NFC + Unknown.NFC + DLNA + Unknown.DLNA + Wi
reless.Charging + Unknown.WirelessCharging + FeliCa.RFID.Smart.Card + Unknown.Fe
liCaRFIDSmartCard + Headset + Cable + Adapter + Exterior.Packaging + Documentati
on, data = LevelTwonomissing)
> summary(fit2_no.missing)

Call:
lm(formula = Retail.Price ~ LCD + OLED + Unknown.DisplayType + 
    Screen.Size + Retina + DVGA + FHD + FWVGA + HVGA + nHD + 
    qHD + QVGA + SVGA + WQVGA + WSVGA + WVGA + WXGA + XGA + Unknown + 
    Pixel.Density + Unknown.PixelDensity + X65K.Colors + X256K.Colors + 
    X262K.Colors + X16M.Colors + X16.7M.Colors + Unknown.NumberofColors + 
    CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Li.P.Battery + 
    Li.Ion.Battery + Unknown.BatteryType + X3.7V.Battery.Voltage.and.Below + 
    X3.75V.Battery.Voltage.and.and.Above + Unknown.BatteryVoltage + 
    Battery.Pack.Rating + Unknown.BatteryPackRating + Soft.Pack + 
```

```
    Hard.Pack + Unknown.BatteryPackaging + PoP + Unknown.PoP +
    Apple.Processor + Broadcom.Processor + Hexa.Core.Processor +
    HiSilicon.Processor + Intel.Processor + Marvell.Processor +
    MediaTek.Processor + Nokia.Processor + NVIDIA.Processor +
    Qualcomm.Processor + Samsung.Processor + Spreadtrum.Processor +
    STMicro.Processor + ST.Ericsson.Processor + TI.Processor +
    Unknown.ProcessorBrand + Clock.Speed + Unknown.ClockSpeed +
    Single.Core + Dual.Core + Quad.Core + Hexa.Core + Octa.Core +
    Unknown.Cores + DDR + DDR2 + DDR2.S4 + DDR3 + DDR3.S4 + LPDDR2 +
    LPDDR3 + Unknown.RAMType + RAM.Capacity + Unknown.RAMCapacity +
    iOS + Android + Windows + Blackberry + Symbian + Unknown.OS +
    BB.7 + BB.7.1 + BB.10 + BB.10.2 + Froyo + Gingerbread + IceCream.Sandwich +
    JellyBean + KitKat + Mango + iOS4 + iOS6 + iOS7 + Win7 +
    Win8 + Win8S + Unknown.OSName + With.External.Included.Memory +
    No.External.Included.Memory + Unknown.ExternalIncludedMemory +
    Rear.Camera + With.Front.Camera + No.Front.Camera + Unknown.FrontCamera +
    IR + Unknown.IR + Wifi + Unknown.Wifi + Bluetooth + Unknown.Bluetooth +
    GPS.GLONASS + Unknown.GPS.GLONASS + FM.Radio + Unknown.FMRadio +
    USB + Unknown.USB + HDMI + Unknown.HDMI + NFC + Unknown.NFC +
    DLNA + Unknown.DLNA + Wireless.Charging + Unknown.WirelessCharging +
    FeliCa.RFID.Smart.Card + Unknown.FeliCaRFIDSmartCard + Headset +
    Cable + Adapter + Exterior.Packaging + Documentation, data = LevelTwonomissi
ng)

Residuals:
     Min       1Q   Median       3Q      Max 
-229.995  -59.567   -0.053   56.014  255.005 

Coefficients: (23 not defined because of singularities)
                                       Estimate Std. Error t value Pr(>|t|)  
(Intercept)                          -4.135e+02  4.663e+02  -0.887 0.376219  
LCD                                  -1.360e+02  1.640e+02  -0.829 0.408011  
OLED                                 -4.851e+01  1.668e+02  -0.291 0.771415  
Unknown.DisplayType                          NA         NA      NA       NA  
Screen.Size                           1.924e+02  8.046e+01   2.391 0.017710 *
Retina                               -4.965e+02  5.210e+02  -0.953 0.341705  
DVGA                                 -3.804e+02  4.850e+02  -0.784 0.433806  
FHD                                  -9.297e+02  7.053e+02  -1.318 0.188926  
FWVGA                                -4.815e+02  3.685e+02  -1.307 0.192782  
HVGA                                 -1.780e+02  2.348e+02  -0.758 0.449293  
nHD                                  -3.271e+02  3.082e+02  -1.061 0.289801  
```

qHD	-5.274e+02	4.038e+02	-1.306	0.192973	
QVGA	7.983e+01	1.829e+02	0.436	0.662928	
SVGA	-3.775e+02	3.903e+02	-0.967	0.334594	
WQVGA	8.810e+01	2.583e+02	0.341	0.733371	
WSVGA	-7.273e+02	4.786e+02	-1.520	0.130138	
WVGA	-4.244e+02	3.516e+02	-1.207	0.228818	
WXGA	-6.991e+02	5.114e+02	-1.367	0.173079	
XGA	-6.838e+02	4.690e+02	-1.458	0.146376	
Unknown	-6.611e+02	4.233e+02	-1.562	0.119856	
Pixel.Density	2.845e+00	1.462e+00	1.946	0.053022	.
Unknown.PixelDensity	NA	NA	NA	NA	
X65K.Colors	-7.416e+01	1.360e+02	-0.545	0.586117	
X256K.Colors	-2.589e+01	1.170e+02	-0.221	0.825107	
X262K.Colors	1.785e+00	7.214e+01	0.025	0.980283	
X16M.Colors	-5.626e-01	7.246e+01	-0.008	0.993813	
X16.7M.Colors	3.988e+01	6.961e+01	0.573	0.567362	
Unknown.NumberofColors	NA	NA	NA	NA	
CGG	1.543e+02	6.029e+01	2.559	0.011195	*
CGG2	5.509e+01	6.331e+01	0.870	0.385179	
CGG3	6.776e+01	7.254e+01	0.934	0.351281	
SR	9.571e+01	5.880e+01	1.628	0.105087	
SP	6.316e+01	6.312e+01	1.001	0.318145	
Unknown.CoverGlass	1.052e+02	6.204e+01	1.696	0.091318	.
Li.P.Battery	2.128e+02	1.618e+02	1.315	0.190015	
Li.Ion.Battery	2.223e+02	1.619e+02	1.373	0.171271	
Unknown.BatteryType	NA	NA	NA	NA	
X3.7V.Battery.Voltage.and.Below	-3.152e+02	1.190e+02	-2.649	0.008688	**
X3.75V.Battery.Voltage.and.and.Above	-3.078e+02	1.202e+02	-2.560	0.011177	*
Unknown.BatteryVoltage	NA	NA	NA	NA	
Battery.Pack.Rating	9.960e-04	2.741e-02	0.036	0.971044	
Unknown.BatteryPackRating	NA	NA	NA	NA	
Soft.Pack	-2.199e+01	8.028e+01	-0.274	0.784425	
Hard.Pack	-3.992e+01	7.666e+01	-0.521	0.603077	
Unknown.BatteryPackaging	NA	NA	NA	NA	
PoP	-1.683e+01	2.201e+01	-0.765	0.445262	
Unknown.PoP	-2.294e+02	1.319e+02	-1.739	0.083453	.
Apple.Processor	-9.613e+01	1.707e+02	-0.563	0.574003	
Broadcom.Processor	6.537e+01	1.086e+02	0.602	0.547769	
Hexa.Core.Processor	1.375e+02	1.827e+02	0.753	0.452507	
HiSilicon.Processor	-2.491e+01	1.176e+02	-0.212	0.832419	
Intel.Processor	-9.067e+01	1.172e+02	-0.774	0.439890	

Marvell.Processor	2.780e+01	1.150e+02	0.242	0.809270	
MediaTek.Processor	-4.485e+01	1.066e+02	-0.421	0.674253	
Nokia.Processor	NA	NA	NA	NA	
NVIDIA.Processor	1.051e+02	1.083e+02	0.970	0.333086	
Qualcomm.Processor	2.811e+01	1.056e+02	0.266	0.790304	
Samsung.Processor	4.179e+01	1.126e+02	0.371	0.710875	
Spreadtrum.Processor	4.794e+01	1.319e+02	0.363	0.716626	
STMicro.Processor	3.468e-01	1.569e+02	0.002	0.998238	
ST.Ericsson.Processor	7.984e+01	1.061e+02	0.752	0.452773	
TI.Processor	7.603e+01	1.057e+02	0.719	0.472722	
Unknown.ProcessorBrand	NA	NA	NA	NA	
Clock.Speed	7.139e+01	4.815e+01	1.483	0.139658	
Unknown.ClockSpeed	1.535e+02	6.462e+01	2.375	0.018438	*
Single.Core	-2.697e+01	3.231e+01	-0.834	0.404978	
Dual.Core	4.077e+01	3.241e+01	1.258	0.209902	
Quad.Core	1.342e+01	4.328e+01	0.310	0.756770	
Hexa.Core	NA	NA	NA	NA	
Octa.Core	8.517e+01	9.231e+01	0.923	0.357249	
Unknown.Cores	NA	NA	NA	NA	
DDR	-1.168e+02	1.329e+02	-0.879	0.380437	
DDR2	-8.288e+01	1.310e+02	-0.633	0.527514	
DDR2.S4	-8.938e+01	1.323e+02	-0.675	0.500131	
DDR3	-1.052e+02	1.491e+02	-0.706	0.481212	
DDR3.S4	1.526e+01	1.585e+02	0.096	0.923388	
LPDDR2	-3.902e+02	2.003e+02	-1.948	0.052716	.
LPDDR3	-1.305e+02	1.427e+02	-0.915	0.361496	
Unknown.RAMType	NA	NA	NA	NA	
RAM.Capacity	6.172e+01	2.893e+01	2.134	0.034055	*
Unknown.RAMCapacity	1.491e+02	4.821e+01	3.092	0.002258	**
iOS	NA	NA	NA	NA	
Android	1.235e+02	6.302e+01	1.960	0.051324	.
Windows	-4.820e+01	1.265e+02	-0.381	0.703642	
Blackberry	2.184e+01	1.400e+02	0.156	0.876193	
Symbian	NA	NA	NA	NA	
Unknown.OS	NA	NA	NA	NA	
BB.7	-6.547e+01	1.658e+02	-0.395	0.693359	
BB.7.1	-5.734e+00	1.836e+02	-0.031	0.975115	
BB.10	-3.400e+01	1.701e+02	-0.200	0.841832	
BB.10.2	NA	NA	NA	NA	
Froyo	-1.395e+02	7.705e+01	-1.811	0.071568	.
Gingerbread	-1.310e+02	6.210e+01	-2.110	0.036060	*

IceCream.Sandwich	-1.535e+02	6.232e+01	-2.462	0.014615	*
JellyBean	-2.415e+02	6.389e+01	-3.780	0.000205	***
KitKat	-3.207e+02	9.479e+01	-3.384	0.000854	***
Mango	1.204e+02	1.270e+02	0.947	0.344492	
iOS4	NA	NA	NA	NA	
iOS6	-7.401e+00	1.962e+02	-0.038	0.969949	
iOS7	NA	NA	NA	NA	
Win7	-1.685e+02	1.606e+02	-1.049	0.295241	
Win8	-4.677e+01	1.172e+02	-0.399	0.690239	
Win8S	NA	NA	NA	NA	
Unknown.OSName	NA	NA	NA	NA	
With.External.Included.Memory	-6.374e+01	4.815e+01	-1.324	0.187037	
No.External.Included.Memory	-5.079e+01	5.308e+01	-0.957	0.339729	
Unknown.ExternalIncludedMemory	NA	NA	NA	NA	
Rear.Camera	NA	NA	NA	NA	
With.Front.Camera	7.208e+01	4.178e+01	1.725	0.085996	.
No.Front.Camera	5.696e+01	4.374e+01	1.302	0.194320	
Unknown.FrontCamera	NA	NA	NA	NA	
IR	3.504e+01	5.368e+01	0.653	0.514625	
Unknown.IR	-9.288e+01	5.859e+01	-1.585	0.114450	
Wifi	7.935e+01	1.096e+02	0.724	0.469893	
Unknown.Wifi	1.532e+02	1.195e+02	1.282	0.201399	
Bluetooth	-1.648e+02	2.044e+02	-0.806	0.421004	
Unknown.Bluetooth	-1.901e+02	2.068e+02	-0.919	0.359158	
GPS.GLONASS	-6.763e+01	6.573e+01	-1.029	0.304724	
Unknown.GPS.GLONASS	-1.821e+02	9.703e+01	-1.876	0.062012	.
FM.Radio	-3.365e+01	2.809e+01	-1.198	0.232287	
Unknown.FMRadio	-3.435e+01	3.566e+01	-0.963	0.336541	
USB	8.449e+01	6.578e+01	1.284	0.200421	
Unknown.USB	1.078e+02	6.930e+01	1.555	0.121483	
HDMI	1.596e+01	3.676e+01	0.434	0.664708	
Unknown.HDMI	3.093e+01	5.878e+01	0.526	0.599286	
NFC	4.071e+01	2.202e+01	1.849	0.065946	.
Unknown.NFC	6.731e+01	6.140e+01	1.096	0.274188	
DLNA	4.831e+01	1.998e+01	2.418	0.016456	*
Unknown.DLNA	-2.182e+01	6.681e+01	-0.327	0.744285	
Wireless.Charging	1.095e+02	9.493e+01	1.153	0.250228	
Unknown.WirelessCharging	5.950e+01	2.060e+01	2.889	0.004277	**
FeliCa.RFID.Smart.Card	3.132e+02	1.253e+02	2.499	0.013226	*
Unknown.FeliCaRFIDSmartCard	-1.352e+02	5.061e+01	-2.673	0.008123	**
Headset	4.896e+01	2.232e+01	2.193	0.029389	*

```
Cable                                      4.800e+00  8.502e+01   0.056 0.955032
Adapter                                   -2.316e+01  3.981e+01  -0.582 0.561383
Exterior.Packaging                        -7.092e+01  1.309e+02  -0.542 0.588525
Documentation                              2.530e+02  1.996e+02   1.267 0.206414
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 107.6 on 208 degrees of freedom
Multiple R-squared:  0.8249,   Adjusted R-squared:  0.7289
F-statistic: 8.596 on 114 and 208 DF,  p-value: < 2.2e-16
```

Table 4: Level Two Prediction Results

```
> with(LevelTwonomissingRandom, data.frame(Retail.Price, pred_price,
 error = Retail.Price-pred_price))
   Retail.Price  pred_price       error
1        490.00  671.721205 -181.721205
2        450.00  228.936392  221.063608
3        449.99  480.531485  -30.541485
4        799.99  836.564389  -36.574389
5        599.99  509.706567   90.283433
6        649.99  464.127984  185.862016
7        200.00  289.706747  -89.706747
8        387.93  421.617532  -33.687532
9        379.99  110.021550  269.968450
10       219.99  200.181453   19.808547
11       175.00   -7.009715  182.009715
12       161.76  301.328546 -139.568546
13       790.00  662.615223  127.384777
14       149.00  392.784308 -243.784308
15       180.00  177.458172    2.541828
16       400.00  250.743040  149.256960
17       684.99  174.216584  510.773416
18       449.99  451.968876   -1.978876
19       399.99  495.594371  -95.604371
20       355.00  370.045160  -15.045160
21       474.00  488.273050  -14.273050
22       699.99 -177.957490  877.947490
23       399.99  333.963383   66.026617
24       629.99  689.622490  -59.632490
25       361.48  357.980314    3.499686
26       383.21  272.218682  110.991318
27       380.00  590.722617 -210.722617
28       403.78  396.305713    7.474287
29       180.00  236.340051  -56.340051
30       549.99  150.452825  399.537175
31       194.37  248.895327  -54.525327
32       599.00 -258.054397  857.054397
33       408.42  230.973818  177.446182
34       371.64  236.138708  135.501292
35       742.82  705.365880   37.454120
```

Table 5: Retail Model Cross-validation regression output (without release date)

```
> fit1_PerformancePhone <- lm(formula = Retail.Price ~ LCD + OLED + Unkno
wn.DisplayType + Screen.Size + Pixel.Density + Unknown.PixelDensity + X65
K.Colors + X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors + Un
known.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass +
 RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity + Unknown.Rear
CameraCapacity + X4.and.Below.RearLensElements + X5.and.above.RearLensEle
ments + Unknown.RearLensElements + With.Front.Camera + No.Front.Camera +
Unknown.FrontCamera + X0.3.to.1.3.FrontCameraCapacity + X1.6.to.5.FrontCa
meraCapacity + VGA.FrontCameraCapacity + Unknown.FrontCameraCapacity + Lo
g.InternalMemory + Unknown.InternalMemory + Li.P.Battery + Li.Ion.Battery
 + Unknown.BatteryType + Battery.Pack.Rating + Unknown.BatteryPackRating
+ Headset + Unknown.Headset + USB2.0 + USB3.0 + Unknown.USB.Version, data
 = subset(Level1.1_PerformancePhone, select= c( -X,-SI.NO,-Phone,-Brand,-
Mfg.Cost,-Unknown.Mfg.Cost,-Elec.Cost,-Unknown.Elec.Cost,-Retina,-DVGA,-F
HD,-FWVGA,-HVGA,-nHD,-qHD,-QVGA,-SVGA,-WQVGA,-WSVGA,-WVGA,-WXGA,-XGA,-Unk
nown,-X3.7V.Battery.Voltage.and.Below,-X3.75V.Battery.Voltage.and.Above,-
Unknown.BatteryVoltage,-Soft.Pack,-Hard.Pack,-Unknown.BatteryPackaging,-P
oP,-Unknown.PoP,-Clock.Speed,-Unknown.ClockSpeed,-iOS,-Android,-Windows,-
Blackberry,-Symbian,-Unknown.OS,-BB.7,-BB.7.1,-BB.10,-BB.10.2,-Froyo,-Gin
gerbread,-IceCream.Sandwich,-JellyBean,-KitKat,-Mango,-iOS.4,-iOS.6,-iOS.
7,-Win.7,-Win.8,-Win.8S,-Unknown.OSName,-With.External.Included.Memory,-N
o.External.Included.Memory,-Unknown.ExternalIncludedMemory,-Cloud,-MicroS
D,-Unknown.ExternalMemoryType,-Zero.Extendability,-X7.to.32.Extendability
,-X64.to.128.Extendability,-Unknown.External.Extendability,-Rear.Camera,-
FrontOpticalSize,-Unknown.FrontOpticalSize,-X1.to.3.FrontCameraLensElemen
ts,-X4.to.5.FrontCameraLensElements,-Unknown.FrontCameraLensElements,-Blu
etooth.Version,-Cable,-Unknown.Cable,-Adapter,-Unknown.Adapter,-Exterior.
Packaging,-Unknown.Packaging,-Documentation,-Unknown.Documentation,-Q1.14
,-Q2.14,-Q1.13,-Q2.13,-Q3.13,-Q4.13,-Q1.12,-Q2.12,-Q3.12,-Q4.12,-Q1.11,-Q
2.11,-Q3.11,-Q4.11,-Q1.10,-Q2.10,-Q3.10,-Q4.10,-Q2.09,-Unknown.Release.Da
te)))
> summary(fit1_PerformancePhone)

Call:
lm(formula = Retail.Price ~ LCD + OLED + Unknown.DisplayType + 
    Screen.Size + Pixel.Density + Unknown.PixelDensity + X65K.Colors + 
    X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors + 
    Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverG
lass + 
    RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity + 
    Unknown.RearCameraCapacity + X4.and.Below.RearLensElements + 
    X5.and.above.RearLensElements + Unknown.RearLensElements + 
    With.Front.Camera + No.Front.Camera + Unknown.FrontCamera + 
    X0.3.to.1.3.FrontCameraCapacity + X1.6.to.5.FrontCameraCapacity + 
    VGA.FrontCameraCapacity + Unknown.FrontCameraCapacity + Log.InternalM
emory + 
    Unknown.InternalMemory + Li.P.Battery + Li.Ion.Battery + 
    Unknown.BatteryType + Battery.Pack.Rating + Unknown.BatteryPackRating
 + 
    Headset + Unknown.Headset + USB2.0 + USB3.0 + Unknown.USB.Version, 
    data = subset(Level1.1_PerformancePhone, select = c(-X, -SI.NO, 
        -Phone, -Brand, -Mfg.Cost, -Unknown.Mfg.Cost, -Elec.Cost, 
        -Unknown.Elec.Cost, -Retina, -DVGA, -FHD, -FWVGA, -HVGA, 
        -nHD, -qHD, -QVGA, -SVGA, -WQVGA, -WSVGA, -WVGA, -WXGA, 
```

```
        -XGA, -Unknown, -X3.7V.Battery.Voltage.and.Below, -X3.75V.Battery
.Voltage.and.Above,
        -Unknown.BatteryVoltage, -Soft.Pack, -Hard.Pack, -Unknown.Battery
Packaging,
        -PoP, -Unknown.PoP, -Clock.Speed, -Unknown.ClockSpeed,
        -iOS, -Android, -Windows, -Blackberry, -Symbian, -Unknown.OS,
        -BB.7, -BB.7.1, -BB.10, -BB.10.2, -Froyo, -Gingerbread,
        -IceCream.Sandwich, -JellyBean, -KitKat, -Mango, -iOS.4,
        -iOS.6, -iOS.7, -Win.7, -Win.8, -Win.8S, -Unknown.OSName,
        -With.External.Included.Memory, -No.External.Included.Memory,
        -Unknown.ExternalIncludedMemory, -Cloud, -MicroSD, -Unknown.Exter
nalMemoryType,
        -Zero.Extendability, -X7.to.32.Extendability, -X64.to.128.Extenda
bility,
        -Unknown.External.Extendability, -Rear.Camera, -FrontOpticalSize,

        -Unknown.FrontOpticalSize, -X1.to.3.FrontCameraLensElements,
        -X4.to.5.FrontCameraLensElements, -Unknown.FrontCameraLensElement
s,
        -Bluetooth.Version, -Cable, -Unknown.Cable, -Adapter,
        -Unknown.Adapter, -Exterior.Packaging, -Unknown.Packaging,
        -Documentation, -Unknown.Documentation, -Q1.14, -Q2.14,
        -Q1.13, -Q2.13, -Q3.13, -Q4.13, -Q1.12, -Q2.12, -Q3.12,
        -Q4.12, -Q1.11, -Q2.11, -Q3.11, -Q4.11, -Q1.10, -Q2.10,
        -Q3.10, -Q4.10, -Q2.09, -Unknown.Release.Date)))

Residuals:
   Min     1Q Median     3Q    Max
-205.7  -69.9   -8.4   64.2  362.6

Coefficients: (13 not defined because of singularities)
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                      217.5873   249.7315    0.87  0.38543
LCD                               -6.4397    27.0191   -0.24  0.81205
OLED                                   NA         NA      NA       NA
Unknown.DisplayType                    NA         NA      NA       NA
Screen.Size                       34.0543    31.5429    1.08  0.28259
Pixel.Density                      0.6641     0.2422    2.74  0.00710 **
Unknown.PixelDensity                   NA         NA      NA       NA
X65K.Colors                            NA         NA      NA       NA
X256K.Colors                           NA         NA      NA       NA
X262K.Colors                     -23.3706    98.2426   -0.24  0.81240
X16M.Colors                     -156.9505    75.9675   -2.07  0.04109 *
X16.7M.Colors                   -135.7156    75.9979   -1.79  0.07679 .
Unknown.NumberofColors                 NA         NA      NA       NA
CGG                               33.1453    26.5622    1.25  0.21465
CGG2                             -12.8215    39.2414   -0.33  0.74447
CGG3                              44.5103    51.8932    0.86  0.39284
SR                               -89.4524    54.4439   -1.64  0.10313
SP                                69.5333    56.6153    1.23  0.22191
Unknown.CoverGlass                     NA         NA      NA       NA
RAM.Capacity                      11.7894    33.2249    0.35  0.72337
Unknown.RAMCapacity               98.4802    58.4708    1.68  0.09487 .
Rear.Camera.Capacity               2.0757     2.3852    0.87  0.38601
Unknown.RearCameraCapacity        93.8094    94.8042    0.99  0.32451
X4.and.Below.RearLensElements    -62.6869    42.8623   -1.46  0.14635
X5.and.above.RearLensElements    -53.5714    35.6414   -1.50  0.13559
Unknown.RearLensElements               NA         NA      NA       NA
With.Front.Camera                193.4532    94.1886    2.05  0.04227 *
No.Front.Camera                  161.7814   102.8415    1.57  0.11846
Unknown.FrontCamera                    NA         NA      NA       NA
X0.3.to.1.3.FrontCameraCapacity   -8.2188    32.4469   -0.25  0.80049
```

```
X1.6.to.5.FrontCameraCapacity    -34.5558    35.2352   -0.98  0.32881    
VGA.FrontCameraCapacity                NA         NA      NA       NA    
Unknown.FrontCameraCapacity            NA         NA      NA       NA    
Log.InternalMemory               150.6085    43.6831    3.45  0.00079 ***
Unknown.InternalMemory           129.4761    64.4612    2.01  0.04694 *  
Li.P.Battery                       6.4674   103.3898    0.06  0.95023    
Li.Ion.Battery                    58.5225    98.2095    0.60  0.55243    
Unknown.BatteryType                    NA         NA      NA       NA    
Battery.Pack.Rating               -0.0379     0.0423   -0.90  0.37149    
Unknown.BatteryPackRating              NA         NA      NA       NA    
Headset                          -93.7492    75.5290   -1.24  0.21707    
Unknown.Headset                 -249.0307   136.7809   -1.82  0.07128 .  
USB2.0                            79.3887    81.5835    0.97  0.33257    
USB3.0                           119.2553   153.7646    0.78  0.43961    
Unknown.USB.Version               73.2838    83.3996    0.88  0.38141    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 112 on 114 degrees of freedom
Multiple R-squared:  0.47,     Adjusted R-squared:  0.326 
F-statistic: 3.26 on 31 and 114 DF,  p-value: 2.53e-06
```

Table 6: Retail Model Cross-validation Prediction Results (without release date)

```
> with(Level1.1_PerformancePhoneRandom, data.frame(Retail.Price, pr
ed_price, error = Retail.Price-pred_price))
   Retail.Price pred_price  error
1           699        655   43.7
2           450        344  106.1
3           720        653   67.4
4           533        546  -13.2
5           545        488   56.8
6           779        656  123.3
7           449        525  -75.7
8           550        679 -129.1
9           550        565  -14.6
10          500        592  -92.3
11          547        704 -156.8
12          630        479  151.0
13          693        732  -38.3
14          549        510   39.0
15          700        662   37.8
> Level1.1_PerformancePhone_Predictions <- with(Level1.1_Performanc
ePhoneRandom, data.frame(Retail.Price, pred_price, error = Retail.P
rice-pred_price))
> sqrt(mean(Level1.1_PerformancePhone_Predictions$error^2))
[1] 89.2
```

Table 7: Retail Model Cross-validation regression output (with release date)

```
> fit1_PerformancePhoneWithRelease <- lm(formula = Retail.Price ~ LCD + O
LED + Unknown.DisplayType + Screen.Size + Pixel.Density + Unknown.PixelDe
nsity + X65K.Colors + X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.
Colors + Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.C
overGlass + RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity + U
nknown.RearCameraCapacity + X4.and.Below.RearLensElements + X5.and.above.
RearLensElements + Unknown.RearLensElements + With.Front.Camera + No.Fron
t.Camera + Unknown.FrontCamera + X0.3.to.1.3.FrontCameraCapacity + X1.6.t
o.5.FrontCameraCapacity + VGA.FrontCameraCapacity + Unknown.FrontCameraCa
pacity + Log.InternalMemory + Unknown.InternalMemory + Li.P.Battery + Li.
Ion.Battery + Unknown.BatteryType + Battery.Pack.Rating + Unknown.Battery
PackRating + USB2.0 + USB3.0 + Unknown.USB.Version + Headset + Unknown.He
adset + Q1.14 + Q2.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q
3.12 + Q4.12 + Q1.11 + Q2.11 + Q3.11 + Q4.11 + Q1.10 + Q2.10 + Q3.10 + Q4
.10 + Q2.09 + Unknown.Release.Date, data = subset(Level1.1_PerformancePho
ne, select= c( -X,-SI.NO,-Phone,-Brand,-Mfg.Cost,-Unknown.Mfg.Cost,-Elec.
Cost,-Unknown.Elec.Cost,-Retina,-DVGA,-FHD,-FWVGA,-HVGA,-nHD,-qHD,-QVGA,-
SVGA,-WQVGA,-WSVGA,-WVGA,-WXGA,-XGA,-Unknown,-X3.7V.Battery.Voltage.and.B
elow,-X3.75V.Battery.Voltage.and.Above,-Unknown.BatteryVoltage,-Soft.Pack
,-Hard.Pack,-Unknown.BatteryPackaging,-PoP,-Unknown.PoP,-Clock.Speed,-Unk
nown.ClockSpeed,-iOS,-Android,-Windows,-Blackberry,-Symbian,-Unknown.OS,-
BB.7,-BB.7.1,-BB.10,-BB.10.2,-Froyo,-Gingerbread,-IceCream.Sandwich,-Jell
yBean,-KitKat,-Mango,-iOS.4,-iOS.6,-iOS.7,-Win.7,-Win.8,-Win.8S,-Unknown.
OSName,-With.External.Included.Memory,-No.External.Included.Memory,-Unkno
wn.ExternalIncludedMemory,-Cloud,-MicroSD,-Unknown.ExternalMemoryType,-Ze
ro.Extendability,-X7.to.32.Extendability,-X64.to.128.Extendability,-Unkno
wn.External.Extendability,-Rear.Camera,-FrontOpticalSize,-Unknown.FrontOp
ticalSize,-X1.to.3.FrontCameraLensElements,-X4.to.5.FrontCameraLensElemen
ts,-Unknown.FrontCameraLensElements,-Bluetooth.Version,-Documentation,-Un
known.Documentation)))
> summary(fit1_PerformancePhoneWithRelease)

Call:
lm(formula = Retail.Price ~ LCD + OLED + Unknown.DisplayType + 
    Screen.Size + Pixel.Density + Unknown.PixelDensity + X65K.Colors + 
    X256K.Colors + X262K.Colors + X16M.Colors + X16.7M.Colors + 
    Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverG
lass + 
    RAM.Capacity + Unknown.RAMCapacity + Rear.Camera.Capacity + 
    Unknown.RearCameraCapacity + X4.and.Below.RearLensElements + 
    X5.and.above.RearLensElements + Unknown.RearLensElements + 
    With.Front.Camera + No.Front.Camera + Unknown.FrontCamera + 
    X0.3.to.1.3.FrontCameraCapacity + X1.6.to.5.FrontCameraCapacity + 
    VGA.FrontCameraCapacity + Unknown.FrontCameraCapacity + Log.InternalM
emory + 
    Unknown.InternalMemory + Li.P.Battery + Li.Ion.Battery + 
    Unknown.BatteryType + Battery.Pack.Rating + Unknown.BatteryPackRating
 + 
    USB2.0 + USB3.0 + Unknown.USB.Version + Headset + Unknown.Headset + 
    Q1.14 + Q2.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + 
    Q3.12 + Q4.12 + Q1.11 + Q2.11 + Q3.11 + Q4.11 + Q1.10 + Q2.10 + 
    Q3.10 + Q4.10 + Q2.09 + Unknown.Release.Date, data = subset(Level1.1_
PerformancePhone, 
    select = c(-X, -SI.NO, -Phone, -Brand, -Mfg.Cost, -Unknown.Mfg.Cost, 
        -Elec.Cost, -Unknown.Elec.Cost, -Retina, -DVGA, -FHD, 
```

```
        -FWVGA, -HVGA, -nHD, -qHD, -QVGA, -SVGA, -WQVGA, -WSVGA,
        -WVGA, -WXGA, -XGA, -Unknown, -X3.7V.Battery.Voltage.and.Below,
        -X3.75V.Battery.Voltage.and.Above, -Unknown.BatteryVoltage,
        -Soft.Pack, -Hard.Pack, -Unknown.BatteryPackaging, -PoP,
        -Unknown.PoP, -Clock.Speed, -Unknown.ClockSpeed, -iOS,
        -Android, -Windows, -Blackberry, -Symbian, -Unknown.OS,
        -BB.7, -BB.7.1, -BB.10, -BB.10.2, -Froyo, -Gingerbread,
        -IceCream.Sandwich, -JellyBean, -KitKat, -Mango, -iOS.4,
        -iOS.6, -iOS.7, -Win.7, -Win.8, -Win.8S, -Unknown.OSName,
        -With.External.Included.Memory, -No.External.Included.Memory,
        -Unknown.ExternalIncludedMemory, -Cloud, -MicroSD, -Unknown.Exter
nalMemoryType,
        -Zero.Extendability, -X7.to.32.Extendability, -X64.to.128.Extenda
bility,
        -Unknown.External.Extendability, -Rear.Camera, -FrontOpticalSize,

        -Unknown.FrontOpticalSize, -X1.to.3.FrontCameraLensElements,
        -X4.to.5.FrontCameraLensElements, -Unknown.FrontCameraLensElement
s,
        -Bluetooth.Version, -Documentation, -Unknown.Documentation)))

Residuals:
    Min      1Q  Median      3Q     Max
-229.51  -53.84   -2.75   46.37  249.63

Coefficients: (17 not defined because of singularities)
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                       56.0456   319.4930    0.18   0.8611
LCD                               -8.9442    25.7537   -0.35   0.7291
OLED                                   NA         NA      NA       NA
Unknown.DisplayType                    NA         NA      NA       NA
Screen.Size                       38.2226    31.4050    1.22   0.2265
Pixel.Density                      0.7188     0.2396    3.00   0.0034 **
Unknown.PixelDensity                   NA         NA      NA       NA
X65K.Colors                            NA         NA      NA       NA
X256K.Colors                           NA         NA      NA       NA
X262K.Colors                      19.1568    99.4182    0.19   0.8476
X16M.Colors                     -130.4981    75.8368   -1.72   0.0884 .
X16.7M.Colors                    -38.5089    81.6774   -0.47   0.6383
Unknown.NumberofColors                 NA         NA      NA       NA
CGG                               36.1882    26.3710    1.37   0.1731
CGG2                             -37.3366    38.1295   -0.98   0.3299
CGG3                              30.4615    54.7631    0.56   0.5793
SR                               -86.4043    53.3849   -1.62   0.1088
SP                                66.1803    53.5374    1.24   0.2194
Unknown.CoverGlass                     NA         NA      NA       NA
RAM.Capacity                      28.5235    34.4572    0.83   0.4098
Unknown.RAMCapacity               95.2117    58.7330    1.62   0.1082
Rear.Camera.Capacity               1.0608     2.3008    0.46   0.6458
Unknown.RearCameraCapacity        52.7952   103.6827    0.51   0.6118
X4.and.Below.RearLensElements   -130.0918    49.0505   -2.65   0.0093 **
X5.and.above.RearLensElements    -61.8793    37.1283   -1.67   0.0988 .
Unknown.RearLensElements               NA         NA      NA       NA
With.Front.Camera                275.9188    98.2635    2.81   0.0060 **
No.Front.Camera                  301.9860   108.0508    2.79   0.0062 **
Unknown.FrontCamera                    NA         NA      NA       NA
X0.3.to.1.3.FrontCameraCapacity  -21.1866    33.6351   -0.63   0.5302
X1.6.to.5.FrontCameraCapacity    -19.8758    35.6678   -0.56   0.5786
VGA.FrontCameraCapacity                NA         NA      NA       NA
Unknown.FrontCameraCapacity            NA         NA      NA       NA
Log.InternalMemory               148.3246    44.4749    3.34   0.0012 **
Unknown.InternalMemory            96.0291    65.6106    1.46   0.1465
```

```
Li.P.Battery                          -34.2210   100.5395   -0.34   0.7343
Li.Ion.Battery                         25.1594    95.4238    0.26   0.7926
Unknown.BatteryType                         NA         NA      NA       NA
Battery.Pack.Rating                    -0.0244     0.0406   -0.60   0.5490
Unknown.BatteryPackRating                   NA         NA      NA       NA
USB2.0                                133.8000    81.1554    1.65   0.1024
USB3.0                                208.5708   151.6505    1.38   0.1722
Unknown.USB.Version                   152.3587    83.2166    1.83   0.0702 .
Headset                               -90.2161   119.3113   -0.76   0.4514
Unknown.Headset                      -279.3056   210.9859   -1.32   0.1886
Q1.14                                 -97.0405   120.7958   -0.80   0.4237
Q2.14                                       NA         NA      NA       NA
Q1.13                                 -74.0662   120.0029   -0.62   0.5385
Q2.13                                -157.1495   115.7005   -1.36   0.1775
Q3.13                                 -60.1907   121.8811   -0.49   0.6225
Q4.13                                -112.7029   116.1568   -0.97   0.3343
Q1.12                                 -79.0294   130.3078   -0.61   0.5456
Q2.12                                  47.2064   122.5305    0.39   0.7009
Q3.12                                 -52.1375   120.5890   -0.43   0.6664
Q4.12                                -110.3318   120.3824   -0.92   0.3616
Q1.11                                 182.9747   139.8850    1.31   0.1939
Q2.11                                 106.1554   144.6261    0.73   0.4647
Q3.11                                 -71.1458   134.8055   -0.53   0.5989
Q4.11                                  66.7750   131.6079    0.51   0.6130
Q1.10                                       NA         NA      NA       NA
Q2.10                                  66.0287   174.0645    0.38   0.7053
Q3.10                                   0.6871   231.2231    0.00   0.9976
Q4.10                                -123.6827   146.2937   -0.85   0.3999
Q2.09                                       NA         NA      NA       NA
Unknown.Release.Date                        NA         NA      NA       NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 102 on 98 degrees of freedom
Multiple R-squared:  0.622,    Adjusted R-squared:  0.441
F-statistic: 3.43 on 47 and 98 DF,  p-value: 1.39e-07
```

Table 8: Retail Model Cross-validation Prediction Results (with release date)

```
> with(Level1.1_PerformancePhoneRandom, data.frame(Retail.Price, pre
d_price, error = Retail.Price-pred_price))
   Retail.Price pred_price   error
1           699        686   12.90
2           450        203  246.63
3           720        656   64.31
4           533        523    9.66
5           545        516   28.23
6           779        741   38.34
7           449        433   16.05
8           550        693 -143.37
9           550        568  -17.81
10          500        662 -161.90
11          547        742 -194.92
12          630        294  335.56
13          693        761  -67.62
14          549        540    8.62
15          700        756  -56.01
> Level1.1_PerformancePhone_Predictions <- with(Level1.1_Performance
PhoneRandom, data.frame(Retail.Price, pred_price, error = Retail.Pri
ce-pred_price))
> sqrt(mean(Level1.1_PerformancePhone_Predictions$error^2))
[1] 135
```

Table 9: Display Model Regression Output (without release date)

```
> fit <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + Pix
el.Density + X16M.Colors + X16.7M.Colors + Unknown.NumberofColor
s + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass, data = Lev
el1_PerformancePhoneDisplay)
> summary(fit)

Call:
lm(formula = Display.Module.Cost ~ LCD + OLED + Screen.Size + 
    Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.Number
ofColors + 
    CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass, data = Lev
el1_PerformancePhoneDisplay)

Residuals:
    Min      1Q  Median      3Q     Max 
-13.231  -4.345  -0.483   4.805  18.421 

Coefficients: (3 not defined because of singularities)
                        Estimate Std. Error t value Pr(>|t|)    
(Intercept)            -5.828112  14.091023   -0.41   0.6815    
LCD                    -8.001246   2.780623   -2.88   0.0065 ** 
OLED                          NA         NA      NA       NA    
Screen.Size             9.318218   2.105355    4.43  7.8e-05 ***
Pixel.Density          -0.000196   0.021686   -0.01   0.9928    
X16M.Colors            -5.098502   8.485267   -0.60   0.5515    
X16.7M.Colors           8.643324   8.469886    1.02   0.3140    
Unknown.NumberofColors        NA         NA      NA       NA    
CGG                     2.199954   3.427754    0.64   0.5249    
CGG2                    1.762882   3.952733    0.45   0.6581    
CGG3                   -3.872993   4.028992   -0.96   0.3425    
SR                      9.884885   6.856613    1.44   0.1576    
SP                      7.982813   4.798151    1.66   0.1044    
Unknown.CoverGlass            NA         NA      NA       NA    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.84 on 38 degrees of freedom
Multiple R-squared:  0.649,	Adjusted R-squared:  0.557 
F-statistic: 7.03 on 10 and 38 DF,  p-value: 3.99e-06
```

Table 10: Display Model Regression Output with Adjusted Intercept (without release date)

```
> fit <- lm(Display.Module.Cost ~ LCD + OLED + I(Screen.Size-3)+
 I(Pixel.Density-250) + X16M.Colors + X16.7M.Colors + Unknown.Nu
mberofColors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass,
 data = Level1_PerformancePhoneDisplay)
> summary(fit)

Call:
lm(formula = Display.Module.Cost ~ LCD + OLED + I(Screen.Size -
    3) + I(Pixel.Density - 250) + X16M.Colors + X16.7M.Colors +
    Unknown.NumberofColors + CGG + CGG2 + CGG3 + SR + SP + Unkno
wn.CoverGlass,
    data = Level1_PerformancePhoneDisplay)

Residuals:
    Min      1Q  Median      3Q     Max
-13.231  -4.345  -0.483   4.805  18.421

Coefficients: (3 not defined because of singularities)
                        Estimate Std. Error t value Pr(>|t|)
(Intercept)            22.077539   9.123659    2.42   0.0204 *
LCD                    -8.001246   2.780623   -2.88   0.0065 **
OLED                          NA         NA      NA       NA
I(Screen.Size - 3)      9.318218   2.105355    4.43  7.8e-05 ***
I(Pixel.Density - 250) -0.000196   0.021686   -0.01   0.9928
X16M.Colors            -5.098502   8.485267   -0.60   0.5515
X16.7M.Colors           8.643324   8.469886    1.02   0.3140
Unknown.NumberofColors        NA         NA      NA       NA
CGG                     2.199954   3.427754    0.64   0.5249
CGG2                    1.762882   3.952733    0.45   0.6581
CGG3                   -3.872993   4.028992   -0.96   0.3425
SR                      9.884885   6.856613    1.44   0.1576
SP                      7.982813   4.798151    1.66   0.1044
Unknown.CoverGlass            NA         NA      NA       NA
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.84 on 38 degrees of freedom
Multiple R-squared:  0.649,    Adjusted R-squared:  0.557
F-statistic: 7.03 on 10 and 38 DF,  p-value: 3.99e-06
```

Table 11: Display Model Regression Output (with release date)

```
> fit1 <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + 
Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.Numberof
Colors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Q1
.14 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q3.12 + 
Q4.12 + Q4.11, data = Level1_PerformancePhoneDisplay)
> summary(fit1)

Call:
lm(formula = Display.Module.Cost ~ LCD + OLED + Screen.Size + 
    Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.Numb
erofColors + 
    CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Q1.14 + 

    Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q3.12 + Q4
.12 + 
    Q4.11, data = Level1_PerformancePhoneDisplay)

Residuals:
    Min      1Q  Median      3Q     Max 
-11.855  -3.119   0.015   3.256  15.123 

Coefficients: (4 not defined because of singularities)
                       Estimate Std. Error t value Pr(>|t|)   
(Intercept)              5.5217    15.8232    0.35   0.7296   
LCD                     -5.8787     2.9903   -1.97   0.0589 . 
OLED                         NA         NA      NA       NA   
Screen.Size              8.3904     2.5339    3.31   0.0025 **
Pixel.Density           -0.0124     0.0229   -0.54   0.5912   
X16M.Colors             -1.1922     8.9051   -0.13   0.8944   
X16.7M.Colors            6.1662    10.6414    0.58   0.5668   
Unknown.NumberofColors       NA         NA      NA       NA   
CGG                     -2.0301     4.0278   -0.50   0.6180   
CGG2                    -0.9552     4.2453   -0.23   0.8236   
CGG3                    -5.9374     4.5634   -1.30   0.2035   
SR                      10.6784    11.1152    0.96   0.3446   
SP                       6.0210     5.1116    1.18   0.2484   
Unknown.CoverGlass           NA         NA      NA       NA   
Q1.14                   -1.8093     8.3817   -0.22   0.8306   
Q1.13                   -1.2381     8.2456   -0.15   0.8817   
Q2.13                    0.5794     7.5862    0.08   0.9396   
Q3.13                    4.7245     7.6223    0.62   0.5402   
Q4.13                    5.9264     9.5192    0.62   0.5384   
Q1.12                  -17.0293    13.7729   -1.24   0.2262   
Q2.12                  -12.3474     6.7051   -1.84   0.0758 . 
Q3.12                   -5.0917     6.7462   -0.75   0.4565   
Q4.12                   -1.1127     8.0772   -0.14   0.8914   
Q4.11                        NA         NA      NA       NA   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.65 on 29 degrees of freedom
Multiple R-squared:  0.745,	Adjusted R-squared:  0.579 
F-statistic: 4.47 on 19 and 29 DF,  p-value: 0.000158
```

Table 12: Display Model Regression Output (with release date and smartphone brand)

```
> fit2 <- lm(Display.Module.Cost ~ LCD + OLED + Screen.Size + P
ixel.Density + X16M.Colors + X16.7M.Colors + Unknown.NumberofCo
lors + CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Q1.14
 + Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q3.12 + Q4.1
2 + Q4.11 + Apple + HTC + Huawei + LG + Moto + Nokia + Samsung 
+ Sony + Oppo, data = Level1_PerformancePhoneDisplay)
> summary(fit2)

Call:
lm(formula = Display.Module.Cost ~ LCD + OLED + Screen.Size + 
    Pixel.Density + X16M.Colors + X16.7M.Colors + Unknown.Numbe
rofColors + 
    CGG + CGG2 + CGG3 + SR + SP + Unknown.CoverGlass + Q1.14 + 
    Q1.13 + Q2.13 + Q3.13 + Q4.13 + Q1.12 + Q2.12 + Q3.12 + Q4.
12 + 
    Q4.11 + Apple + HTC + Huawei + LG + Moto + Nokia + Samsung 
+ 
    Sony + Oppo, data = Level1_PerformancePhoneDisplay)

Residuals:
   Min     1Q Median     3Q    Max 
-10.09  -2.69   0.00   3.21  11.29 

Coefficients: (5 not defined because of singularities)
                        Estimate Std. Error t value Pr(>|t|)   
(Intercept)              7.47676   18.09717    0.41   0.6837   
LCD                     -3.41419    4.92143   -0.69   0.4954   
OLED                          NA         NA      NA       NA   
Screen.Size              8.41273    2.95787    2.84   0.0097 **
Pixel.Density           -0.00761    0.02449   -0.31   0.7592   
X16M.Colors             -7.35895   10.56726   -0.70   0.4938   
X16.7M.Colors            0.00313   12.79454    0.00   0.9998   
Unknown.NumberofColors        NA         NA      NA       NA   
CGG                     -0.82864    4.91410   -0.17   0.8677   
CGG2                     1.20027    4.53818    0.26   0.7940   
CGG3                    -7.63222    4.71965   -1.62   0.1208   
SR                       6.16408   14.30033    0.43   0.6708   
SP                       1.66842    8.83091    0.19   0.8520   
Unknown.CoverGlass            NA         NA      NA       NA   
Q1.14                    4.43634    9.22306    0.48   0.6355   
Q1.13                    1.71335    8.87274    0.19   0.8487   
Q2.13                    3.63869    8.68207    0.42   0.6794   
Q3.13                    8.84498    8.64593    1.02   0.3179   
Q4.13                    9.76947   10.78764    0.91   0.3754   
Q1.12                  -12.51143   14.52579   -0.86   0.3988   
Q2.12                   -8.21662    7.91150   -1.04   0.3108   
Q3.12                   -4.93128    8.27423   -0.60   0.5576   
Q4.12                    2.91258    9.22948    0.32   0.7554   
Q4.11                         NA         NA      NA       NA   
Apple                   -8.01130    8.42357   -0.95   0.3524   
HTC                     -7.20589    6.95609   -1.04   0.3120   
Huawei                   0.57123    9.50509    0.06   0.9526   
LG                      -4.44230    7.86208   -0.57   0.5780   
Moto                    -4.48590    9.19524   -0.49   0.6307   
Nokia                    7.59284    9.05182    0.84   0.4110   
```

```
Samsung                  -1.17832    8.43015   -0.14   0.8902
Sony                           NA         NA      NA       NA
Oppo                      2.09536    9.86433    0.21   0.8338
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.59 on 21 degrees of freedom
Multiple R-squared:  0.819,	Adjusted R-squared:  0.585 
F-statistic: 3.51 on 27 and 21 DF,  p-value: 0.00223
```

APPENDIX II: SMARTPHONE DATABASE CREATED FOR THIS RESEARCH

SI.No	Phone	Brand
1	iPhone 5S	Apple
2	iPhone 5C	Apple
3	iPhone 5	Apple
4	iPhone 4S	Apple
5	iPhone 4	Apple
6	iPhone 3G S	Apple
7	Fonepad Note 6	ASUS
8	Fonepad Note 7	ASUS
9	PadFone 2	ASUS
10	PadFone Infinity 2	ASUS
11	PadFone Infinity	ASUS
12	PadFone	ASUS
13	Z10	Blackberry
14	Z30	Blackberry
15	Porsche Design P’9982	Blackberry
16	Torch 9860	Blackberry
17	Curve 9380	Blackberry
18	Curve 9370	Blackberry
19	Curve 9360	Blackberry
20	Curve 9320	Blackberry
21	Q5	Blackberry
22	Storm2 9550	Blackberry
23	Storm2 9520	Blackberry
24	Torch 9850	Blackberry

25	7 Mozart	HTC
26	7 Trophy	HTC
27	8XT	HTC
28	Amaze 4G	HTC
29	Butterfly S	HTC
30	Butterfly/Deluxe	HTC
31	Desire	HTC
32	Desire 200	HTC
33	Desire 300	HTC
34	Desire 310	HTC
35	Desire 400 dual sim	HTC
36	Desire 500	HTC
37	Desire 600 dual sim	HTC
38	Desire 601 / HTC Zara	HTC
39	Desire 601 dual sim	HTC
40	Desire 606w	HTC
41	Desire 608t	HTC
42	Desire 700 dual sim	HTC
43	Desire C	HTC
44	Desire HD/Ace	HTC
45	Desire Q	HTC
46	Desire S	HTC
47	Desire SV	HTC
48	Desire U	HTC
49	Desire V	HTC
50	Desire VC	HTC
51	Desire X	HTC
52	Desire XC	HTC
53	DROID DNA	HTC

54	Droid Incredible	HTC
55	DROID Incredible 2	HTC
56	EVO 3D	HTC
57	Evo 4G	HTC
58	Evo 4G LTE	HTC
59	EVO Design 4G	HTC
60	Explorer/Pico	HTC
61	First	HTC
62	Google Nexus One	HTC
63	HD2	HTC
64	HD7	HTC
65	Hero	HTC
66	Incredible S	HTC
67	Inspire	HTC
68	Inspire 4G	HTC
69	J	HTC
70	Legend	HTC
71	ONE LTE	HTC
72	One Dual Sim	HTC
73	One M7	HTC
74	One M8	HTC
75	One Max 99HWN008-00	HTC
76	One Max 8088	HTC
77	One mini	HTC
78	One S	HTC
79	One SC	HTC
80	One SU	HTC
81	One SV	HTC
82	One V	HTC

83	One VX	HTC
84	One X	HTC
85	One XC	HTC
86	One X AT&T	HTC
87	One X LTE	HTC
88	One X+ PM63100	HTC
89	One X+ S728e PM35110	HTC
90	One XL	HTC
91	Radar	HTC
92	Radar 4G PI06110	HTC
93	Rio	HTC
94	Rezound	HTC
95	Rhyme	HTC
96	Salsa	HTC
97	Sensation XE	HTC
98	Sensation XL	HTC
99	ThunderBolt 4G	HTC
100	Titan	HTC
101	Titan II	HTC
102	Velocity 4G	HTC
103	Vivid	HTC
104	Wildfire	HTC
105	Wildfire S	HTC
106	Windows Phone 8S	HTC
107	Windows Phone 8X / HTC Accord	HTC
108	Windows Phone 8X CDMA	HTC
109	Activa 4G	Huawei
110	Ascend D quad	Huawei
111	Ascend D quad XL	Huawei

112	Ascend D1 Quad XL U9510E	Huawei
113	Ascend D1 XL U9500E	Huawei
114	Ascend D2	Huawei
115	Ascend G300	Huawei
116	Ascend G312	Huawei
117	Ascend G330	Huawei
118	Ascend G330D U8825D	Huawei
119	Ascend G350	Huawei
120	Ascend G500	Huawei
121	Ascend G510	Huawei
122	Ascend G520	Huawei
123	Ascend G525	Huawei
124	Ascend G526	Huawei
125	Ascend G600	Huawei
126	Ascend G615	Huawei
127	Ascend G700	Huawei
128	Ascend G740	Huawei
129	Ascend II	Huawei
130	Ascend Mate	Huawei
131	Ascend Mate 2	Huawei
132	Ascend Mate MT1	Huawei
133	Ascend Mate2 4G	Huawei
134	Ascend P1	Huawei
135	Ascend P1 LTE	Huawei
136	Ascend P1 XL U9200E	Huawei
137	Ascend P1s	Huawei
138	Ascend P2	Huawei
139	Ascend P6	Huawei
140	Ascend Q M660	Huawei

141	Ascend W1	Huawei
142	Ascend W2	Huawei
143	Ascend Y	Huawei
144	Ascend Y200	Huawei
145	Ascend Y201 Pro	Huawei
146	Ascend Y210D	Huawei
147	Ascend Y300	Huawei
148	Ascend Y320	Huawei
149	Ascend Y511	Huawei
150	Ascend Y530	Huawei
151	C8815	Huawei
152	Fusion 2 U8665	Huawei
153	Fusion U8652	Huawei
154	G610s	Huawei
155	Honor 2	Huawei
156	Honor 3	Huawei
157	Honor 3C	Huawei
158	Honor 3X G750	Huawei
159	Huawei U8860 Honor	Huawei
160	Impulse 4G	Huawei
161	M886 Mercury	Huawei
162	Premia 4G M931	Huawei
163	Prism U8651T	Huawei
164	Prism II U8686	Huawei
165	Summit	Huawei
166	T8300	Huawei
167	U8500 IDEOS X2	Huawei
168	Ideos U8150-B	Huawei
169	U8520 Duplex	Huawei

170	U8650 Sonic	Huawei
171	U8800 IDEOS X5	Huawei
172	U8800 Pro	Huawei
173	U8850 Vision	Huawei
174	U9000 IDEOS X6	Huawei
175	A269i	Lenovo
176	A369i	Lenovo
177	A390	Lenovo
178	A390e	Lenovo
179	A516	Lenovo
180	A60	Lenovo
181	A60+	Lenovo
182	A500	Lenovo
183	A630	Lenovo
184	A65	Lenovo
185	A690	Lenovo
186	A706	Lenovo
187	A770e	Lenovo
188	A800	Lenovo
189	A820	Lenovo
190	A830	Lenovo
191	A850	Lenovo
192	A5000-E	Lenovo
193	ideaPhone A586	Lenovo
194	ideaPhone P780	Lenovo
195	K800	Lenovo
196	ideaPhone K860i	Lenovo
197	ideaPhone K900	Lenovo
198	LePad S2005	Lenovo

199	LePad A2105	Lenovo
200	LePhone A660	Lenovo
201	LePhone A789	Lenovo
202	LePhone K860	Lenovo
203	LePhone S2	Lenovo
204	P700i	Lenovo
205	P770	Lenovo
206	S560	Lenovo
207	ideaPhone S650	Lenovo
208	S720	Lenovo
209	S820	Lenovo
210	S880	Lenovo
211	S890	Lenovo
212	S920	Lenovo
213	S930	Lenovo
214	Vibe X S960	Lenovo
215	Vibe Z K910	Lenovo
216	BL40 New Chocolate	LG
217	E900 Optimus 7	LG
218	Escape P870	LG
219	Fireweb	LG
220	G Flex	LG
221	G Pro Lite	LG
222	G Pro Lite Dual	LG
223	G2	LG
224	Google Nexus 4 E960	LG
225	Google Nexus 5	LG
226	Intuition VS950	LG
227	KM900 Arena	LG

228	L70 D320n	LG
229	Lucid 4G VS840	LG
230	Lucid2 VS870	LG
231	Motion 4G MS770	LG
232	Nitro HD	LG
233	Jil Sander E906	LG
234	Optimus 2X	LG
235	Optimus 2X SU660	LG
236	Optimus 3D Cube SU870	LG
237	Optimus 3D Max P720	LG
238	Optimus 3D P920	LG
239	Optimus 4G LTE P935	LG
240	Optimus 4X HD P880	LG
241	Optimus Black P970	LG
242	Optimus F3 LS720	LG
243	Optimus F3Q	LG
244	Optimus F5 P875	LG
245	Optimus F6	LG
246	Optimus F7	LG
247	Optimus G E970	LG
248	Optimus G E975	LG
249	Optimus G LS970	LG
250	Optimus G Pro E985	LG
251	Optimus G Pro F240L	LG
252	Optimus GJ E975W	LG
253	Optimus Hub E510	LG
254	Optimus L1 II E410	LG
255	Optimus L3 E400	LG
256	Optimus L3 E405	LG

257	Optimus L3 II Dual E435	LG
258	Optimus L3 II E430	LG
259	Optimus L4 II Dual E445	LG
260	Optimus L4 II E440	LG
261	Optimus L5 E612	LG
262	Optimus L5 Dual E615	LG
263	Optimus L5 E610	LG
264	Optimus L5 II Dual E455 / Optimus Duet	LG
265	Optimus L5 II E460	LG
266	Optimus L7 II Dual P715	LG
267	Optimus L7 II P710	LG
268	Optimus L7 P700	LG
269	Optimus L9 II	LG
270	Optimus L9 P760	LG
271	Optimus L9 P768e	LG
272	Optimus L9 P769	LG
273	Optimus LTE II F-160LV	LG
274	Optimus LTE III F260S	LG
275	Optimus LTE LU6200	LG
276	Optimus LTE SU640	LG
277	Optimus LTE Tag	LG
278	Optimus LTE2	LG
279	Optimus M+ MS695	LG
280	Optimus Net	LG
281	Optimus Net Dual	LG
282	Optimus One P500	LG
283	Optimus Pad V909	LG
284	Optimus Sol E730	LG
285	Optimus True HD LTE P936	LG

286	Optimus Vu F100S	LG
287	Optimus V VM670	LG
288	Optimus Vu II F200	LG
289	Optimus Vu P895	LG
290	Optimus Zone VS410	LG
291	Prada 3.0	LG
292	Spectrum II 4G VS930	LG
293	Spectrum 4G VS920	LG
294	Splendor Us730	LG
295	Spirit 4G	LG
296	T375 Cookie Smart	LG
297	T385	LG
298	Vu 3 F300L	LG
299	Vu-Plus	LG
300	Canvas 4 A210	Micromax
301	Canvas Turbo	Micromax
302	A116 Canvas HD	Micromax
303	A110 Canvas 2	Micromax
304	A114 Canvas 2.2	Micromax
305	A77 Canvas Juice	Micromax
306	A111 Canvas Doodle	Micromax
307	A117 Canvas Magnus	Micromax
308	A94 Canvas Mad	Micromax
309	A119 Canvas XL	Micromax
310	A240 Canvas Doodle 2	Micromax
311	A110Q Canvas 2 Plus	Micromax
312	A74 Canvas Fun	Micromax
313	A76	Micromax
314	Canvas Turbo Mini	Micromax

315	A63 Canvas Fun	Micromax
316	A67 Bolt	Micromax
317	A61 Bolt	Micromax
318	A88	Micromax
319	A92	Micromax
320	A115 Canvas 3D	Micromax
321	A87 Ninja 4.0	Micromax
322	A89 Ninja	Micromax
323	A113 Canvas Ego	Micromax
324	A57 Ninja 3.0	Micromax
325	A45	Micromax
326	A100	Micromax
327	A90	Micromax
328	A75	Micromax
329	A90s	Micromax
330	A101	Micromax
331	A50 Ninja	Micromax
332	A73	Micromax
333	A52	Micromax
334	A85	Micromax
335	A56	Micromax
336	Superfone Punk A44	Micromax
337	A84	Micromax
338	A80	Micromax
339	ATRIX	Motorola
340	ATRIX 2 MB865	Motorola
341	ATRIX 4G	Motorola
342	ATRIX HD MB886	Motorola
343	ATRIX TV XT682	Motorola

344	ATRIX TV XT687	Motorola
345	BRAVO MB520	Motorola
346	CITRUS WX445	Motorola
347	DEFY	Motorola
348	Defy Mini XT321	Motorola
349	Defy Mini XT320	Motorola
350	DEFY XT535	Motorola
351	DEFY XT556	Motorola
352	DEFY XT557D	Motorola
353	DEFY+	Motorola
354	DROID 4 XT894	Motorola
355	DROID BIONIC XT875	Motorola
356	DROID Maxx	Motorola
357	DROID Mini	Motorola
358	DROID RAZR HD	Motorola
359	DROID RAZR M XT907	Motorola
360	DROID RAZR MAXX	Motorola
361	DROID RAZR MAXX HD	Motorola
362	DROID RAZR XT912	Motorola
363	DROID Ultra	Motorola
364	DROID X	Motorola
365	DROID X ME811	Motorola
366	DROID X2	Motorola
367	Electrify 2 XT881	Motorola
368	Electrify M XT905	Motorola
369	FIRE XT	Motorola
370	MILESTONE XT720	Motorola
371	Moto G	Motorola
372	MOTO ME525 / Defy MB525	Motorola

373	MOTO MT870	Motorola
374	Moto X XT1060	Motorola
375	Moto X XT1058	Motorola
376	MOTO XT615	Motorola
377	MOTO XT882	Motorola
378	MotoGO TV EX440	Motorola
379	Motoluxe	Motorola
380	Motoluxe MT680	Motorola
381	Motoluxe XT389	Motorola
382	Motoluxe XT685	Motorola
383	Motoluxe XT788	Motorola
384	Motosmart Me XT303	Motorola
385	MOTOSMART MIX XT550	Motorola
386	MT917	Motorola
387	Photon 4G MB855	Motorola
388	Photon Q	Motorola
389	QUENCH	Motorola
390	Quench XT3 XT502	Motorola
391	Quench XT5 XT502	Motorola
392	RAZR D3 XT920	Motorola
393	RAZR HD XT925	Motorola
394	RAZR i XT890	Motorola
395	RAZR M XT905	Motorola
396	RAZR MAXX	Motorola
397	RAZR V MT887	Motorola
398	RAZR V XT885	Motorola
399	RAZR V XT889	Motorola
400	RAZR XT910	Motorola
401	XT301	Motorola

402	XT319	Motorola
403	XT390	Motorola
404	XT532	Motorola
405	XT681	Motorola
406	XT701	Motorola
407	XT720 MOTOROI	Motorola
408	XT760	Motorola
409	XT800 ZHISHANG	Motorola
410	XT928	Motorola
411	500	Nokia
412	603	Nokia
413	700	Nokia
414	701	Nokia
415	800c	Nokia
416	801T	Nokia
417	808 PureView	Nokia
418	Asha 230	Nokia
419	Asha 308	Nokia
420	Asha 309	Nokia
421	Asha 310	Nokia
422	Asha 311	Nokia
423	Asha 501	Nokia
424	Asha 502 Dual SIM	Nokia
425	Asha 503	Nokia
426	Asha 503 Dual SIM	Nokia
427	C6-01	Nokia
428	C7	Nokia
429	E7	Nokia
430	Lumia 1020	Nokia

431	Lumia 1320	Nokia
432	Lumia 1520	Nokia
433	Lumia 505	Nokia
434	Lumia 510	Nokia
435	Lumia 520	Nokia
436	Lumia 525	Nokia
437	Lumia 610	Nokia
438	Lumia 610 NFC	Nokia
439	Lumia 620	Nokia
440	Lumia 625	Nokia
441	Lumia 625H	Nokia
442	Lumia 710	Nokia
443	Lumia 710 T-Mobile	Nokia
444	Lumia 720	Nokia
445	Lumia 800	Nokia
446	Lumia 810	Nokia
447	Lumia 820	Nokia
448	Lumia 822	Nokia
449	Lumia 900	Nokia
450	Lumia 900 AT&T / RM-808	Nokia
451	Lumia 920	Nokia
452	Lumia 925	Nokia
453	Lumia 928	Nokia
454	Lumia NOK928W	Nokia
455	X RM-980	Nokia
456	N8	Nokia
457	N9	Nokia
458	Oro	Nokia
459	T7	Nokia

460	X6	Nokia
461	X6 16GB	Nokia
462	X6 8GB	Nokia
463	X7-00	Nokia
464	Ativ S I8750	Samsung
465	ATIV Odyssey SCH-I930	Samsung
466	Ativ S Neo SGH-I187	Samsung
467	ATIV S Neo SPH-800	Samsung
468	Captivate Glide SGH-I927	Samsung
469	Galaxy Ace GT-S5830	Samsung
470	Galaxy Ace 2 I8160	Samsung
471	Galaxy Ace 3	Samsung
472	Galaxy Ace Duos S6802	Samsung
473	Galaxy Ace Duos GT-S6352	Samsung
474	Galaxy Ace II X S7560M	Samsung
475	Galaxy Ace Plus S7500	Samsung
476	Galaxy Ace S5830I	Samsung
477	Galaxy Appeal SGH-I827	Samsung
478	Galaxy Attain 4G SCH-R920	Samsung
479	Galaxy Axiom SCH-R830	Samsung
480	Galaxy Camera EK-GC100	Samsung
481	Galaxy Core I8260	Samsung
482	Galaxy Core Plus	Samsung
483	Galaxy Discover SGH-S730M	Samsung
484	Galaxy Express 2	Samsung
485	Galaxy Express SGH-I437	Samsung
486	Galaxy Express I8730	Samsung
487	Galaxy Fame S6810	Samsung
488	Galaxy Fame Lite GT-S6790N	Samsung

489	Galaxy Fit S5670	Samsung
490	Galaxy Fresh S7390	Samsung
491	Galaxy Gio S5660	Samsung
492	Galaxy Grand 2	Samsung
493	Galaxy Grand 2 Duos SM-G7102	Samsung
494	Grand Neo GT-I9060	Samsung
495	Galaxy Grand I9080	Samsung
496	Galaxy Grand I9082	Samsung
497	Galaxy Infinite SCH-I759	Samsung
498	Galaxy J	Samsung
499	Galaxy Light	Samsung
500	Galaxy Mega 5.8 I9150	Samsung
501	Galaxy Mega GT-I9200	Samsung
502	Galaxy Mega GT-I9205	Samsung
503	Galaxy mini 2 S6500	Samsung
504	Galaxy Mini S5570	Samsung
505	Galaxy Music GT-S6010	Samsung
506	Galaxy Nexus I9250	Samsung
507	Galaxy Note 3	Samsung
508	Galaxy Note 3 Neo SM-N7505	Samsung
509	Galaxy Note 3 SM-N900A	Samsung
510	Galaxy Note II N7100	Samsung
511	Galaxy Note GT-I9220	Samsung
512	Galaxy Note N7000	Samsung
513	Galaxy Pocket Neo S5310	Samsung
514	Galaxy Pocket Plus GT-S5301	Samsung
515	Galaxy Premier GT-I9260	Samsung
516	Galaxy R Style SHV-E170K	Samsung
517	Galaxy Ring SPH-M840	Samsung

518	Galaxy Round G910S	Samsung
519	Galaxy Rugby Pro SGH-I547	Samsung
520	Galaxy Rush SPH-M830	Samsung
521	Galaxy S Duos 2 S7582	Samsung
522	Galaxy S Duos S7562	Samsung
523	Galaxy S II HD LTE	Samsung
524	Galaxy S II Plus GT-I9105P	Samsung
525	Galaxy S II Skyrocket	Samsung
526	Galaxy S III I747	Samsung
527	Galaxy S III GT-I9308	Samsung
528	Galaxy SIII Mini GT-I8190	Samsung
529	Galaxy S4 Active LTE-A	Samsung
530	Galaxy S4 Active SGH-I537	Samsung
531	Galaxy S4 GT-I9500	Samsung
532	Galaxy S4 mini GT-I9195	Samsung
533	Galaxy S4 zoom	Samsung
534	Galaxy S5 SM-G900H	Samsung
535	Galaxy Star Pro S7260	Samsung
536	Galaxy Star GT-S5280	Samsung
537	Galaxy Star Plus GT-S7262	Samsung
538	Galaxy Stratosphere II SCH-I415	Samsung
539	Galaxy Style Duos SCH-I829	Samsung
540	Galaxy Trend Duos GT-S7562	Samsung
541	Galaxy Trend Duos II S7572	Samsung
542	Galaxy Trend Lite GT-S7390	Samsung
543	Galaxy Trend Plus GT-S7580	Samsung
544	Galaxy W I8150	Samsung
545	Galaxy Win I8550	Samsung
546	Galaxy Win GT-I8552	Samsung

547	Galaxy Win Pro SM-G3812	Samsung
548	Galaxy Y Duos S6102	Samsung
549	Galaxy Young GT-S5360	Samsung
550	Galaxy Young S6310	Samsung
551	Galaxy Beam GT-I8530	Samsung
552	Galaxy Xcover 2 GT-S7710L	Samsung
553	Galaxy S Lightray SCH-R940	Samsung
554	Glide SGH-I927R	Samsung
555	Gravity Q T289	Samsung
556	Gravity SMART SGH-T589	Samsung
557	Google Nexus S	Samsung
558	Illusion SCH-I110	Samsung
559	I8190 Galaxy S III mini	Samsung
560	I9000 Galaxy S	Samsung
561	I9003 Galaxy SL	Samsung
562	I9070 Galaxy S Advance	Samsung
563	Galaxy S II I9100	Samsung
564	I9105 Galaxy S II Plus	Samsung
565	I9190 Galaxy S4 mini	Samsung
566	I929 Galaxy S II Duos	Samsung
567	I9295 Galaxy S4 Active	Samsung
568	Galaxy S III GT-I9300	Samsung
569	I9305 Galaxy S III	Samsung
570	I9502 Galaxy S4	Samsung
571	Galaxy S4 GT-I9505	Samsung
572	I9506 Galaxy S4	Samsung
573	Infuse 4G SGH-I997	Samsung
574	REX 70 GT-S3802	Samsung
575	Rex 80 GT-S5222R	Samsung

576	Rex 90 GT-S5292	Samsung
577	Rugby Smart SGH-I847	Samsung
578	S3850 Corby II	Samsung
579	S7710 Galaxy Xcover 2	Samsung
580	Star 3 Duos S5222	Samsung
581	Galaxy Victory SPH-L300	Samsung
582	Wave Y S5380	Samsung
583	Xperia M	Sony
584	Xperia C	Sony
585	Xperia Z1	Sony
586	Xperia Z	Sony
587	Xperia Z1 Compact	Sony
588	Xperia L	Sony
589	Xperia SP	Sony
590	Xperia E	Sony
591	Xperia J	Sony
592	Xperia Z Ultra	Sony
593	Xperia ZR	Sony
594	Xperia U	Sony
595	Xperia ZL	Sony
596	Xperia S	Sony
597	Xperia V	Sony
598	Xperia Z1s	Sony
599	Xperia P	Sony
600	Xperia miro	Sony
601	Xperia E dual	Sony
602	Xperia go	Sony
603	Xperia tipo	Sony
604	Xperia T	Sony

605	Xperia sola	Sony
606	Xperia SL	Sony
607	Xperia neo L	Sony
608	Xperia ion LTE	Sony
609	Xperia acro S	Sony
610	Xperia TX	Sony
611	Xperia tipo dual	Sony
612	Xperia ion HSPA	Sony
613	Xperia T LTE	Sony
614	Xperia acro HD SO-03D	Sony
615	Xperia SX SO-05D	Sony
616	Xperia acro HD SOI12	Sony
617	Xperia GX SO-04D	Sony
618	A500S	Xolo
619	A800	Xolo
620	X900 AZ510	Xolo
621	Q3000	Xolo
622	Q1000	Xolo
623	Q1000 Opus	Xolo
624	Q700s	Xolo
625	A500S IPS	Xolo
626	Q700	Xolo
627	Q2000	Xolo
628	A600	Xolo
629	Q800	Xolo
630	Q1000s	Xolo
631	A500	Xolo
632	Q700i	Xolo
633	Q500	Xolo

634	Q600	Xolo
635	Q900	Xolo
636	Play	Xolo
637	Q800 X-Edition	Xolo
638	A500L	Xolo
639	X1000	Xolo
640	LT900	Xolo
641	X910	Xolo
642	X500	Xolo
643	Nubia Z5S	ZTE
644	Blade III	ZTE
645	Nubia Z5 mini	ZTE
646	Grand X U970	ZTE
647	Grand X Pro	ZTE
648	Blade	ZTE
649	Blade G V880G	ZTE
650	Blade V	ZTE
651	Geek V975	ZTE
652	Grand X IN	ZTE
653	Grand S	ZTE
654	Grand X Quad V987	ZTE
655	Grand S Flex	ZTE
656	Nubia Z5	ZTE
657	Blade Q Mini	ZTE
658	Skate	ZTE
659	Kis III V790	ZTE
660	Grand Memo U9815	ZTE
661	Blade III Pro	ZTE
662	Blade C V807	ZTE

663	V889M	ZTE
664	Vital N9810	ZTE
665	V887	ZTE
666	Kis V788	ZTE
667	Open	ZTE
668	Tania	ZTE
669	Warp 4G	ZTE
670	Avid 4G	ZTE
671	Avail	ZTE
672	Grand X LTE T82	ZTE
673	Warp	ZTE
674	Flash	ZTE
675	Skate Acqua	ZTE
676	Grand Era U895	ZTE
677	Blade II V880+	ZTE
678	Imperial	ZTE
679	Reef	ZTE
680	Warp Sequent	ZTE
681	Anthem 4G	ZTE
682	Score	ZTE
683	Director	ZTE
684	Era	ZTE
685	FTV Phone	ZTE
686	N880E	ZTE
687	V880E	ZTE
688	U880E	ZTE
689	Nova 3.5	ZTE
690	Libra	ZTE
691	Orbit	ZTE

692	Score M	ZTE
693	PF200	ZTE
694	U900	ZTE
695	N919	ZTE
696	Max N9520	ZTE
697	Supreme N9810	ZTE
698	V818	ZTE
699	Engage LT N8000	ZTE
700	V987	ZTE
701	Render MWP3505US	ZTE
702	San Francisco II P736V (aka Orange San Francisco II)	ZTE
703	V889D	ZTE
704	Engage V8000	ZTE
705	Fury N850	ZTE
706	Z998	ZTE
707	Discover P9090	Pantech
708	Marauder ADR910LVW	Pantech
709	Perception ADR930LVW	Pantech
710	Pocket P9060	Pantech
711	Renue P6030	Pantech
712	Swift P6020	Pantech
713	Liquid E3 E380	Acer
714	Liquid S1 S510	Acer
715	Liquid S2 S520	Acer
716	Liquid Z3 Z130	Acer
717	Liquid Z5 Z150	Acer
718	5891	Coolpad
719	8180	Coolpad
720	8295	Coolpad

721	9960	Coolpad
722	Quattro 5860E	Coolpad
723	Xuan Ying SII 8750	Coolpad
724	Digital Find 5 X909	Oppo
725	N1	Oppo
726	N1T	Oppo
727	R809T	Oppo
728	Real R813T	Oppo
729	T29	Oppo
730	Ulike 2S U707T	Oppo
731	Ulike U705T	Oppo
732	Vivo E3	BBK
733	Vivo S6	BBK
734	Vivo S7	BBK
735	Vivo X510w	BBK
736	Vivo Y19t	BBK
737	T660	K-Touch
738	U86	K-Touch
739	Kiss U90	K-Touch
740	V8	K-Touch
741	W68	K-Touch
742	W619	K-Touch
743	W806	K-Touch
744	Hydro Edge C5215	Kyocera
745	Hyrdo ELITE C6750	Kyocera
746	Torque E6710	Kyocera
747	Urbano Progresso KYY04MDA	Kyocera
748	ARROWS Me F-11D	Fujitsu

749	Arrows V F-04E	Fujitsu
750	ARROWS Z ISW13F	Fujitsu
751	Raku-Raku F-12D	Fujitsu
752	W626	Philips
753	Xenium W6500	Philips
754	Xenium W8355	Philips
755	Xenium W8510	Philips

APPENDIX III: COMPLETE SMARTPHONE BILL-OF-MATERIAL (BOM)

<table>
<tr><th>LEVEL 0</th><th>LEVEL 1</th><th>LEVEL 2</th><th>LEVEL 3</th></tr>
<tr><td rowspan="5">Smartphone</td><td rowspan="3">Display Type
• LCD
• OLED</td><td>Display Module
• Screen Size
• Resolution Type
• Pixel Density
• Number of Colors
• Backlight</td><td></td></tr>
<tr><td>Touchscreen Panel
• Resistive
• Pro-Cap
• Surface Cap
• Infrared
• Acoustic Wave</td><td>Lamination Type/ technology:
• C/G/G
• ToG (touch on glass)/ SoL (Sensor on Lens)
• In-cell
• On-cell</td></tr>
<tr><td>Cover Glass
• CGG
• CGG2
• CGG3
• SR
• SP</td><td></td></tr>
<tr><td>Battery(based on Cell Type)
• Lithium-Ion
• Lithium-Polymer</td><td>Voltage(V)
Pack Rating(mAh)
Package Type: Soft/Hard</td><td></td></tr>
<tr><td></td><td>SoC:</td><td></td></tr>
</table>

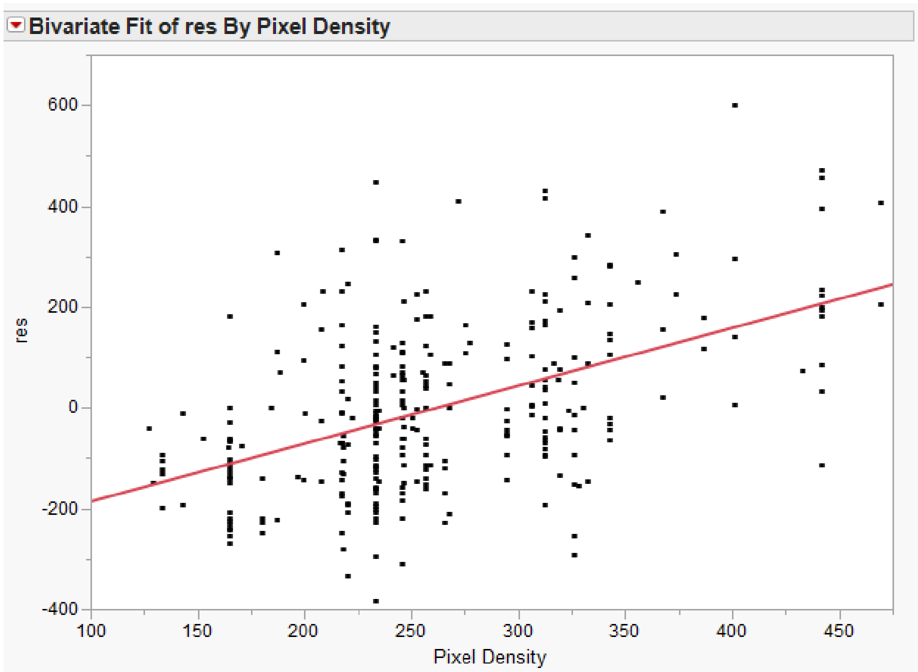
	SoC (Application Processor) & PoP (Package-on-Package containing RAM) based on Brand • Apple • Broadcom • Hexa-Core • HiSilicon • Intel • Marvell • MediaTek • Nokia • NVIDIA • Samsung • ST Micro • ST-Ericsson • TI	Clock Speed Number of Cores	
		RAM: RAM Type (LPDDR#) RAM Capacity	
	Operating System • iOS • Blackberry • Android • Windows • Symbian	**iOS:** iOS4, iOS6, iOS7 **Android:** Froyo, Gingerbread, Ice Cream Sandwich, Jelly Bean, Kit Kat **Blackberry:** BB7, BB7.1, BB10, BB10.2	

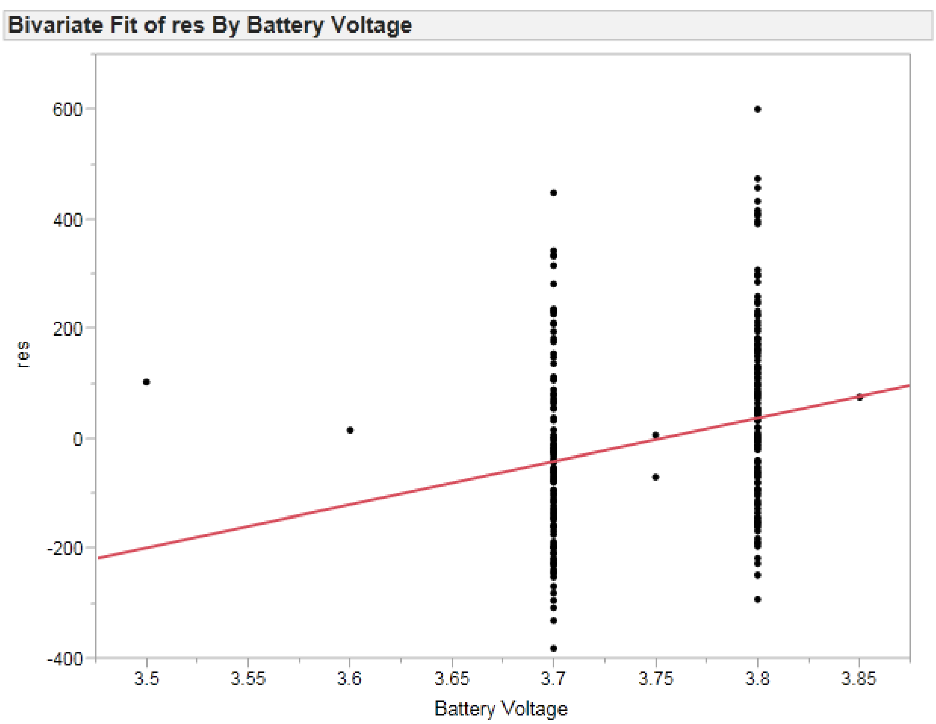
		Windows: Window 7, Window 8, Window 8S	
	Storage (Optional; hence not included at this level)	Internal (1/0)	Capacity (in GB) Type
		External (1/0)	Capacity (in GB) Type Capacity Extendability
	Camera (Optional; hence not included at this level)	Rear Camera (1/0)	Type Capacity (in MP) Optical Size Lens Elements Optical Zoom
		Front Camera (1/0)	Type Capacity (in MP) Optical Size Lens Elements Optical Zoom
	Sensors (Optional; hence not included at this level)	Sensor(1/0)	Accelerometer (1/0)
			Ambient Light (1/0)
			Proximity Sensor (1/0)

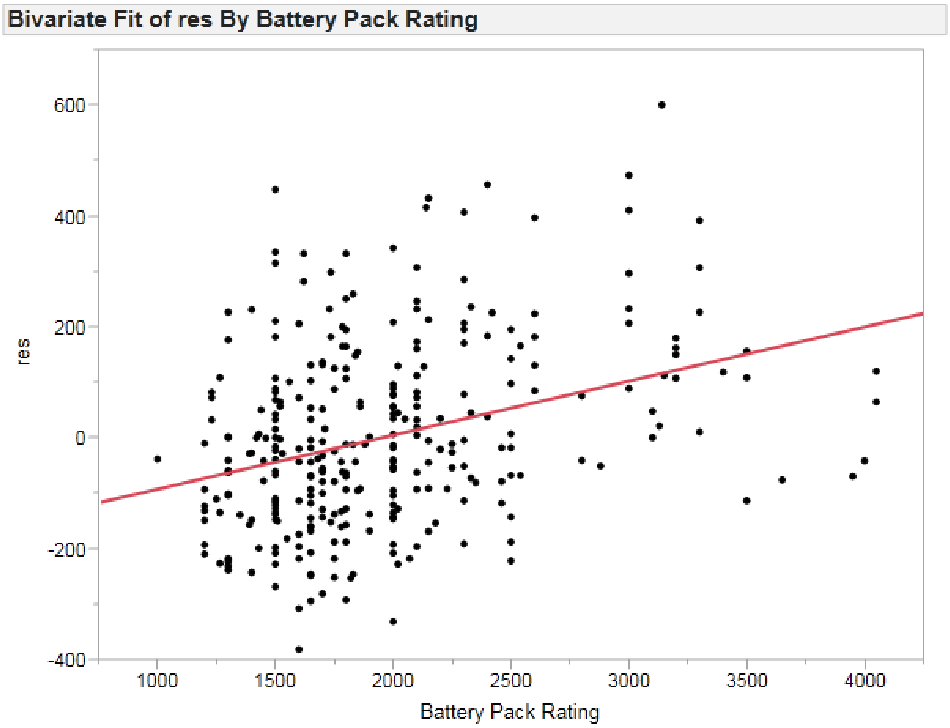
			Electronic Compass (1/0)
			Gyroscope (1/0)
			Magnetometer (1/0)
			Temperature Sensor (1/0)
			Barometer (1/0)
			Geomagnetic Sensor (1/0)
			Humidity Sensor (1/0)
	Connectivity (Optional; hence not included at this level)	IR (1/0)	
		WiFi (1/0)	
		Bluetooth (1/0)	**Bluetooth Version:** 2.0, 2.1, 3.0, 3.1, 4.0
		GPS/GLONASS (1/0)	
		FM Radio (1/0)	
		Micro USB (1/0)	**Micro USB Version:** 2.0, 3.0
		HDMI (1/0)	
		DLNA (1/0)	
	Accessories (Optional; hence not included at this level)	Packaging	
		Headset	
		Adapter	
		Cable	

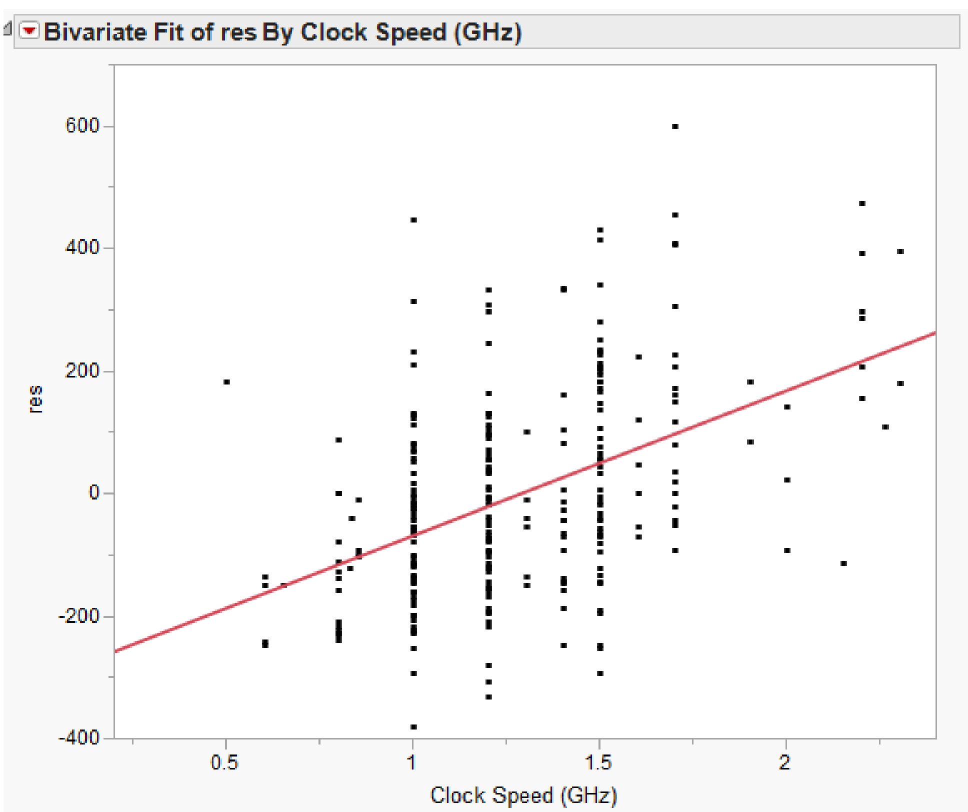
		Documentation	

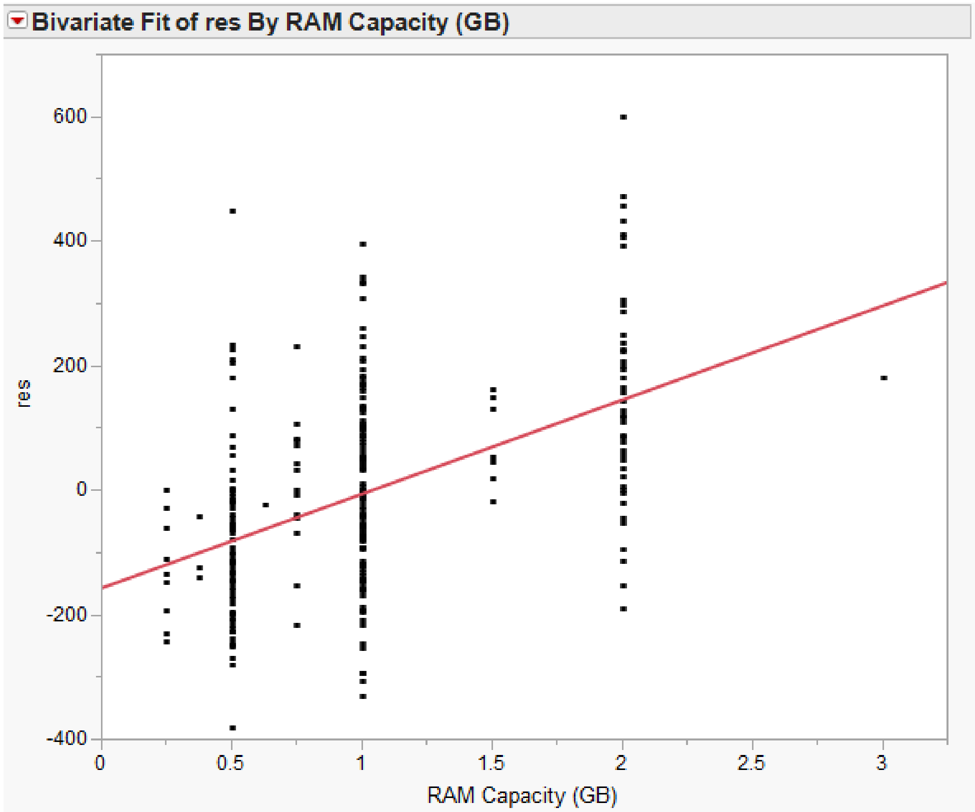
APPENDIX IV: RESIDUAL PLOTS FOR INITIAL ANALYSIS

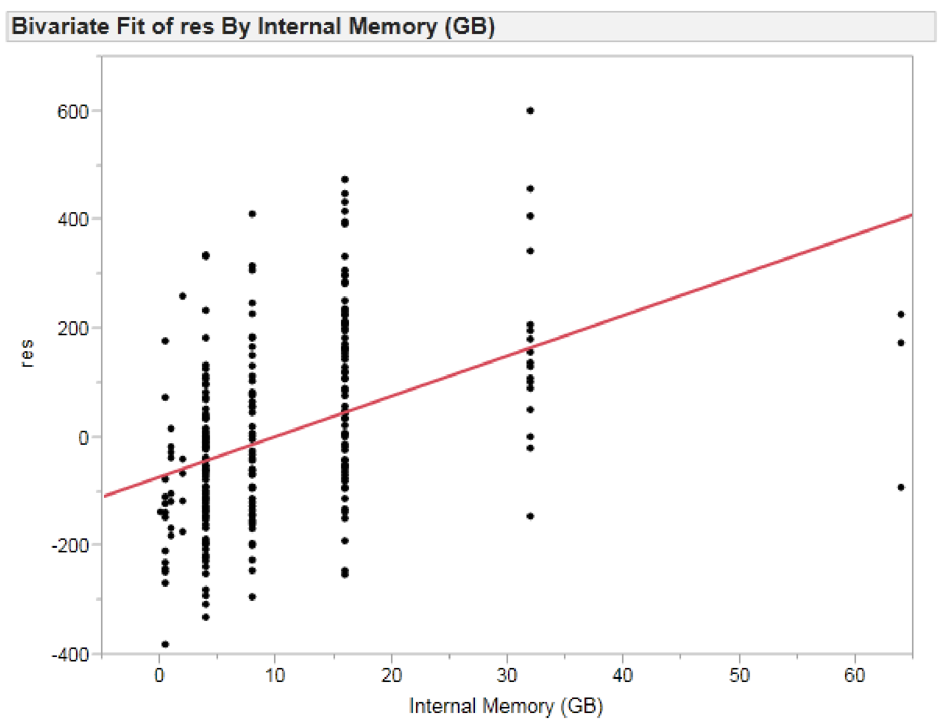




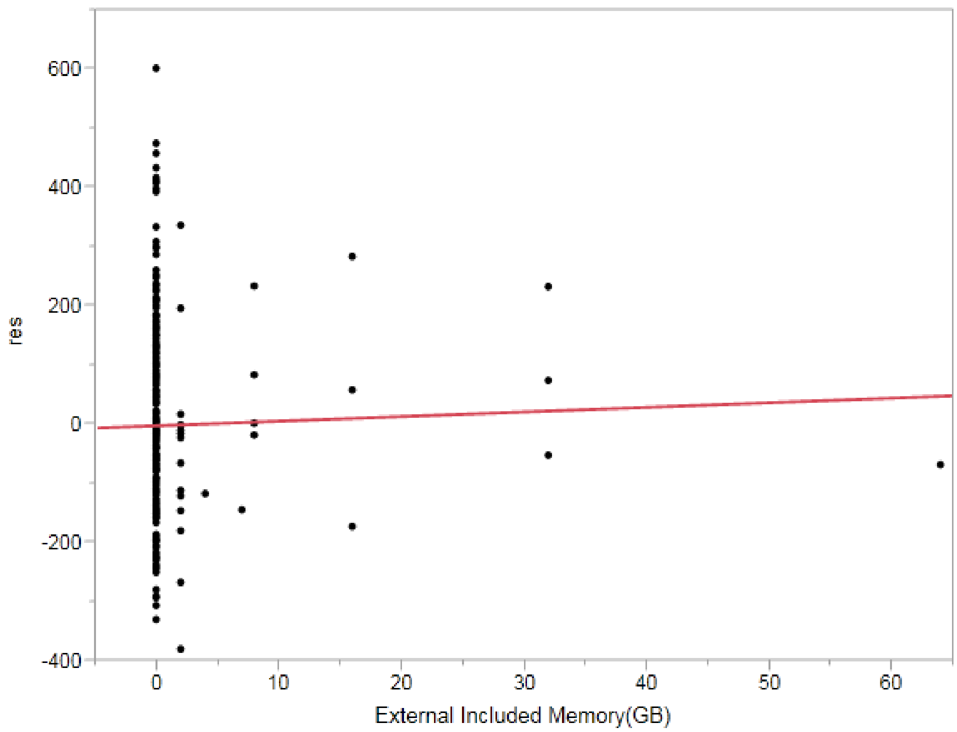

Bivariate Fit of res By Battery Pack Rating
600
400
200
0
-200
-400
res
1000
1500
2000
2500
3000
3500
4000
Battery Pack Rating


Bivariate Fit of res By Clock Speed (GHz)
600
400
200
0
-200
-400
res
0.5
1
1.5
2
Clock Speed (GHz)

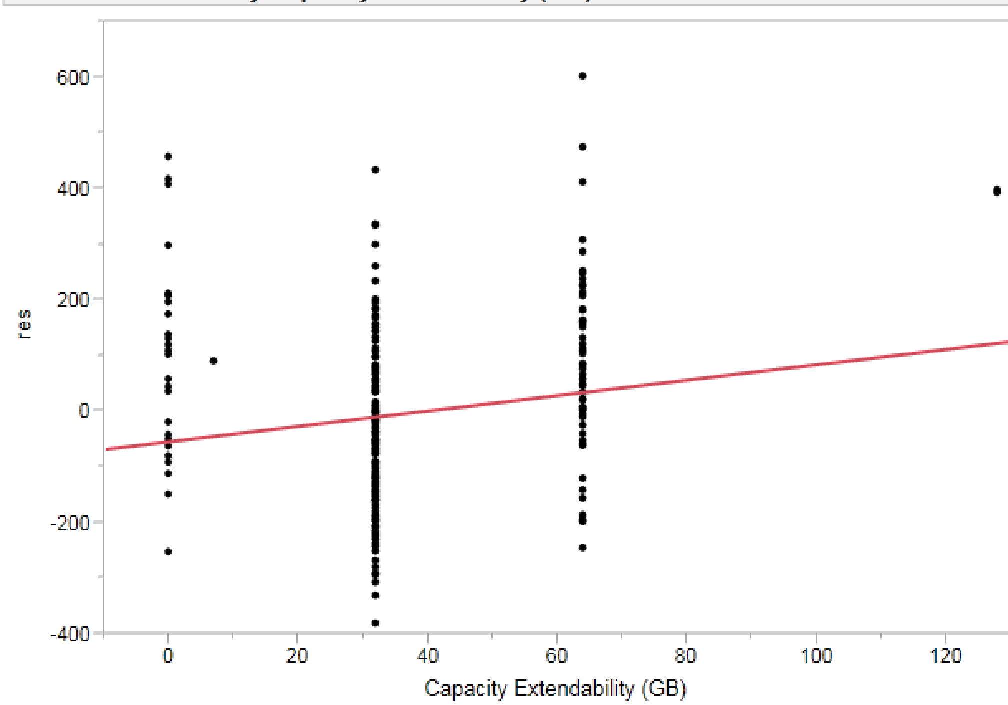

Bivariate Fit of res By RAM Capacity (GB)
600
400
200
0
-200
-400
res
0
0.5
1
1.5
2
2.5
3
RAM Capacity (GB)


Bivariate Fit of res By Internal Memory (GB)
600
400
200
0
-200
-400
res
0
10
20
30
40
50
60
Internal Memory (GB)

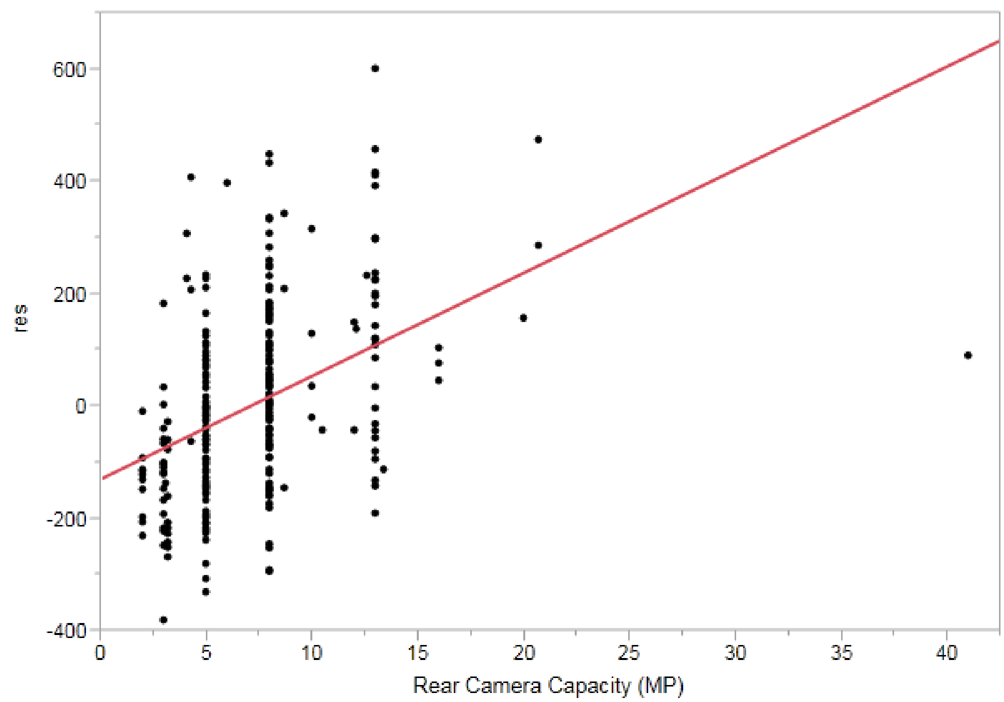
Bivariate Fit of res By External Included Memory(GB)



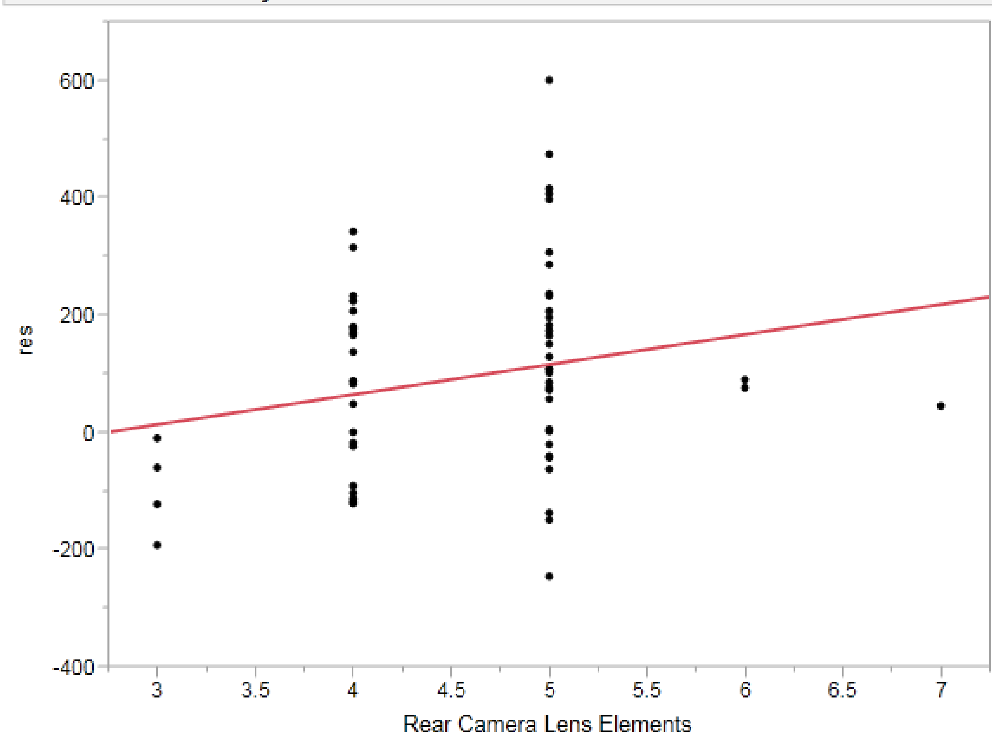
Bivariate Fit of res By Capacity Extendability (GB)

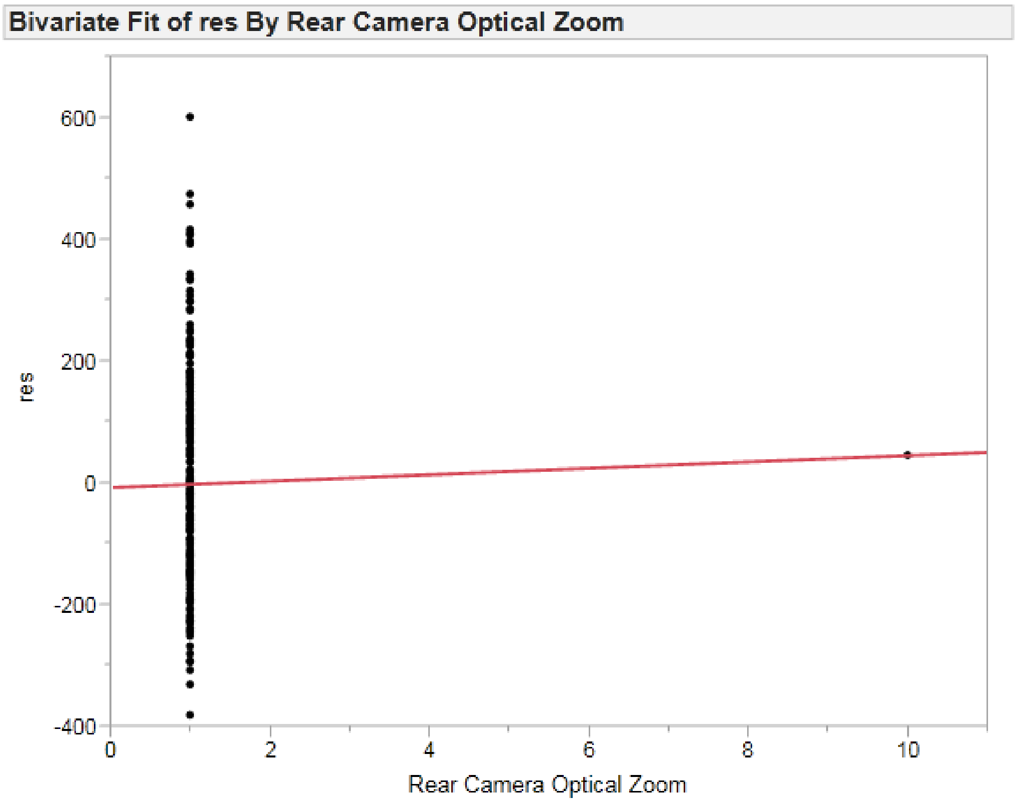


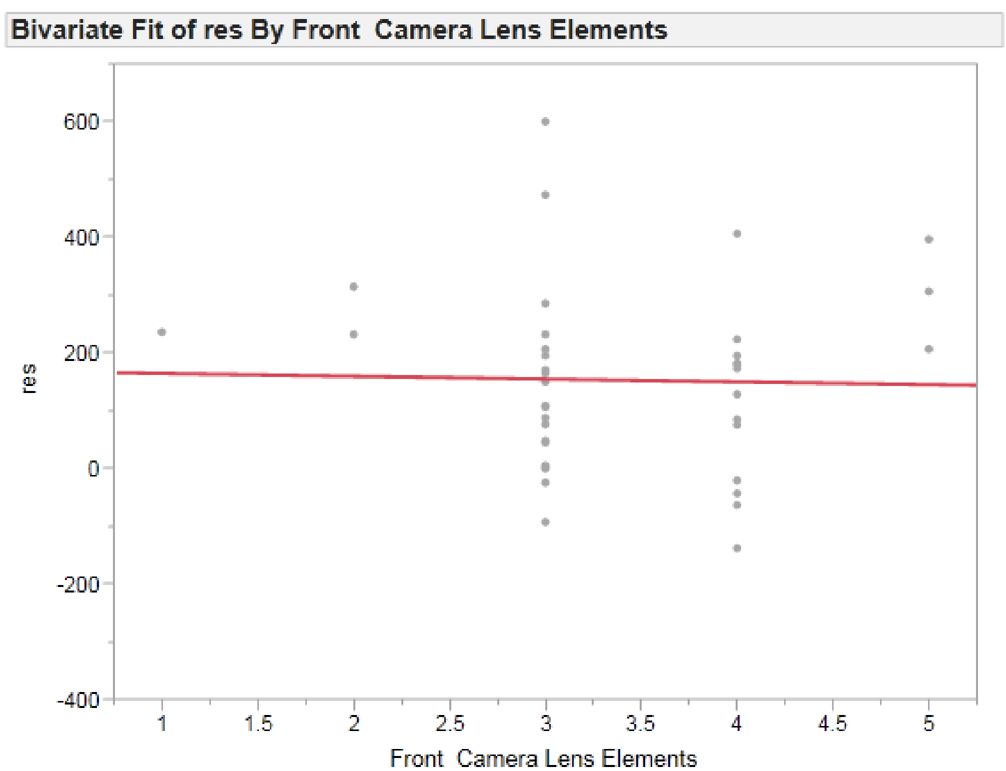
Bivariate Fit of res By Rear Camera Capacity (MP)

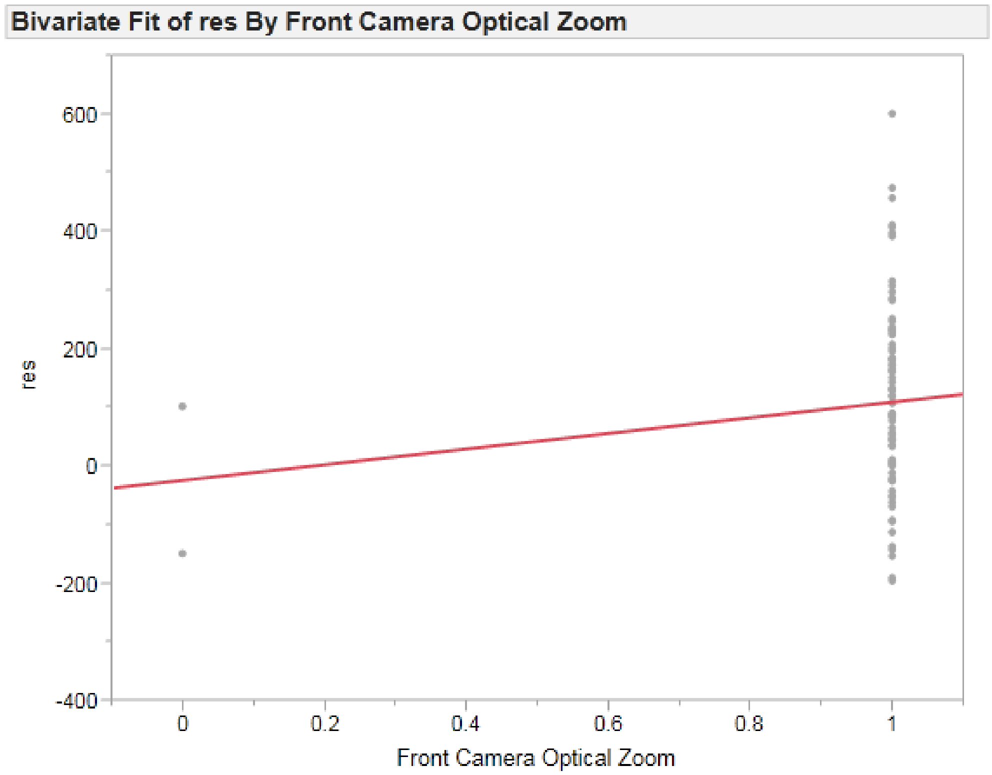


Bivariate Fit of res By Rear Camera Lens Elements




Bivariate Fit of res By Rear Camera Optical Zoom
600
400
200
0
-200
-400
res
0
2
4
6
8
10
Rear Camera Optical Zoom


Bivariate Fit of res By Front Camera Lens Elements
600
400
200
0
-200
-400
res
1
1.5
2
2.5
3
3.5
4
4.5
5
Front Camera Lens Elements


Bivariate Fit of res By Front Camera Optical Zoom
600
400
200
0
-200
-400
res
0
0.2
0.4
0.6
0.8
1
Front Camera Optical Zoom

APPENDIX V: COMPLETE LIST OF SMARTPHONES USED FOR PARETO CHART

Phone	Brand	Display Module	Camera	Battery
iPhone 5S	Apple	33.74	14.89	4.99
iPhone 5C	Apple	33.41	13.96	4.97
iPhone 4	Apple	23.52	15.03	5.76
iPhone 3G S	ASUS	25.96	6.17	5.06
PadFone 2	ASUS	38.64	11.77	4.7
EVO 3D	HTC	27.92	25.95	2.98
Evo 4G LTE	HTC	17.2	9.7	4.74
First	HTC	35.3	12.05	4.96
ONE LTE	HTC	38.41	20.27	5.26
One M7	HTC	36.75	20.61	5.16
One M8	HTC	34.92	22.55	5.4
One Max 8088	HTC	41.5	16.86	6.92
One mini	HTC	37.86	16.23	4.36
One SV	HTC	37.49	12.96	3.85
One X LTE	HTC	21.19	12.23	4.27
One X+ S728e PM35110	HTC	28.4	9.81	2.84
ThunderBolt 4G	HTC	18.3	12.34	3.02
Ascend D1 Quad XL U9510E	Huawei	36.1	10.03	4.52
Ascend P6	Huawei	37.13	15.67	4.73
Impulse 4G	LG	25.27	5.88	3.12
ideaPhone P780	LG	51.66	11.26	7.92
G Flex	LG	46.49	12.29	6.26
G2	LG	52.8	18.11	5.6
Google Nexus 4 E960	LG	50.86	7.85	4.33
Google Nexus 5	Motorola	46.92	14.1	4.6
Nitro HD	LG	32.29	12.41	3.13
Optimus G Pro F240L	LG	44.71	17.81	5.31
Optimus LTE III F260S	LG	39.03	8.43	3.15
ATRIX HD MB886	Motorola	18.62	8.88	3.14
DEFY XT557D	Motorola	33.54	7.34	3.6

DROID RAZR XT912	Motorola	36.39	15.53	4.06
DROID Ultra	Motorola	62.13	17.37	4.41
Moto X XT1060	Motorola	42.13	18.4	4.62
Photon 4G MB855	Motorola	19.44	11.53	4
Lumia 1020	Nokia	59.23	47.19	4.8
Lumia 800	Nokia	31.17	7.15	2.82
Lumia 900	Nokia	21.85	9.31	3.96
Lumia 920	Nokia	39.37	16.62	3.71
N8	Nokia	27.2	18.46	3.58
N9	Nokia	33.91	10.38	2.7
Ativ S I8750	Samsung	41.87	14.41	4.71
Galaxy Mega GT-I9205	Samsung	54.84	15.99	6.21
Galaxy Nexus I9250	Samsung	34.27	10.3	3.38
Galaxy Note 3 SM-N900A	Samsung	69.83	17.37	6.61
Galaxy Note II N7100	Samsung	51.39	14.57	5.64
Galaxy Pocket Plus GT-S5301	Samsung	27.46	4.16	2.44
Galaxy S III I747	Samsung	36.6	14.34	4.4
Galaxy S4 Active SGH-I537	Samsung	44.83	15.43	6.05
Galaxy S4 GT-I9500	Samsung	34.4	14.99	5.56
Galaxy S4 mini GT-I9195	Samsung	40.92	15.5	4.31
Galaxy S4 zoom	Samsung	45.15	46.36	4.31
Galaxy S5 SM-G900H	Samsung	45.93	19.02	5.33
Galaxy Trend Duos II S7572	Samsung	40.72	5.27	3.07
Galaxy Young GT-S5360	Samsung	26.77	4.94	2.79
Galaxy S4 GT-I9505	Samsung	34.4	14.51	5.69
Rex 90 GT-S5292	Samsung	33.58	5.33	2.09
Xperia Z1	Sony	52.23	17.22	7.32
Xperia Z	Sony	36.07	14.8	5.04
Xperia Z1 Compact	Sony	47.59	16.92	4.93
Xperia Z Ultra	Sony	68.25	13.11	6.77
Xperia S	Sony	23.93	13.56	3.55
X900 AZ510	Xolo	13.41	9.95	3.69
Q600	Xolo	37.28	7.92	3.49
X1000	Xolo	34.27	10.38	4.47
Nubia Z5	ZTE	44.49	14.61	4.73
Discover P9090	Pantech	48.92	20.15	4.24

Pocket P9060	Pantech	18.64	7.56	3.02
Digital Find 5 X909	Oppo	52.23	16.01	4.96
N1	Oppo	50.65	9.85	7.34
	Average =	37.82	14.20	4.54

APPENDIX VI: SHOULD-COST MODEL INTERFACE

Display Cost Model

Base* smartphone display cost =	$22.08

Note: Enter 1 to select type in each display feature, unless specified otherwise

Display Type		Screen Size		Pixel Density		Number of Colors		Cover Glass Type					
LCD	1	Screen Size (in inches)	5	Input Density (ppi)	317	16M Colors		CGG		CGG3		Scratch resistant	
OLED						16.7M Colors	1	CGG2	1			Shatter-Proof	

Display with:

Display Type	LCD	0			
Screen Size(")	5				
Pixel Density(ppi)	317				
Colors	0	16.7M Colors			
Cover Glass	0	CGG2	0	0	0

Display Cost =	$43.11

***Base Phone:** OLED Display, 3" Screen Size, 250ppi Pixel Density