# Describing, Assessing and Embedding Flexibility in System Architectures with Application to Wireless Terrestrial Networks and Handset Processors

by

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## Abstract

This thesis presents a framework that can be used to identify the flexibility attributes and determine the value of embedding flexibility in system architectures, from the context of network based wireless applications and wireless handset processors Flexibility is first defined and the three dimensions of flexibility – performance, capacity and functionality are explored. This analysis is used to formulate a general model of the dimensions of flexibility. The analysis to determine the value of embedding flexibility is then done using the example of a flexible handset processor. The Black-Scholes model and the Binomial model are presented as methods for computing the economics of financial options. These methods are then applied to computing the value of flexibility options. In order to determine the value of the underlying asset, which is one of the terms needed for the valuation of flexibility, two approaches are presented: conjoint analysis and concept engineering. The bounds of time to expiation are explored. The cost of embedding flexibility is then assessed. Finally, a few methods are proposed for determining the optimal flexibility design vector and implementing a portfolio of real option based flexibility strategy.

Thesis Supervisor: Olivier L. de Weck
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# Acknowledgements

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# Nomenclature

## Abbreviations

| | |
|---|---|
| 2G | 2nd Generation |
| 3G | 3rd Generation |
| 3GPP | 3rd Generation Partnership Project |
| ANSI | American National standard Institute |
| ARPU | Average Revenue Per User |
| ASIC | Application Specific Integrated circuit |
| BSC | Base Station Controller |
| CDMA | Code Division Multiple Access |
| CPU | Central Processing Unit |
| DSP | Digital Signal Processing |
| EDGE | Enhanced Data for GSM Evolution |
| ETSI | European Telecommunication Standard Institute |
| FCC | Federal Communication Commission |
| GGSN | Gateway GPRS Support Node |
| GSM | Global System Mobile |
| HLR | Home Location Register |
| ISDN | Integrated Services Digital Network |
| ISUP | ISDN User Part |
| ITU-T | International Telecommunication Council - Telecom |
| JPEG | Joint Photographic Expert Group |
| LCD | Liquid Crystal Display |
| MAP | Mobile Application Part |
| MPEG | Motion Picture Expert Group |
| MSC | Mobile Switching Center |
| NPV | Net Present Value |
| OHG | Operators Harmonization Group |
| PDA | Personal Digital Assistant |
| PLMN | Public Line Mobile Network |
| POP | Point Of Presence |
| PSTN | Public Switched Telephone Network |

| | |
|---|---|
| PV | Present Value |
| QFD | Quality Function Deployment |
| RISC | Reduced Instruction Set Computer |
| ROA | Real Option Analysis |
| SGSN | Serving GPRS Support None |
| SIM | Subscriber Identity Module |
| SM | State Machine |
| SMS | Short Message Service |
| SMSC | Short Message Service Center |
| SOC | System On Chip |
| TCAP | Transaction Capability Application Part |
| TDD | Time Division Duplex |
| TDM | Time Division Multiplexing |
| TDMA | Time Division Multiple Access |
| VAS | Value Added Services |
| VLR | Visitor Location Register |
| WDCDMA | Wideband CDMA |

## Symbols

| | |
|---|---|
| A | Current value of underlying assets |
| Ca | Capacity attributes |
| Cf | Flexibility cost vector |
| Ci | Flexibility implementation cost vector |
| Dfv | Flexibility design option vector |
| Dp | Flexibility design parameter vector |
| Dv | Design option vector |
| Fa | Functionality attributes |
| N(d) | Value of normal distribution at d |
| Pa | Performance attributes |
| r | Risk free interest rate |
| T | Time of expiration |
| Tc | Capacity time window |

| | |
|---|---|
| Tf | Functionality time window |
| Tp | Performance time window |
| V | Value of call option |
| Vi | Flexibility value vector |
| Vv | Option value vector |
| X | Exercise price |
| σ | Volatility of underlying asset |
| Inv | Net Incremental value of Investment |
| $C_{Fixed}$ | Cost to the enterprise for fixed design option |
| $C_{Flex}$ | Cost to the enterprise for flexible design option |
| Vmod | Value of a module/feature to the customer |

*C h a p t e r   1*

# Introduction

## 1.1   Motivation

Flexibility is very critical in addressing changing customer needs in the highly competitive market scenario that we see around us nowadays. There is a general recognition that flexibility is a desirable quality if there is bounded uncertainty in the future usage of the system. These uncertainties can be due to dynamic customer needs, technology, corporate strategy, market conditions, competitive scenario, economic and regulatory policies among other factors.

Due to this, a key interest in industry today is to embed flexibility in Product and System Architecture. In order to embark on a research initiative on flexibility, we need to substantiate the dimension and attributes of flexibility and establish the methods by which flexibility can be described in a rigorous but generic fashion.

Flexibility can be understood as the innate ability of a system or product to support new functions and to perform these at some finite range of operating conditions and capacity levels during later stages of its lifecycle. Usually the range of expected behavior is fixed in a specification. One of the definitions of Flexibility in the published literature is *the property of a system that allows it to respond to changes in its initial objectives and requirements – both in terms of capabilities and attributes- occurring after the system has been fielded* [1].

This differs from robustness, where a fixed behavior is specified for an uncertain range of external influences onto the system. It also differs from agility, which is the ability of a system to be modified or adapt itself to wholly unanticipated operating conditions or functional requirements as shown in Figure 1   Flexible Design Objective Space (Adapted from [1])).
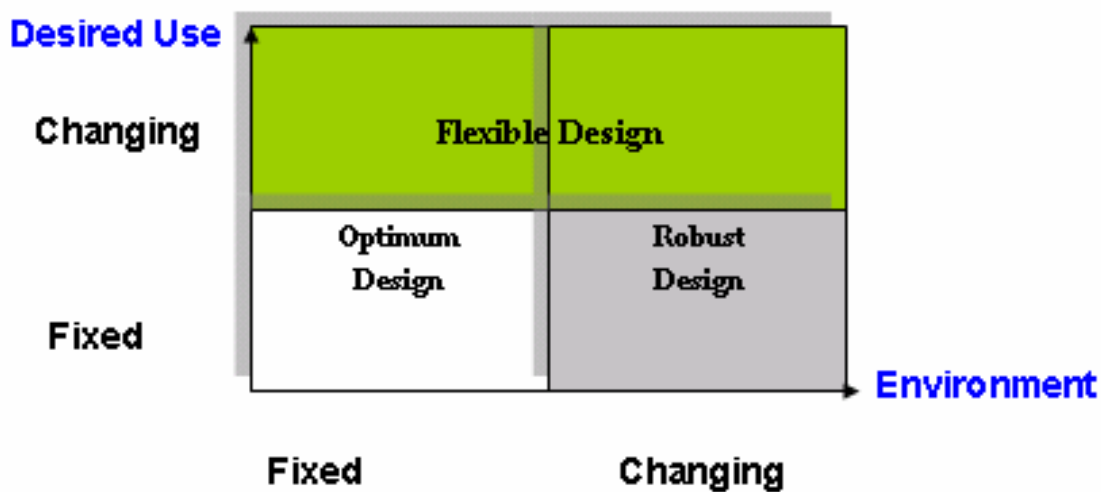


Figure 1  Flexible Design Objective
Space (Adapted from [1]))

As mentioned earlier, there is a general recognition that flexibility is a desirable quality if there is bounded uncertainty in the future usage of the system. Flexibility can be used to address this uncertainty. Flexibility generally comes at the expense of other system characteristics such as performance, robustness or cost.

This thesis is motivated by the exploration such tradeoffs in the context of system and product architecture. Apart from this, evaluation of the conditions where a flexible

architecture is no longer financially viable vis-à-vis fixed architectures is very important from the point of view of product design, placement and deployment strategy.

## 1.2    Objectives

As identified as one of the possible research areas in the Architecture Trade Methodology research initiative [3], the primary research objective of this thesis is in describing, assessing and embedding flexibility in Product and System Architectures. This thesis will contribute to research in architecture flexibility by demonstrating how alternative valuation methods such as conjoint analysis and concept engineering can yield an estimate of product option value, yielding information on the relative value of flexibility options during product design.
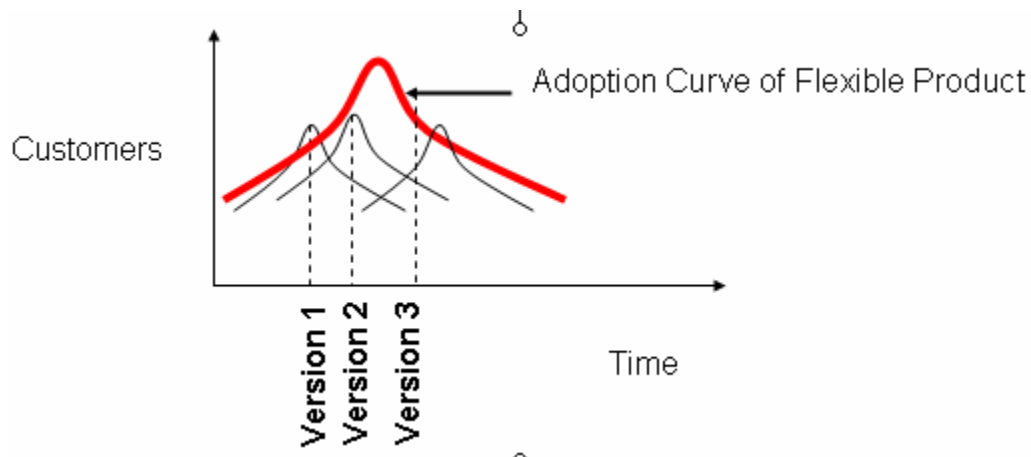


Figure 2  Adoption curve of a flexible product

In particular, the effect of timing between the decision to implement provisions for flexibility in a product ("designing slots") and actually taking advantage of the flexibility ("populating the slots") will be investigated in relation to the underlying industry dynamics.

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The proposed framework will be illustrated using the quantitative sample problem of a flexible processor for a wireless handset to demonstrate how a flexible product can be used for a consolidated adoption curve as shown in Figure 2 Adoption curve of a flexible product.

### 1.2.1 Describing Flexibility

Crawley [4] explains that goods and services deliver value to beneficiaries, primarily by acting on one or more operands [4].
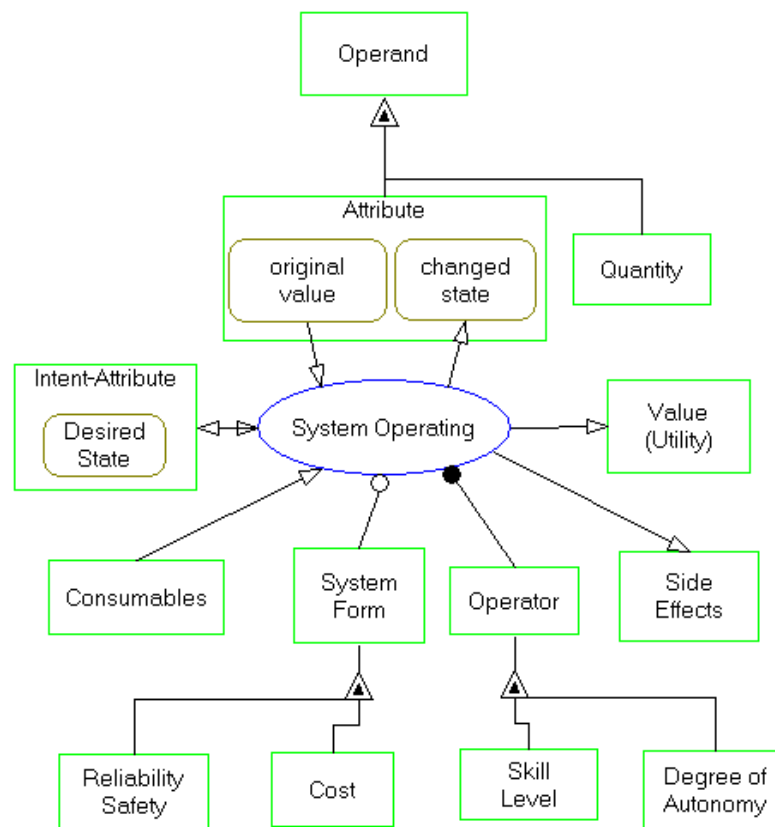


Figure 3 : Generic Object-Process-Diagram of
System Operating. Source [4]

The operand in matter transportation systems are passengers and cargo. In information transfer systems – such as wireless networks - the operands can be real time voice signals, alphanumeric messages, data files or multimedia data streams. The information transfer process is described by communications theory. The wireless terrestrial networks described in this thesis are made up of a number of different elements such as base stations, transmitters and servers. An important element is the end user terminal (handset), which is either source or sink in the information transfer process. An object-process description for generic systems has been developed by Crawley, see Figure 3 : Generic Object-Process-Diagram of System Operating.

We can refer to this generic view to develop a more specific view of the dimensions of flexibility. Functional flexibility can be expressed as the ability to either effect different types of processes on the same operand, or to effect the same process on different types of operands, see Figure 4 OPD Representation of Flexibility: Functional flexibility.
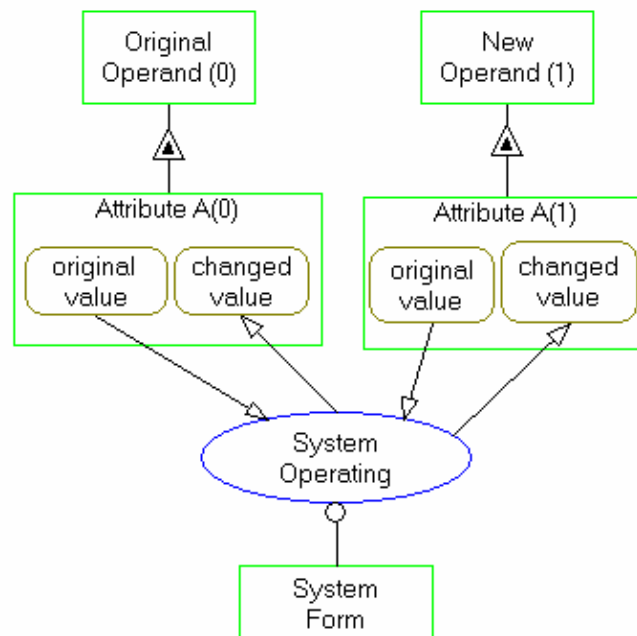


Figure 4 OPD Representation of Flexibility:
Functional flexibility
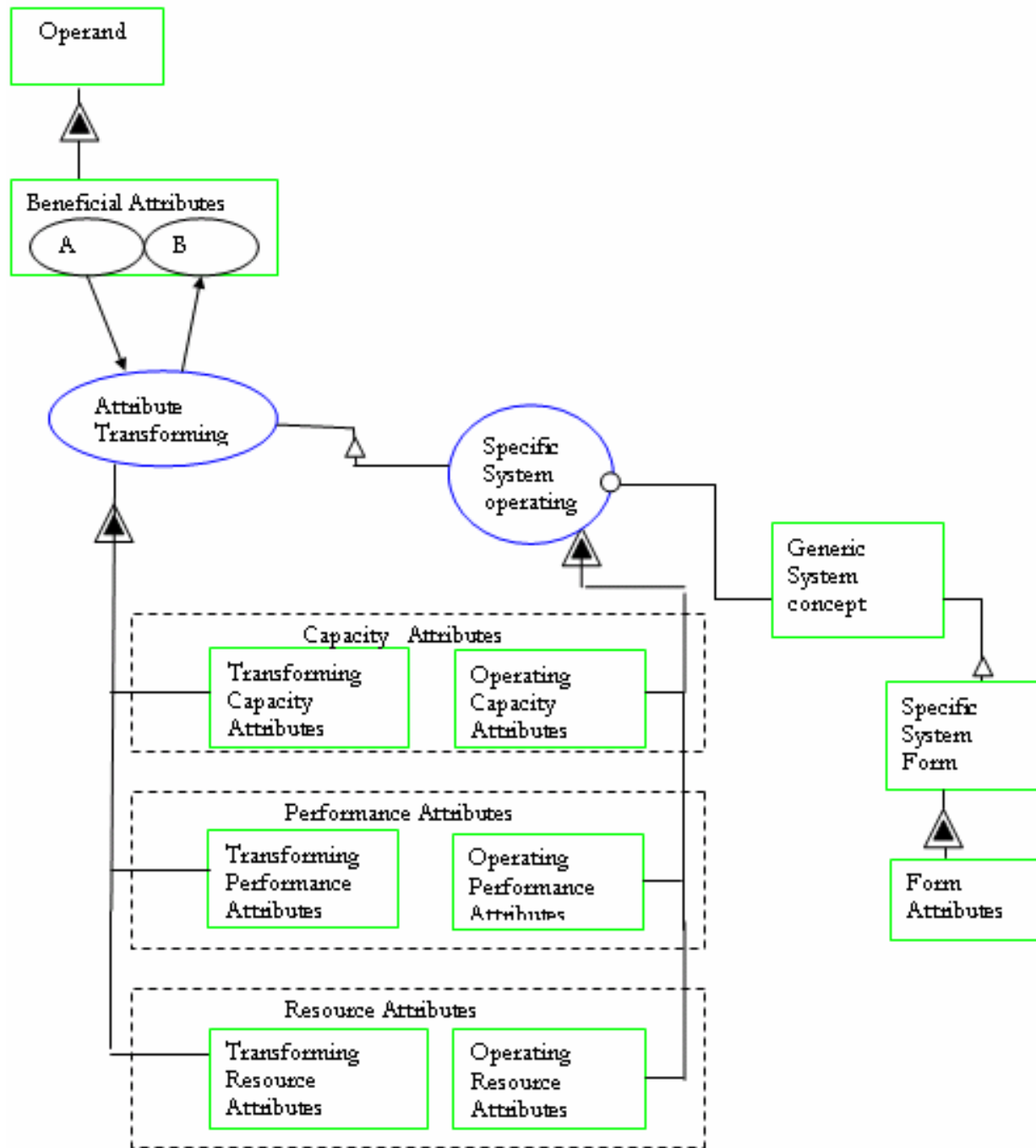
Figure 5 OPD Representation of Flexibility:
Capacity and Performance Flexibility

The notion of performance can be understood as the difference between the changed state and the desired state, capacity is related to the quantity (amount of) operand see Figure 5 OPD Representation of Flexibility: Capacity and Performance Flexibility.

These dimensions would be defined by the range of the Performance and the Capacity related attributes which are part of the transforming attribute of the primary intent and the operating attribute of the process. There is another class of attributes which are "Resource Attributes" (e.g. Cost) , which would set the constraints for the architectural tradeoff and cost/benefit analysis.

Product flexibility can be achieved by activating dormant features or adding to existing features to provide enhanced functionality along these dimensions at a later part of product life cycle.

**Why Three Dimensions?**

Product flexibility could mean flexibility in multiple features of a product. A rigorous analysis, which includes quantification of the range of such features, accessing the cost and value of embedding this range of features would be a complex task.

We used Crawley's architectural framework [4] to derive three categories of favorable product "features". These categories are –

Transformation of the beneficial attributes of the primary intent: Almost all products, transform one or many beneficial attributes. The Transformation process  defines the first category of flexibility dimension. For example

Figure 6 Intent-Process-Object Diagram for 2G GSM Network , shows that the primary intent of enabling outdoor voice conversation is enabled by the process of mobile voice call. The Transformation process acts on a set of attributes. We can also see them as inputs to the transformation function.

The second dimension is defined by the volume of these inputs. In the example shown in Figure 6 Intent-Process-Object Diagram for 2G GSM Network , this dimension will drive the (traditional) voice calls capacity supported by the network. The set of attributes that are transformed, have a "rate" of transformation.

The third dimension is defined by this rate. In the example shown in Figure 6 Intent-Process-Object Diagram for 2G GSM Network , this dimension can be characterized how fast the primary intent is transformed (rate of enabling of voice conversation). This will drive the (traditional) peak calls/second metrics of the network.

We should remember, however, that there could be attributes that are related to the operation of a product and those could have a set of parallel flexibility dimensions apart of these three. An example of an operating performance measure might be the Mean Time Between Failure (MTBF).

Thus the motivation for the classification of the flexibility dimensions is due to two important reasons:

1. Ease of identification of the "features" that would make the product flexible.

2. Ease of quantification of the range of these features.
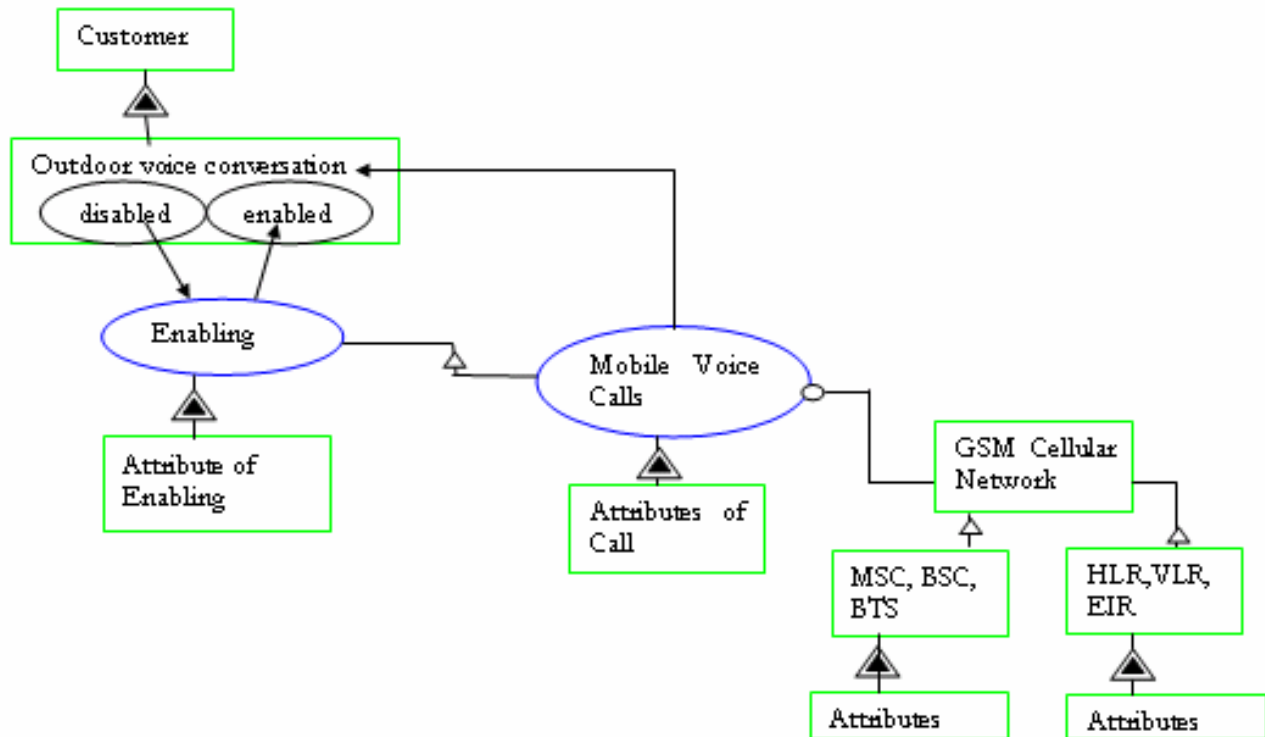


Figure 6 Intent-Process-Object Diagram for 2G GSM
Network

The objective of this thesis is to quantify a range of the functional, performance and capacity attributes which would make the product "flexible" and then analyze the tradeoff between the resource attributes and the value delivered due to flexibility.

The Functional, Capacity and Performance flexibility dimensions are the "results" of a flexible product. These dimensions can be achieved by Reconfigurability, Platforming and Extensibility [9]. Some examples of flexibility dimensions with respect to different industry segments are described in the following sections.

**Hardware (Processors)**

 A processor design optimized for only a particular class of application, leads to the constraint of meeting needs of only one market segment.   There is an uncertainty associated with how the application scenario, will evolve. Implementing design features for a flexible feature (e.g. cache architecture), we incur a cost in terms of additional design effort, complexity and allocation of resources, which detract from traditional performance metrics (for example it may lead to higher power and die cost ).

By implementing flexible design features which enable customization of  applications, by enabling of an additional on-chip cache at a later decision point in time we can potentially maximize the net benefit by meeting new market needs which may translate into a higher ASP (average selling price) for each unit when the new features are enabled.   These features can be:

- Operating Power Supply range changed to support mobile/desktop functionality.
- Multi-Threading enabled for greater CPU performance.
- Security features enabled in wireless handsets for premium market segments.
- Additional cache enabled for better performance.

**Software (Network Applications)**

A distributed network application can be designed, keeping in mind the functional, capacity and performance scalability. Such an application could have "hooks" to add a feature, or increase the application capacity at a later point in time.  These features can be

- Capacity of the database increased to meet increased capacity needs
- Additional servers, with different instances of the application running in a load sharing mode to increase the performance of the network application.
- Additional application features enabled (either on the same server or on different server).

The software "flexibility" features can be designed and embedded in a product and activated later based on license agreements (increased capacity or functionality). Configurability, which is particularly important from the point of view of software products, can be is perceived as a feature in a product to enable the flexibility dimensions in the future.

**Civil Architecture**

The concept of extensibility, as defined by Crawley [4] was to enable a system to be scaled up significantly in the future or "organically integrate with a larger systems". For this, he believes that there should be a "master plan" to have a future map of this extensibility and the interfaces must be designed with this in mind. Provision for expansion slots for an additional bedroom or a new barn under the master plan of a house could be example of this extensibility.

From the context of the dimensions of flexibility, the provision to add an additional bedroom provides a capacity flexibility and provision to add a new barn provides a functional flexibility.

**Transportation**

Blended Body Wing architecture presents an excellent example of modular platform architecture, which enables flexibility [5]. The use of a single flexible platform enables Boeing to be able to design a system which can be adapted to meet the demands of the market. Boeing invests large amounts of R&D capital investment, in face of uncertainty (it can not predict accurately the demand for either type of aircraft - Commercial, Cargo, and Military, or the quantities of these). By designing a BWB platform as shown in Figure 7 Reusable Components , Boeing can adapt the final mix of products manufactured based on the actual market demand without the need to design a new aircraft from scratch.
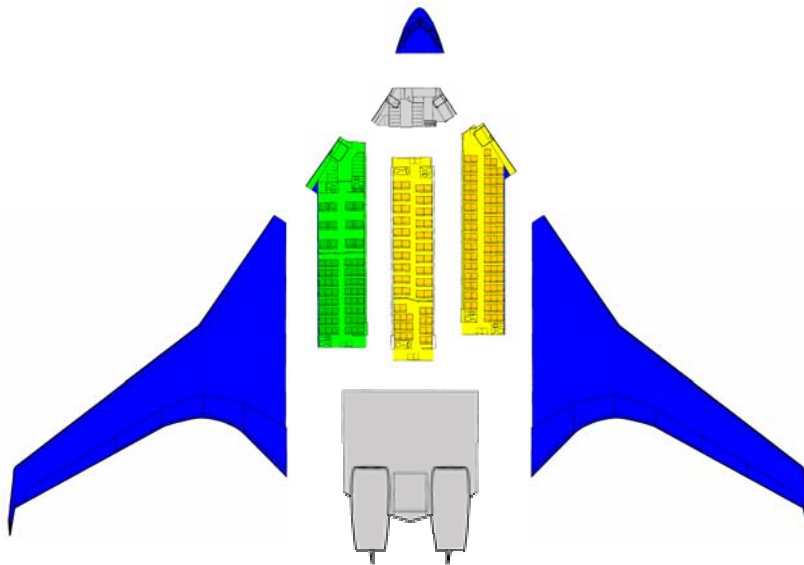


Figure 7 Reusable Components (Source [5]): The blue components – cockpit and wings are common among the whole product family. The green and yellow components are customized, while the grey components are unique for each variant.

### 1.2.2 Assessing Flexibility

The flexibility in each of the dimensions identified in the research effort will be assessed critically from the point of engineering and management domains. The engineering domain would include (among others) performance and cost penalty due to embedding flexibility. Management domain would include analysis of impact of architectural flexibility on the market competitiveness by a financial evaluation of the optimal flexibility options.

### 1.2.2 Embedding Flexibility

The dimensions of flexibility identified in the definition are investigated to a practical depth to gather further insight in embedding flexibility into products and system architectures. Some of the aspects that are covered include -

- Study of performance, capacity and functionality from the context of network based wireless applications.

- Formulation of a general model of the dimensions of flexibility for network based application.

- The overlap of flexibility objective space with the overall objective space. – in other words what are appropriate functional operating modes of the system and what performance bandwidths (upper and lower) bounds are appropriate? de Weck has shown a way to map the Design space to the Objective space using a system model, to evaluate different architectures [3]. The Flexibility objective space can be mapped to a subset of this Objective Space, which would necessitate incorporation of a range of

design space in the overall flexible architecture, see Figure 8 Flexibility Design and Objective .

The identification of the flexibility objective space will depend on factors that would address uncertainties due to dynamic customer needs, technology, corporate strategy, market conditions, competitive scenario, economic and regulatory policies among other factors. An example of this space is shown in Figure 1   Flexible Design Objective Space (Adapted from [1])).
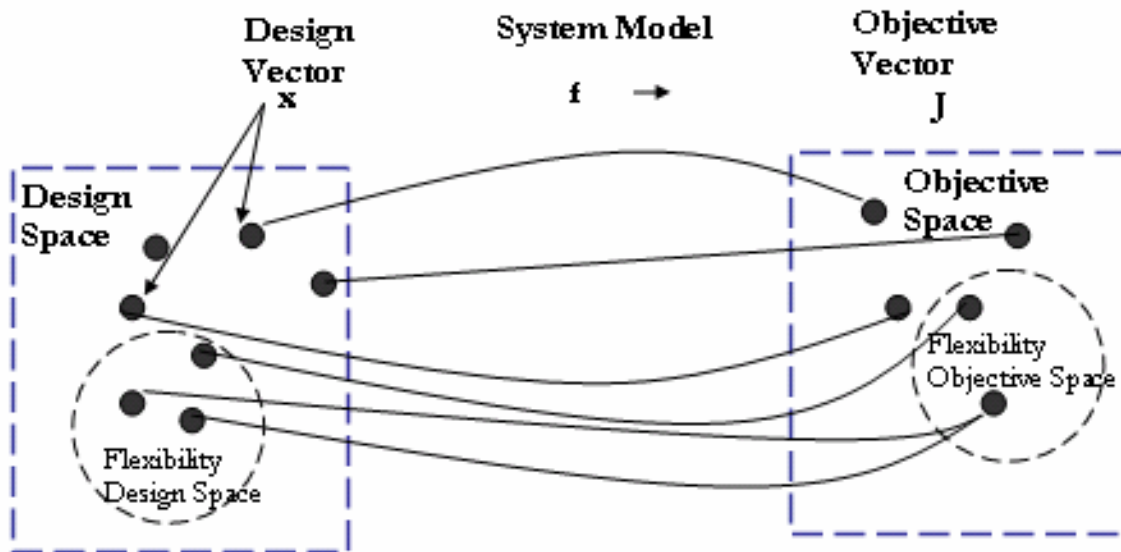


Figure 8 Flexibility Design and Objective Space.
Adapted from [6].

### 1.2.3   Approach

### 1.2.3.1  Methodology

The dimensions of flexibility are explored using the components of a wireless communication network (PLMN). The analysis is used to formulate a generic framework of flexibility in Network Application space.

The framework for determining cost of embedding flexibility for a product is established, based on the quantification of flexible design space as a sub-set of the overall design space for the product. The analysis to determine the value of embedding flexibility is then done using the real options approach.  The Black-Scholes model and the Binomial model are presented as methods for computing the economics of financial options.  These methods are then applied to computing the value of flexibility options.  In order to determine the value of the underlying asset, which is one of the terms needed for the valuation of flexibility, two approaches are presented: conjoint analysis and concept engineering. The bounds of time to expiation are explored. Whenever possible a baseline system/product with no flexibility embedded in it is used as a reference system. Thus flexibility is treated as a "real option in a project", rather than real option on a project. This requires a reinterpretation of time to expiration. The overall framework, mapping the design space to the objective space, with respect to the cost and value of flexibility is shown in Figure 9 Flexibility Framework.

**Flexibility Design Vector** **Objective Space** **Future Opportunities**
(Functionality, Capacity, Performance)

$Dp = [Dp1, Dp2]$

$Cf = [Cf1, Cf2, Cf3]$
(Cost of flexibility design)

$F(t) = [Nf, Tf, Sf, Mf, Cf, Ef]$
(N=need,
T=technology,
S=strategy,
M=market,
C=competitors,
E=economy)

Value of Flexibility
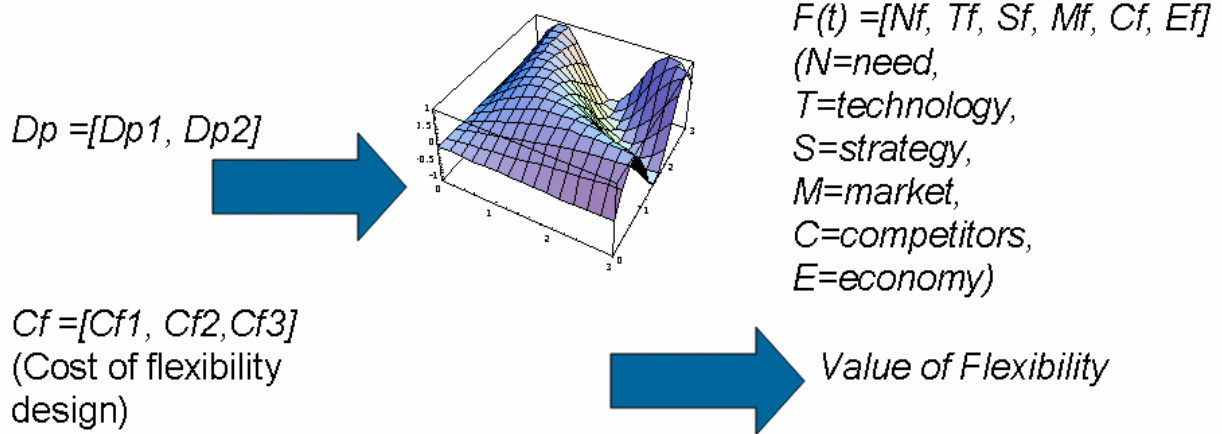
Figure 9 Flexibility Framework

Finally, a method is proposed for determining the optimal flexibility design vector and implementing a chain of real option based flexibility strategy. . This approach is based on T. Luehrmann's approach [25] of developing a strategy as a portfolio of, possibly nested, real options.

### 1.2.3.2  Structure of Thesis

Chapter 1: Defines the scope and objective of the thesis – Describing, Embedding and Assessing Flexibility, in product and system architectures with respect to terrestrial wireless networks and handsets.

Chapter 2 Lists the Literature Reference - publications reviewed and referenced in the thesis. The main focus here is to highlight the difference between embedding flexibility in

products and architectures as "real options in projects" as opposed to the more commonly known options "on projects" or the purely financial options.

Chapter 3 : Describing Flexibility : Proposes the dimensions of flexibility for wireless networks and handsets after analyzing the determinants of diffusion in the respective segments. This treats the outcomes of flexibility, i.e. the ways in which flexibility will primarily benefit the user or customer. This chapter will not specify how flexibility is achieved in a product.

Chapter 4: Embedding Flexibility: Develops a generic model, representing most of the nodes in a wireless network, incorporating the flexibility dimensions identified in Chapter 3. These dimensions are then formally defined and an architectural framework is proposed to realize the three dimensions of flexibility from the point of network applications.

Chapter 5: Valuing Flexibility: Builds a mathematical framework to assessing the value a flexibility design option using the real option analysis. Traditional real options theory "on" projects is extended to include building flexibility into products incrementally.

Chapter 6: Assessing Flexibility (Parameters): Lists the methods for determining the values of the option parameters identified in chapter 5. We will see that finding the value of the underlying asset and determining volatility are particularly challenging in a product development environment. This also includes estimating the cost of embedding flexibility.

Chapter 7: Builds the strategy to determine the best flexible design vector based on the methods and results of the preceding chapters and states the conclusions, recommendations and future work that can be done to expand the framework proposed in the thesis.

**Thesis Roadmap**

The information flow organization of the different chapters of the thesis is shown in Figure 10  Thesis Roadmap , to organize the thesis and help the reader.
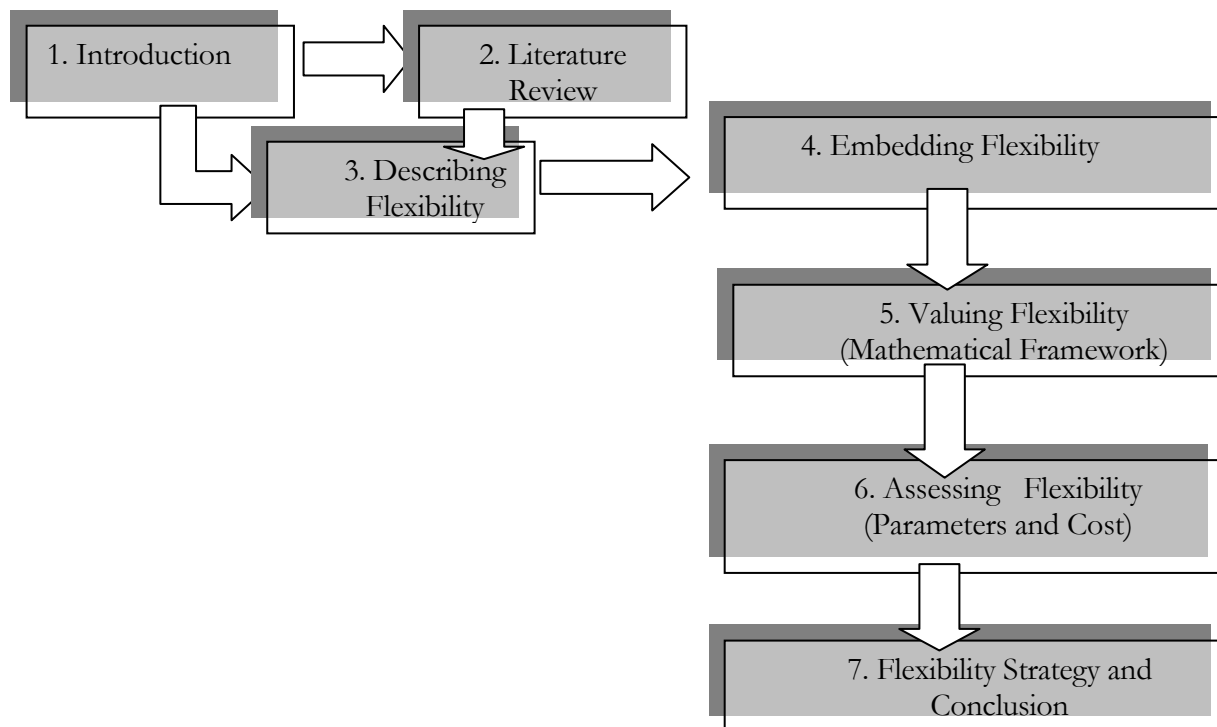


Figure 10  Thesis Roadmap

# *C h a p t e r   2*

# Literature Review

## 2.1 General

Identified as one of the possible research areas in the Architecture Trade Methodology research initiative [3], the primary research objective of the literature review was in the area of describing, assessing and embedding flexibility in System Architectures. This review also includes lecture notes of some of the subjects delivered as part of System Design and Management coursework and patent reviews to identify distributed architecture for wireless networks.

## 2.2 Description of Flexibility

The definition of flexibility as *the property of a system that allows it to respond to changes in its initial objectives and requirements –both in terms of capabilities and attributes- occurring after the system has been fielded*[1] was used as a guideline for the analysis of the outcome or as referred in the thesis as "dimensions" of flexibility. These are also sometimes referred to as "outcomes" of flexibility. In any case these dimensions regard product or system functional attributes that are directly perceived by the customer. Other descriptions of flexibility include – *Flexible systems allow owner to adapt operating conditions* [7] and *the (flexible system) system will have to evolve in the face of changing environments and expectations*

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[4]. Flexibility is one of the desired "ilities" [34,26] from the perspective of System Engineering and System Architecture under uncertainties. An analysis of the relationship of flexibility with extensibility [4,6,9] was also done.

Identification of the primary determinants of diffusion (anything that will cause a favorable diffusion) for the product, within the market context, was the first step to establish the probable objective space [3] for flexibility. These determinants are indicator of the future trends in the industry and thus drive the flexibility dimensions of a product. This study included analysis of the wireless industry (wireless networks and mobile handset processors) from the context of Technology S-Curves [11,36], industry dynamics [36,18,20] and product diffusion [8,18].Identification of the possible product "features" that will cause a positive diffusion included review of publicly available information in the company web sites of the key players in the industry[1] and market intelligence data [11, 8, 31,29].Quantification/Definition of the range of these features(s) for wireless handset processors was done based on analysis of the market research data.

In general, flexibility is embedded in products and systems to be able to better respond to new customer preferences or trends, without having to redesign a product from the ground up.

## 2.3   Embedding Flexibility

This section answers primarily the question of "how is it done"? Thinking about embedding flexibility in the sense of modular innovation [10], we can distinguish three levels of real options, when embedding flexibility in systems or products [9]:

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[1] Wireless Networks : AT&T , Verizon , Vodafone , British Telecom and Mobinet ; Wireless Handset Processors : Intel , Texas Instruments , Analog Devices , Starcore LLC.

- Reserving resources: this means that growth potential is assured by leaving surface area, volume, excess power, computing bandwidth and so forth unused in one generation of the product, such that a future product feature may use this resource, should the option be exercised.

- Designing interfaces: the next step consists in designing interfaces between the baseline product and the area reserved for the flexible product option. These interfaces can be mechanical, energetic or informational. Industry standards and common interface requirements documents (ICDs) significantly facilitate this step.

- Designing the flexible product feature: This next step consists in actually designing the flexible product feature into the product, while using the resources and interfaces provided for by the previous design steps.

Finally, the last step of the "embedding flexibility" process is actually implementing the flexible product feature, which is analogous to actually exercising the real option in the product. This research included analysis of the architectural details from the context of a flexible implementation of    wireless network applications. This research was largely based on publicly available data, patent search [32]. Signaling System 7 [37], provided a good insight of the network protocols. Wireless Network evolution was sufficiently described in Smith and Collin's book on the subject [38]. The ITU-T, ETSI and 3GPP telecommunication standards were also referred[2].

## 2.4    Assessing Flexibility

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[2] IS-41C , IS-95,IS-54, IS-136, GSM-MAP and  3GPP

A study of the different valuation methods - NPV and Real Options, indicated that Real option is better suited for conditions where there is uncertainty [14,15,16]. A good review of the real option approaches in the existing literature was found in Adam Borison's paper [39]. Some of the approaches that were further investigated, based on the categories described in [39] –

- Classic [17,33] - the absence of data on replicating portfolio for flexible options may make this approach impractical. Since flexible product options in innovative industries are not traded on open security markets it is difficult – and often impossible – to find a replicating portfolio for assessing the value of a particular, flexible product feature as a European or American Call Option.

- Subjective [25,19] method uses a subjective assessment of price and volatility of underlying asset. This approach can be used when this assessment is practically possible and the existence of the assumption of a replicating portfolio exists. In absence of this condition, the results would not be accurate.

- Dynamic Programming [17], shows an alternate way of estimating the option price based on binomial lattice. This falls under the category of "simulation", where a set of potential future evolutions is created on the computer and run against the flexible product architectures.

In order to recommend methods to estimate the option parameters (of the chosen method), Conjoint [21,22] and Kano [24] analysis were investigated. Conjoint analysis was found adequate for subjective assessment of the value of the underlying assets, when used in conjunction to product diffusion data. Kano Analysis [24] provides an estimate how well the "customer satisfaction" scales with "flexibility". The basic

concept is to double check the dimensions of diffusion identified in the Description section, to determine whether or not a customer is willing to pay for a scaled of flexible feature.

The flexibility dimensions (Functionality, Capacity and Performance) are explored to mathematically convey the relationships between Flexible design space and the objective space. System Engineering Methods like QFD [30] was studied and recommended for this transformation. The mathematical notation used to map Design Space to Objective Space were based on Olivier de Weck's paper on Architecture Trade Methodology [3].

The cost of implementing flexible design options for wireless network applications was determined using the server costing data available of relevant servers on company website of Sun Microsystems.

Once an optimum design option is defined, assessed and embedded, we reviewed methods to "nurture" this portfolio .The strategy recommended by Luehrman [25], where the chosen portfolio is" tracked" to nurture – or populate/develop the fruitful slots (in his paper, he refers to these as ripe tomatoes) and ignore the unpromising ones, can be used to nurture the flexibility design options. According to this framework each option is assessed using two separate metrics,. First, NPVq, which is the quotient formulation of Net Present Value, which accounts for the value of being able to defer an investment. The second metric, is the cumulative volatility  *sqrt(t), which captures both the time to expiration as well as the riskiness of the option. Here a large volatility is positive due to the asymmetry of possible option value. The value

of a flexible design option can never be negative. However, the initial investment to purchase the real option by reserving resources, designing interfaces or the product feature itself might be lost.

*C h a p t e r   3*

# Describing Flexibility

## 3.1   Introduction

Flexibility can be understood as the ability of a system or product to support new features and to perform these at some finite range of operating conditions and capacity levels during later stages of its lifecycle. The new features can be classified in three important non orthogonal dimensions from the perspective of wireless network applications and handsets:

As described in Chapter 1, **Functional flexibility** can be expressed as the ability to either effect different types of processes on the same operand, or to effect the same process on different types of operands, see Figure 4 OPD Representation of Flexibility: Functional flexibility. From the context of wireless network applications and handsets, this would map into the ability to perform additional (or a range of) functions.

**Capacity flexibility** is related to the quantity (amount of) operand, (see Figure 5 OPD Representation of Flexibility:  Capacity and Performance Flexibility )and will be defined by the Capacity attributes. From the context of wireless network applications and handsets this would map into (among other features) the ability to handle additional (or a range of) quantity of interactions.

**Performance flexibility** can be understood as the difference between the changed state and the desired state and has a 'rate' component. This would be defined by the range of the Performance attribute, see Figure 5 OPD Representation of Flexibility:  Capacity and Performance Flexibility. From the context of wireless network applications and handsets this would map into (among other features) the ability to handle additional (or a range of) interaction rate.

Identification of the primary determinants of diffusion (anything that will cause a favorable diffusion) from the context of product feature, within the market context, is the first step to establish the probable operating space for flexibility. These determinants are indicator of the trends in the industry and thus drive the flexibility dimensions of a product.
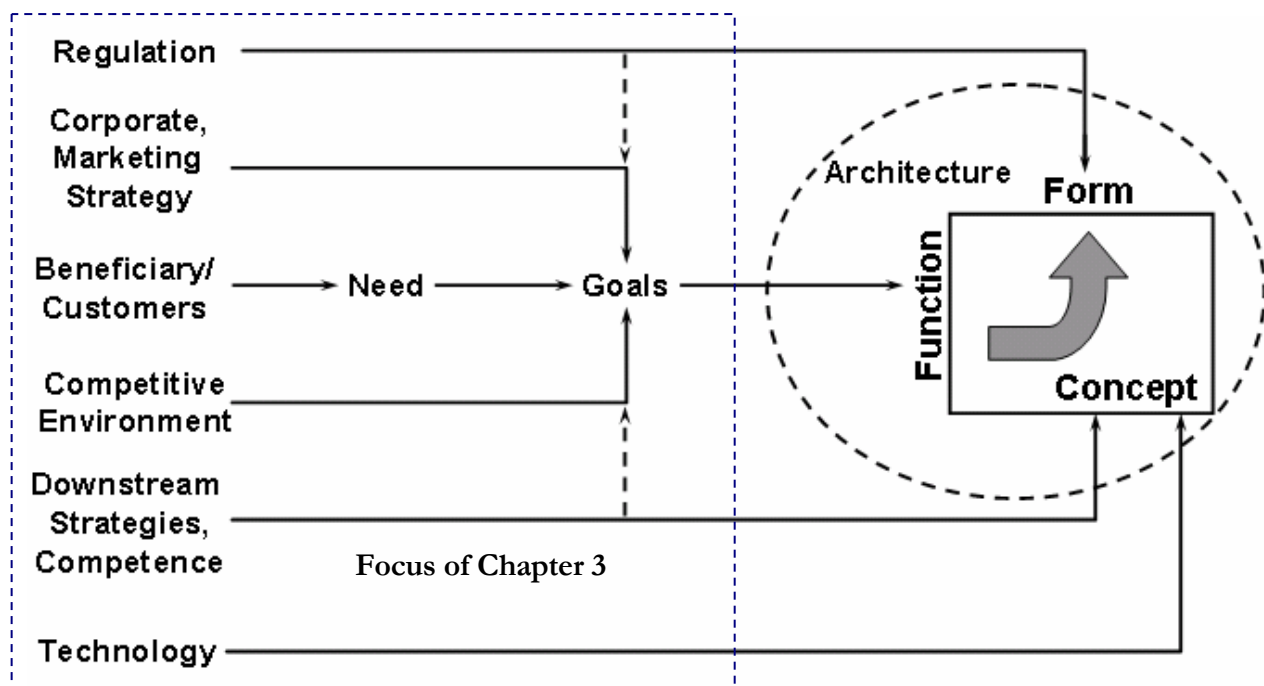


Figure 11  Focus of Chapter 3 (adapted from [4])

The upstream influences in identifying the Needs and Goals for a flexible architecture were mapped to Crawley's framework [4] , as shown in Figure 11  Focus of Chapter 3 (adapted from [4]).

It should be noted that "a range of" functions, volume and rate of interactions can be either more (Forward Flexibility) or less (Backward Flexibility) with reference to the fixed design.

There are two key steps in this process:

- Identification of the possible product "features" that will cause a positive diffusion.

- Quantification/Definition of the range of these features(s) for a flexible product. This range will be the objective space for the flexible product.

This analysis is done for Wireless Networks and Wireless Handset processors in the subsequent sections. The wireless networks are analyzed from a "long term" perspective, which would be typically 4-5 years, based on the current trends of network convergence and upgrade. The wireless handset processors, on the other hand, are analyzed from a "short term" perspective of 1-2 years.
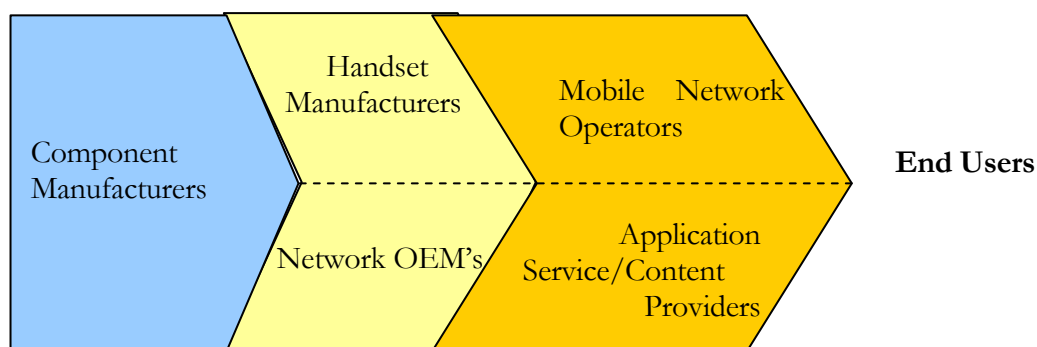


Figure 12  Wireless Value Chain

This analysis was deliberately designed to validate the flexibility dimensions from the point of long and short term determinants of diffusion in different segments of the same value chain as shown in Figure 12 Wireless Value Chain.

We were able to identify the possible product "features" that will cause a positive diffusion for both the cases. Definite quantification/definition of the range of these features(s) for a flexible product was done for the "short term" case of wireless handset processors. This was because, in order to define flexibility features with a bounded uncertainty, we found the current market research data on wireless handset processor diffusion, adequate (in contrast to similar data on wireless networks). One of the flexibility feature identified (cache architecture), is used to analyze the value of flexibility in Chapter 5 (Valuing Flexibility)

Once the determinants of diffusion are identified, these are then classified based on similar attributes to derive the flexibility dimensions that would enable the product(s) to operate in a finite range (flexible objective space) in the overall objective space as shown in Figure 8 Flexibility Design and Objective Space. Adapted from [6].

## 3.2 The Wireless Network

The primary determinants of diffusion for the Wireless Networks are very important to establish the probable operating space for flexibility. These determinants would be an indicator of the trends in the industry and thus drive the flexibility dimensions. In this section, the background of the Wireless Networks is explored, to identify these dimensions.

### 3.2.1 Network Evolution

The overall reference of performance (and from the context of the, flexibility dimensions) of the wireless networks has historically been on two key areas- Call Capacity and Data rate. Though the apparent indicator of increased performance in the evolution of the 2G networks has been the data rate (9.6 Kbps to 2 Mbps), the carriers are more interested in the capacity scaling that the evolving networks provide (from tens to hundreds of users per cell).

The qualitative performance scale for wire line network evolution is based on cost per subscriber (including the fixed infrastructure cost and variable operating costs). Lower the cost, higher is the relative position in this scale. The Technology S-Curves [11] showing the evolution of the wireless networks from 1G to 2G to 3G networks is shown in Figure 13 Wireless and Wire line Network Evolution in North America.

The wireless and wire line S curves have been superimposed to give us an idea of the timeline of evolution and a qualitative view of the comparative performance.
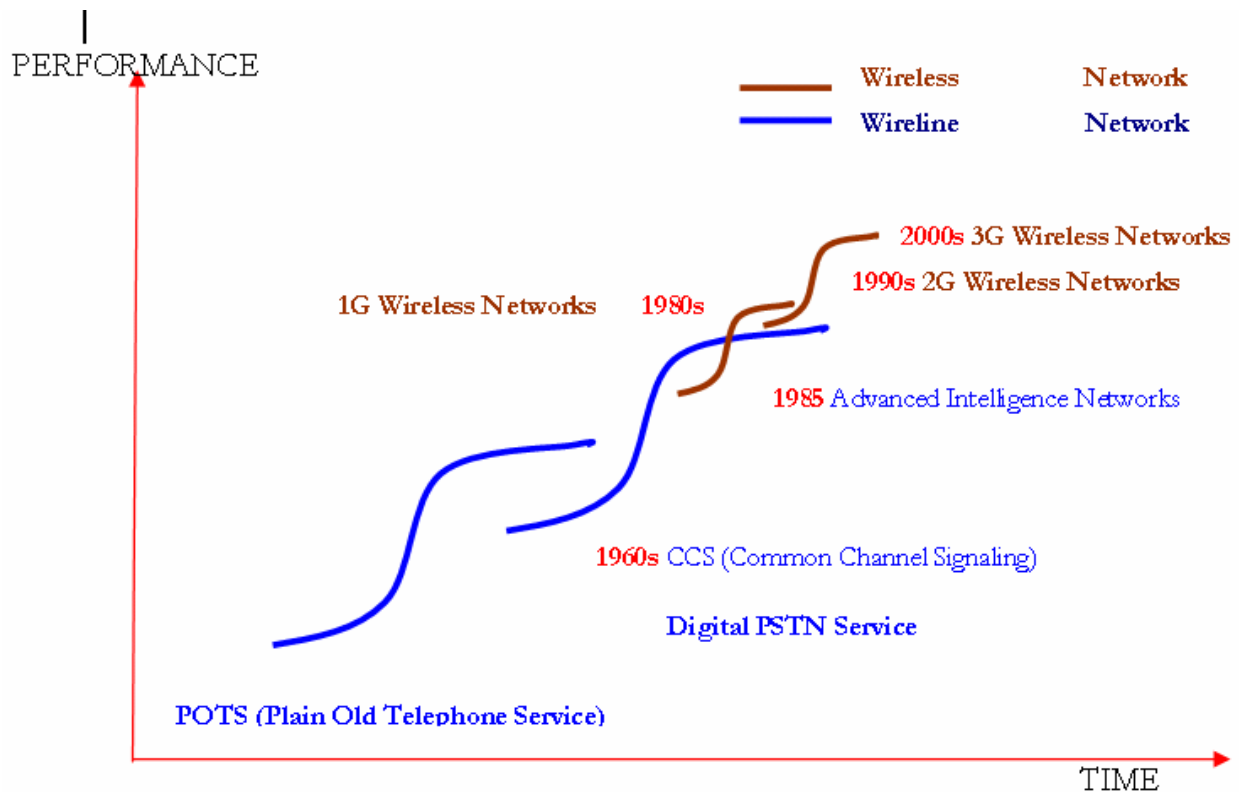
Figure 13 Wireless and Wire line Network
Evolution in North America

Today wireless networks can be set up at fraction of the costs of traditional wireline networks. This is one of the reasons the third world countries are adopting the wireless networks directly (skipping the wireline evolution phase).

**3.2.2   Evolution of Standards**

The Wireless Industry is divided by three dominant standards – GSM, TDMA and CDMA[3]. GSM has evolved as a standard of choice based on overwhelming adoption by users throughout the world as compared to the other two standards [13].



Number of Subscribers
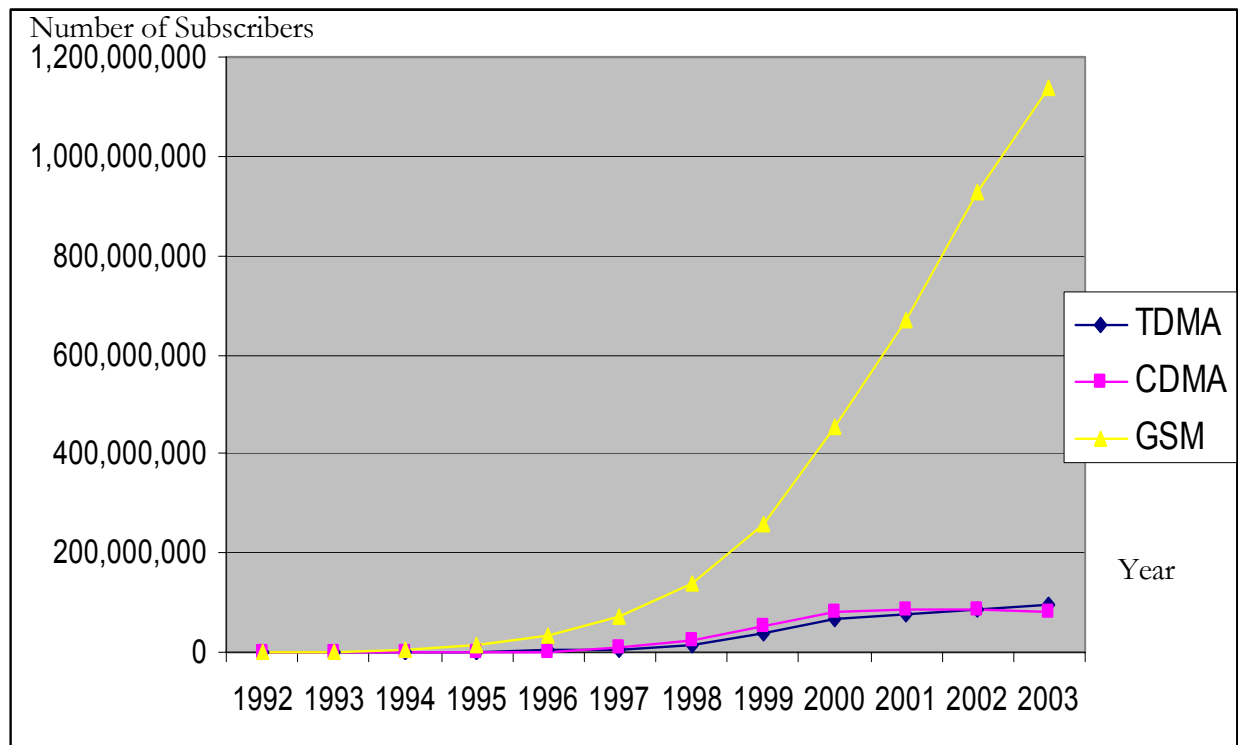
Figure 14 Diffusion for TDMA, CDMA and GSM.
*(Source: [12])*

The diffusion curve of GSM is steep due to the Network Effects and positive feedback due to widespread adoption throughout the world as shown in Figure 14 Diffusion for TDMA, CDMA and GSM. *(Source: [12])*. This diffusion curve is derived using the Lotka Volterra model, which is a simple model of predator-prey interactions.

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[3] See Appendix A for an overview of GSM , TDMA and CDMA frequency allocations and modulation schemes

TDMA and GSM are both based on similar concept of Time division Multiplexing and have joined hands in the "standard tipping" war against CDMA which is considered to be technically superior to TDMA or GSM. This has helped in increasing the installed base of the TDM camp. The global 3G standards are based on CDMA technology. CDMA has higher spectrum efficiency as compared to TDM (TDMA and GSM). Dynamic bandwidth allocation provides flexibility in the maximum number of users supported per cell in CDMA networks; this number is fixed based on the total timeslots in TDMA and GSM networks. In TDM networks, adjacent cell interference is a common problem, in cases where the cell sizes are very small and the carriers have limited bandwidths. This problem is not present in CDMA networks, therefore modification of the existing cell structure is easier, giving flexibility to the network operators to modify or expand their networks.

### 3.2.3   Europe Vs N America in 2G Standard Evolution

ETSI (European Telecommunication Standards Institute) organized the GSM standard, at the Pan-European level. Europe had faced lot of interoperability problems due the multiple Analog Standards that existed before the 2G migration was decided and was motivated to adopt a common standard to mitigate the interoperability problem in the 2G networks. European Wireless Operators strategy to capture value was to build the installed base based on a consensus standard (GSM).

America on the other hand had just one Analog Standard (AMPS) – and evolved to the 2G wireless networks under two paths CDMA (IS-95) and TDMA (IS-136). The American

wireless industry followed the strategy of "Let the Market decide the Standard" strategy. CDMA did not catch on in Europe because it had not developed fully enough to beat GSM during the selection period that ETSI had set.

### 3.2.4   3G Network Evolution

#### 3.2.4.1   *CDMA –Technological Edge*

The Code Division Multiple Access (CDMA) technology was developed by Qualcomm. CDMA is widely considered a better technology as compared to the Time Division Multiplexing technology used by GSM and TDMA because of its superior spectral efficiency and lower installation and equipment costs. The Global wireless standards that are proposed by G3G (Global 3 G Standard Committee) is WDCMA – which is based on CDMA technology.

**Strategic Alignment [18] of Primary Producers (TDMA & GSM)**

In the Evolution to 3G networks, the TDMA and GSM standards aligned to have similar upgrade paths via GPRS, EDGE and WDCDMA (
Figure 15 **Evolution Paths of TDMA, GSM and** CDMA) . This alignment was strategically very important, wherein though the operators would be licensing some portions of the CDMA technology, they could resist the effort of Qualcomm to make CDMA2000 as the worldwide standard, where Qualcomm would have a substantially greater share of the overall value and a possible Winner Takes it all situation. The standard war was resolved after many publicized rounds of confrontations.
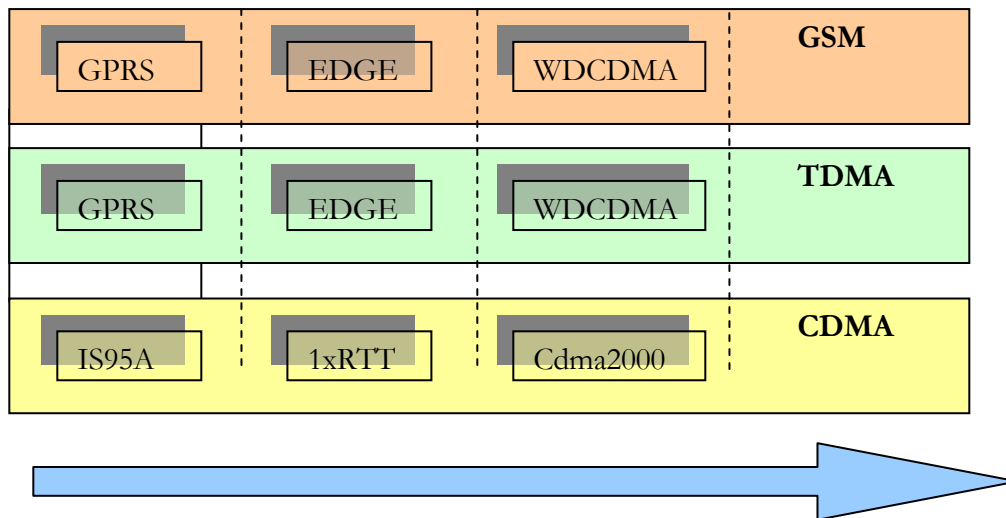
Figure 15 Evolution Paths of TDMA, GSM and

CDMA

**Strategic Alignment of Primary Producers (CDMA & GSM)**

Qualcomm and Ericsson (Dominant Player in the GSM Market) had an Intellectual Property deal in 1999, facilitated by the OHG (Operators Harmonization Group). This resulted in the convergence of three paths of CDMA evolution (cdma 2000, WDCDMA and TDD) TDD standards are not yet finalized. WDCDMA was aligned with the GSM and TDMA evolution path.

This aligned the evolution path of CDMA, TDMA and GSM. As part of the agreement, the companies committed to licensing their essential patents for a single CDMA standard, removing all intellectual property restrictions that currently were in force. Ericsson purchased Qualcomm's terrestrial CDMA wireless infrastructure business, including its research and development facilities in San Diego and Boulder, Colorado. In 2001 Qualcomm and Nokia had a similar cross license agreement.

### 3.2.5   The Future

Due to the efforts of the different standards committee's – the overall wireless industry seems to have tipped towards the CDMA standard. It is interesting to note that the GSM camp would still retain the value it had created due to the early market penetration, based on strategic alignment with a technically superior standard.

This way, it will be able to use its vast installed base and complimentary assets, without the risk of defection in the future. From the context of flexibility we will analyze the wireless network from the context of a single converged standard.

### 3.3   Diffusion in the Wireless Industry

As mentioned earlier, the primary determinants of diffusion are very important to establish the probable objective space for flexibility. These determinants would be an indicator of the trends in the industry and thus drive the flexibility dimensions.

The Diffusion in the Wireless Industry can be perceived in at least two dimensions. The first dimension is the traditional voice service, where the industry is currently wooing the "Late Majority". The Determinant for diffusion in this dimension is the support for increased number of subscribers.  Wireless network operators want to ensure that they can continue to support their existing subscribers (and continue their subscriber base expansion), before introducing the high bandwidth value added services. From the point of view of the Network operators, Cost of deployment and Spectrum allocation would also guide to a big extent the expansion of the networks.

The second dimension is Value Added Applications, where the wireless industry is in the process of crossing the chasm between the Early Adopters and Early Majority. A key Determinant for diffusion for the wireless industry in this dimension, is the subscriber's need for assessing value added data, while on move (apart from the traditional voice connectivity).Value added data includes localized and personalized data, high bandwidth entertainment data, among others.

### 3.3.1 The Voice Dimension - Late Majority

Total number of wireless subscribers has grown at a steady rate since 1995(Figure 16 North American Wireless Subscribers) shows the number of subscribers in North America.
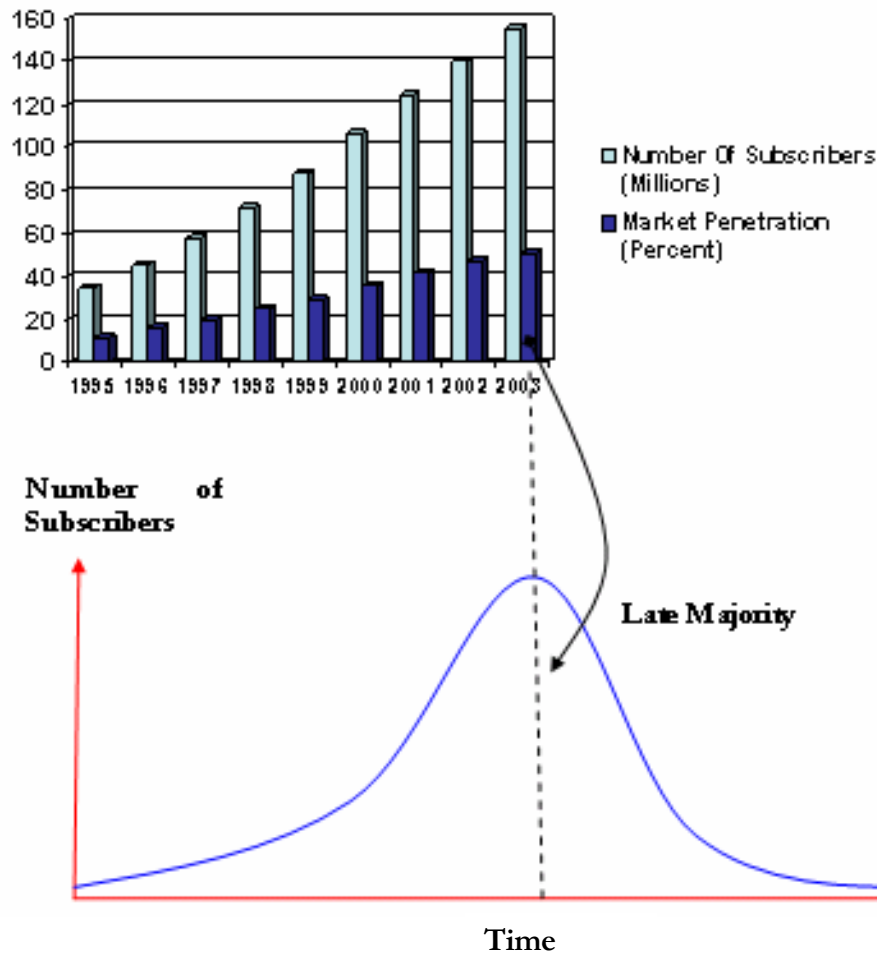
Figure 16  North American Wireless Subscribers

This diffusion, when superimposed on the Technology Adoption Life Cycle Model, currently includes the Early Majority and would be moving towards the Late Majority at the end of 2003 when the projected market penetration is 51 percent. The determinants of diffusion in this dimension are **Cost, Capacity and Spectrum allocation**, which would determine the economics of optimum service expansion [13].

### 3.3.2 Cost

The Network operators are very sensitive about the cost of upgrading their networks, where the projected capacity crunch is about 2 years away, based on the current infrastructure. The cost would have a specific impact on the Diffusion of a particular type of network (CDMA, TDMA, and GSM). CDMA has a higher initial cost, which would make the GSM, TDMA upgrade option attractive to the carriers in the near term. This makes it imperative to calculate the cost and value of embedding a flexible design option. The cost is part of the "resource attribute of transferring" as shown in Figure 5 OPD Representation of Flexibility:  Capacity and Performance Flexibility. The methods to calculate this cost and value are explored in Chapter 5 and Chapter 6.

### 3.3.3 Capacity

The wireless carriers (network operators) want to ensure that they can continue to support their existing subscribers (and continue their subscriber base expansion), before introducing the high bandwidth value added services. The voice service is a proven revenue source – data is not yet. This is an important determinant that would affect the diffusion of wireless network as a whole, where the subscribers are demanding or would demand value added applications (Market Demand).The network capacity in terms of total number of subscribers will directly map into the Capacity dimension of flexibility and is part of the "capacity attribute of transferring" shown in Figure 5 OPD Representation of Flexibility:  Capacity and Performance Flexibility. There is a dimension of performance, which will be related to the peak call rate supported by the network,

which is also part of the overall network capacity, and will be part of the "performance attribute of transferring".

### 3.3.4   Spectrum

The current spectrum restriction per carrier (45 MHz) in particular market limits the market penetration – and thus diffusion in that market. This is therefore part of the "resource attribute of transferring" as shown in Figure 5 OPD Representation of Flexibility:  Capacity and Performance Flexibility.

### 3.3.5   Value Added Applications

The value added applications would increase and sustain the subscriber's base.
Some of the applications facilitate increased air time usage, increasing the ARPU (Average Revenue per User).

#### 3.3.5.1   *Applications – driving the future*

With the industry still looking for the "Killer Application" and innovative startups coming with customized value added applications, to help the network operators capture and retain new market segments once the Chasm [8] between early adopters and early majority is crossed.

Some of the value added applications like Wireless Messaging have expanded the subscriber base to a totally new market segment e.g. the school going teenage segment. These applications are extremely popular in Europe and Asia and are catching up in popularity in the US, where network interoperability issues had prevented the diffusion

of these applications in the past (which have been resolved now). These applications will map into the functional dimension of flexibility.

## 3.4    Wireless Handset Processors

The next generation wireless handsets are growing increasingly complex. The existing battery technologies have not been able to keep in pace with the advancement of circuit technology and power demand of these handsets. The current trend to temporarily solve this problem is to make the handset more "fuel efficient" using system level energy conservation methodologies [28]. It is predicted that a 5X improvement in battery life is achievable by carefully applying these methodologies.

A visible trend in the market is the evolution of wireless PDA's and camera phones. The convergence of the PDA's with cell phones is leading to increased power demands for these complex handheld devices  There is also a trend of migration of increasingly complex PC based office and multimedia applications in these handheld devices.

There is a high possibility of increasingly complex mobile applications, becoming popular in the future. The system level energy conservation methodologies involving dynamic frequency and voltage management, pioneered by Intel, might not be sufficient to keep up to the demands of such applications in long run. Strategic alliances between DSP and RISC houses (as seen by the recent alliance between Intel and Analog devices for PXA 800F which targets the GSM/GPRS data application segment) are indicators of technological trends to address this issue.

In this section, the determinants of diffusion for low power and high performance processors in the wireless segment are explored after analyzing the whole wireless application value chain. This analysis is used to predict the optimal features of such processors (for the next few years), which is critical for early market penetration in a

segment that is predicted to be larger than the desktop segment in a few years. These features would be analyzed from the three flexibility dimensions – Functionality, Performance and Capacity.

## 3.5 The Value Chain

The value chain for wireless applications is shown in Figure 12 Wireless Value Chain. The primary concern of the Mobile Network Operator's (MNO's) today is voice service, which has the lion's share of the current MNO revenues.

## 3.6 End Users

The end user adoption of the wireless applications has not been consistent across the globe. There are distinct geographical patterns that have emerged, like the adoption of 2.5/3G applications in Japan (MOVA/FOMA), SMS applications in Europe and Asia and a lack of adoption of either of these applications in North America.

## 3.7 Applications Service/ Content Providers

Figure 12 Wireless Value Chain, shows Application Service providers parallel to the MNO's in the overall value chain. The Application Service / Content Providers can be also depicted downstream in the value chain after the MNO's. Since the voice service, which is of primary importance in the overall value chain, is directly provided by the MNO's, the parallel representation is chosen for this report.

There is however, a considerable influence of the MNO's on the value proposition of the Application Service / Content Providers. For example, interoperability was a key issue

that limited the diffusion of SMS applications in US. Similar issues (which are discussed in the next section) could influence the adoption/diffusion of future wireless applications.

In this section, wide categories of future wireless applications are explored. These applications are currently in different stages of development. in companies all across the globe.

### 3.7.1   Security Applications

These applications would enable remote access of the mobile computing devices, if the device is lost or stolen. If the device is stolen, it can be activated remotely to "report" mode where it transmits its location to the owner (source: Intel.com)

If the device is lost, the hard drive can be remotely locked to protect critical data. The device can be recovered by activating the "report" mode.

Currently the users of complex mobile computing devices prefer to turn these devices off to conserve battery power. The security applications would need these devices to be "always on" in an analogous mode of Cell Phones, which are also always on to receive data on the control channel (e.g. handoff, incoming call etc).These advanced devices would operate in semi-standby mode and would be location aware.

This would put substantially higher standby power requirement, – a demand that has to be fulfilled partly by a low power monitoring core loop, typically running on a DSP.

### 3.7.2   Gaming Applications

Currently online games can only be played with a PC, although the 128-bit consoles were all developed with some kind of internet connectivity in mind. This market, currently generating revenues of about $152.2 million annually, is affected by the slow rate of broadband adoption [31].

Like online gaming, wireless gaming has the attention of many in the industry, and could cause significant diffusion of wireless data services due to huge network effects.

At the present time, however, most wireless games have primitive graphics. Introduction of better mobile computing processors will make the wireless graphics comparable to the PC consoles. These applications would be very computation intensive and would be a driver of reduced power consumption.

The battery life of basic PDAs with a monochrome screen can be weeks, but as soon as the devices are more sophisticated, with color display and wireless connectivity, battery life can be as short as two or three hours.

Processor power consumption typically accounts for approximately 7 percent to 10 percent of total notebook power consumption, while the LCD, chipset, and graphics consume the most power on a percentage basis at approximately 30 percent, 13 percent and 10 percent, respectively[4]. This data indicates that in the segment of gaming applications, low power CPU would have to be complimented with efficient displays and system level power optimization techniques.

### 3.7.3   Location Applications

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[4] source : Intel.com

The next generation location applications would involve "digital solicitation", where an individual's computing devices would represent his or her interests and would seamlessly interact with the environment, looking for promotions and negotiating offers.

An example scenario is that if you are in the market for a particular type of digital camera, you input your preferences in your wireless computing device, with the price you are wiling to pay. When you go to a mall – your device interacts with the retail outlet "promotional computer" and informs you if such a camera is available.

These applications need a lot of background computation, increased drain power and thus need for low power computation.

### 3.7.4   Multimedia Applications

There is a big potential of video/news on demand applications, which would be very popular with business travelers. One could download a movie in his or her laptop or the latest NBC news clip in his of her handheld computing device. These multimedia applications are again computation intensive causing a demand for efficient, low power processors.

Streaming Multimedia applications like video conferencing and broadcast applications like picture sharing would also need low power multimedia decoding, typically suited for a DSP processor.

*Mobile Network Operators*

**Evolution Path**

The evolution path of the TDMA, CDMA and GSM networks is

shown in

Figure 15 Evolution Paths of TDMA, GSM and CDMA. In US, Wireless Networks based on all three standards, have national footprints.

There are two possible Networks upgrade paths – first is a direct 2.5G-3G upgrade, which costs less than the 2G-2.5G-3G upgrade. Since the recent downturn of the telecom industry, the MNO's have delayed their 3G network deployment and have chosen a 2G-2.5G network upgrade as a stop-gap solution, which will cost considerably less than 2G-3G upgrade and would start the diffusion of low bandwidth data applications.

As a case study, there are two known 3G network deployment in Europe – Mobikom in Austria and 3 in UK and Italy. Both the networks are grossly underutilized and the operators are now offering 3G connection at the same price (or even less as part of promotions) of the conventional 2/2.5 G networks.

Learning by the example of European MNO's, it is likely that the North American MNO's delay their 3G rollout plan. This was indicated by AT&T's announcement to delay their 3G rollout and announcement of their network upgrade to 2.5G (GPRS) last year. 2.5G services are widely available in the US today.

As mentioned earlier, the primary concern of the Mobile Network Operator (MNO) today is the voice service, which has the lion's share of the current MNO revenues. The data applications would be used as a differentiating feature for a few years, to reduce churn,

rather than a dominant revenue source. Interoperability issues like inter-network GPRS roaming, has to be resolved, and can effect the diffusion of data applications.

## Bundling Strategy

There is a trend in European MNO's (Vodafone and Orange), to have strategic alliance with relatively unknown handset manufacturers (in the current market), which enables them to command a lower price and thus less handset subsidization costs. An example is

Similar trends are likely for North American MNO's, making it imperative to identify these handset manufacturers (from the point of view of design wins of mobile handset processors).

## Data Rate

The data rated supported by currently deployed GPRS solutions, as evaluated by Intel, is 53.6 Kbps (source : Intel.com). 1xRTT supports data rate of 40-70 Kbps. Thus applications that can be deployed on this bandwidth are likely to initiate the diffusion of data applications in the wireless networks, in next few years.

### *Handset Manufacturers*

The Asian wireless market had around 100 million 2.5g handsets last year which is predicted to ramp down to 5 million handsets by the end of 2007. 3G handsets are expected to ramp up from 2.5 million in 2003 to 128 million in 2006 [29] see Figure 17 Asia Pacific Handset Sales.

The 2.5G and 3G handsets are predicted to change their dominant status sometime in 2005. NEC, which is the leading handset vendor, has an emphasis on 2.5 G handsets.

# Asia Pacific Handset Sales(Millions)
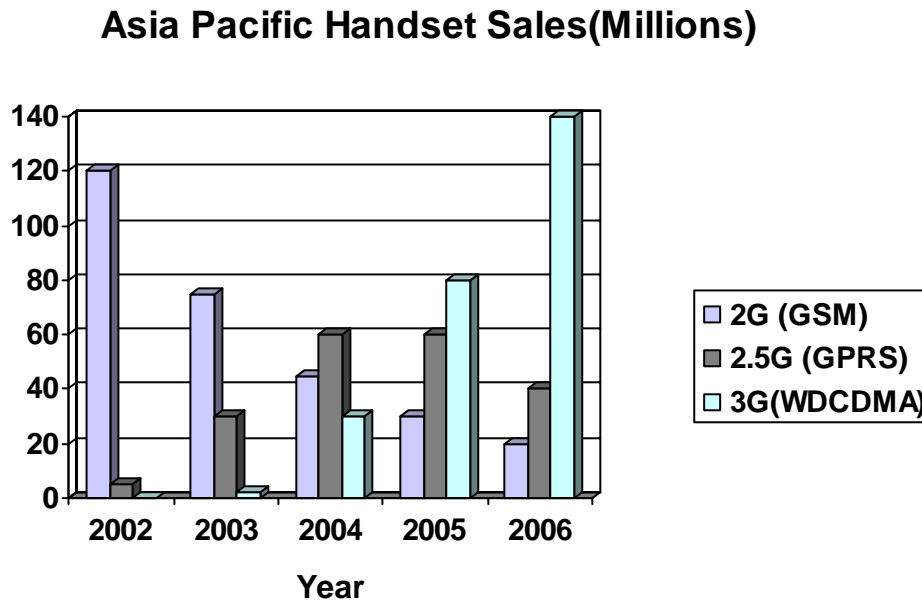


Figure 17 Asia Pacific Handset Sales (Data source: [29])

There is a very high likelihood that similar trends (2.5G handsets dominating the market for the next few years) is followed in the European and North American markets, where 3G network deployments is not as extensive as in Asia.

## 3.8 Processor Manufacturers

As indicated by the application trends, the performance of a processor used in handheld platforms needs to be optimized for both dynamic power consumption as well as standby power consumption. The definition of standby operations in wireless platforms includes monitoring of control channels.

Smaller device geometries result in greater packing densities and lower device switching capacitance which is proportional linearly to the device capacitance. This increases the standby current with every process generation. The handset segment, which typically relies on smaller geometry than desktop segment, will impose a stringent power requirement on desktop processor segment players like Intel.

The wireless application segment is a unique mix of the traditional DSP applications and Desktop applications. , shows the two distinct feature migration path, where dominant players in the desktop application segment, are focusing their efforts in power reduction. The traditional DSP houses are focusing their efforts in making their processors competent to handle complex interfaces (including user interfaces).
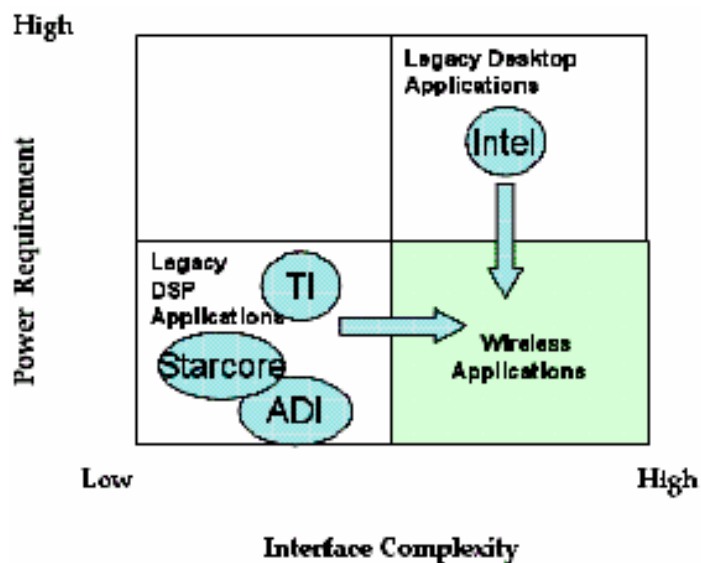


Figure 18 Migration Strategy of key players in the
wireless processor segment.

## 3.9 Approach 1 – Reduce the power

With increasingly complex mobile applications becoming popular, this approach relies on usage of design optimization methodologies to reduce the power demand. It is predicted that a 5X reduction in power consumption is achievable by carefully applying these methodologies. Intel's Dynamic Frequency Management (DFM) and Dynamic Voltage Management (DVM), has been able to reduce power consumption in the Laptop Segment. Incorporating these features in their Personal Internet Client (PCA) architecture is also part of this effort.

Intel has also augmented the system level power management with strategic alliance with Analog Devices, a leader in the DSP segment. Micro Signal Architecture, Jointly developed by Intel and Analog Devices, incorporates the system level power management, GSM/GPRS stack on DSP, Xscale processor and Flash in a singe chip.

## 3.10 Approach 2 – Enhance Interface Complexity

In this approach, the traditional DSP vendors have enhanced their offering by augmenting a low power RISC based I/O processor or an ASIC. TI has followed the System on Chip model by augmenting RISC with their DSP cores for their OMAP™ Architecture. Starcore has similar model for augmenting their DSP core with a RISC based I/O core as their solutions targeted for SOC segment.

**The Future**

Based on the analysis of the Wireless Application value chain from the context of evolution of wireless networks and diffusion of wireless handsets in the US Markets in the next few years, we can conclude that –

- It is more likely that the MNO's in US would follow a (2G - 2.5G – 3G) network upgrade path, than a (2G – 3G)upgrade path.
- The 2.5 G data rates are in the range of traditional 56Kbps dialup connection (GPRS data rates of 53.6 Kbps, and 1XRTT data rates of 40-70 Kbps).
- Interoperability issues are unlikely in the diffusion of data applications as these applications will be TCP/IP based. This will provide substantial network effects. Issues like GPRS Roaming have to be resolved to realize the full potential of data applications.

**Determinants of Diffusion**

- With a bandwidth of around 56 Kbps, the future applications (described in the Application Service Provider section) should be individually assessed for their practical field requirements and these requirements should be formally translated to technical specifications using tools like Quality Function Deployment [1674]. A detailed requirement analysis is beyond the scope of this thesis , but a representative subset of the relevant requirements for near-term diffusion are –

- Efficient Low bandwidth multimedia streaming algorithms should be developed by the processor manufacturers.

- Evaluation and Optimization of low bandwidth digital video codec like H.264 (H.26L), should be performed for mobile handset processors. Microsoft and Nokia's support to the standard and absence of Intellectual Property issues may cause a rapid diffusion of this standard.

- Existing processor architecture can be optimized for better performance for low bandwidth codecs.

- Audio only streaming applications are suited for the identified 56Kbps bandwidth. Applications for downloading and playing MP3 would necessitate optimized MP3 decoder implementation for the handsets

- Real – time multimedia applications like video conferencing could be augmented by relatively lower bandwidth non-real time applications like picture sharing using compression protocols like JPEG-2000.

- High bandwidth codec like MPEG4 is the likely option for 3G bandwidths and thus the optimization of processor performance for MPEG 4 should be in the logical roadmap for the processor vendors.

From the context of wireless handset processors, all these requirements fall in the category of performance optimization. The performance of a processor, with respect to a particular application (like digital video codec) is usually represented in terms of number of clocks cycles expended. The driver of performance flexibility can be determined by the contributors of these cycles. Size of the on-chip cache, for example is one of the drivers of the performance. This is because; cache misses (especially instruction cache) cause a significant amount overhead, which can be reduced by increasing the size of the on-chip

cache. Flexibility analysis, as described in this thesis,  can be used to determine the optimum size of this cache, which could be relatively small for still – picture based applications (based on JPEG) and has to be relatively large for high bandwidth digital video codecs (like MPEG).

**Conclusion**

The study of wireless networks shows that in the future, the diffusion for wireless networks would continue to be guided by value added applications, within the Cost, Capacity and Bandwidth Framework. The value added services would be used by the wireless network operators to reduce churn. These services would determine the new Performance criteria in the Wireless Industry S Curve – extending the current S-Curve, which is in the maturity stage. With respect to wireless networks, it was seen that:

- Cost, Capacity, Bandwidth and Value Added Services (VAS) are indicator of the trends in the industry and thus would drive the flexibility dimensions. These tends would give rise to a mathematical volatility model, which has to be assessed to calculate the value of embedding flexibility.

- The Network Capacity will drive the Capacity dimension of flexibility.

- Spectrum allocation and Cost are the resource attributes that would define the constraints

- The applications (VAS) will drive the Functionality dimension of flexibility.

The study of wireless handset processors indicated that in next one or two years, low bandwidth (56Kbps) applications would drive the diffusion. Performance optimization of the processors, with respect to the computationally intensive cores (e.g. streaming digital video codec like H.264) of these applications will drive the performance dimension of flexibility for the handset processors.

In the original definition of the non orthogonal dimensions of flexibility were defined as:

**Functional flexibility** can be expressed as the ability to either affect different types of processes on the same operand, or to affect the same process on different types of operands, see Figure 4 OPD Representation of Flexibility: Functional flexibility. From the context of wireless network applications and handsets, this would map into the ability to perform additional (or a range of) functions.

**Capacity flexibility** is related to the quantity (amount of) operand see Figure 5 OPD Representation of Flexibility: Capacity and Performance Flexibility,  and will be defined by the Capacity attribute of transferring .From the context of wireless network applications and handsets this would map into (among other features) the ability to handle additional (or a range of) quantity of interactions.

**Performance flexibility** can be understood as the difference between the changed state and the desired state and has a 'rate' component. This would be defined by the range of the Performance attribute of transferring, see Figure 5 OPD Representation of Flexibility:

Capacity and Performance Flexibility . From the context of wireless network applications and handsets this would map into (among other features) the ability to handle additional (or a range of) interaction rate.

Critical analysis of Wireless Networks and Wireless handset processors indicate that all the short and long term determinants of diffusion can be represented along these dimensions. This analysis shed light on the case of "Forward Flexibility" where the objective space identified was "in addition" to the existing operating space (e.g. higher processor performance and network capacity).

There are cases in the industry where "Backward Flexibility" strategies have been successfully implemented, to capture the lower end of the existing market (e.g. Intel's Celeron Processor). These strategies are feasible when there is low or negligible incremental production penalty for a flexible product.

The classification of the individual features in these categories (Functionality, Capacity and Performance) would enable us to perform a three dimensional trade-off analysis along these dimensions, with the resource constraints, and access the value delivered due to flexibility.

In the next chapter, we will explore a specific method to embed flexibility (from the context of wireless network) by building a generic model that could be used to represent most of the nodes in a wireless network, incorporating capacity, performance and functional flexibility.

*C h a p t e r   4*

# Embedding Flexibility

## 4.1 Introduction

In this section, the three dimensions of flexibility investigated in further detail, with respect to wireless networks. In particular we will investigate "how" flexibility can be embedded in wireless networks and handheld device processors in particular. In essence this is creating the real options portfolio. Before finding cost and value we have to understand what the underlying asset actually is. We have, in the last chapter, identified the needs and set the goals for 'flexible" architecture, from the context of Wireless Networks and Handset Processors. In this chapter we focus on the implementation, i.e. Form of the implementation of flexibility or "embedding "flexibility as shown in Figure 19 Focus of Chapter 4.

This analysis is done with the example of two Network based Wireless Applications, which primarily provide the "Functional Flexibility' dimension, which was identified as one of the determinants of diffusion in the last chapter. These applications were chosen because they can be used to demonstrate all the three dimensions of flexibility from a relatively simple context.
 It is then shown that the three dimensions of flexibility can be realized using the concept of a distributed architecture (for wireless network applications).
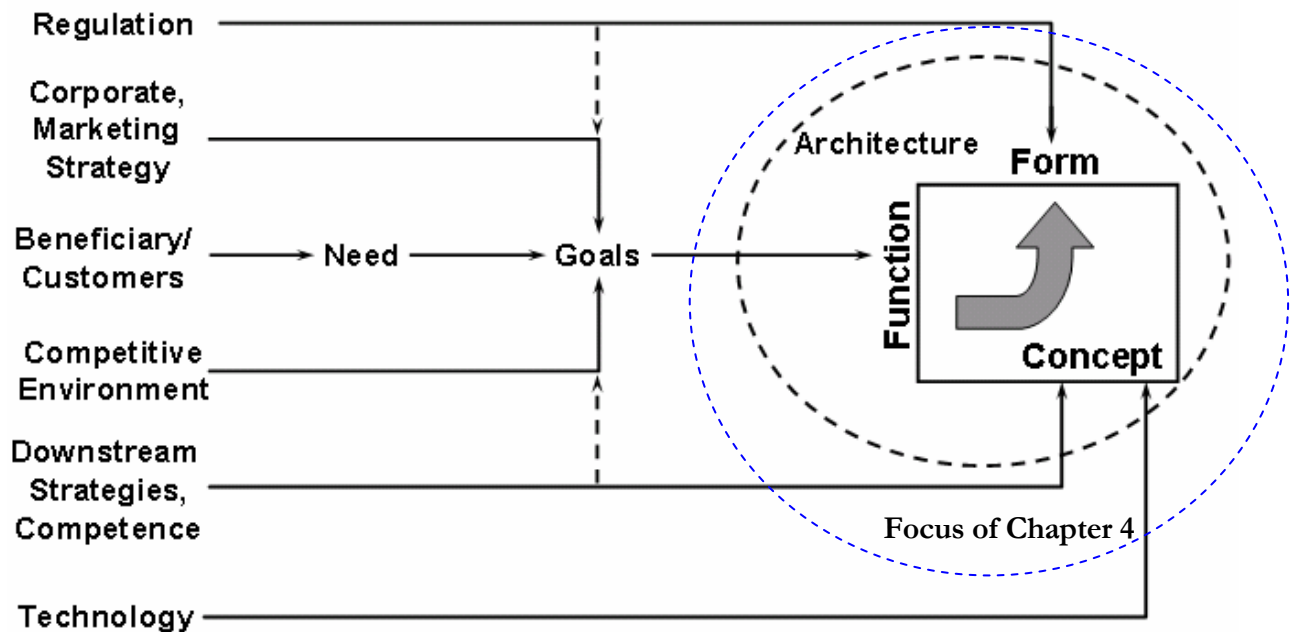
Figure 19 Focus of Chapter 4 (adapted from [4])

## 4.2 Functional Context

The basic functional context of the different nodes in the wireless network is to interact with each other using defined protocols and perform the required functions. There is a separate class of applications which passively monitor these interactions and enable value added services – e.g. Monitoring the network and providing feedback on re-configuration (e.g. add more voice trunks on the congested routes) .One of the commercial applications is to detect international roamers and send customized messages (like exchange rate – Local weather forecast etc).Our study of flexibility will start with this context and the

generic model developed would be expanded to represent all the nodes in a wireless network.

A brief overview of the architecture of wireless networks and description of the nodes is provided in the next section.

## 4.3 Network Architecture

A simplified form of the wireless network is shown in Figure 20 Simplified (2G) Wireless Network
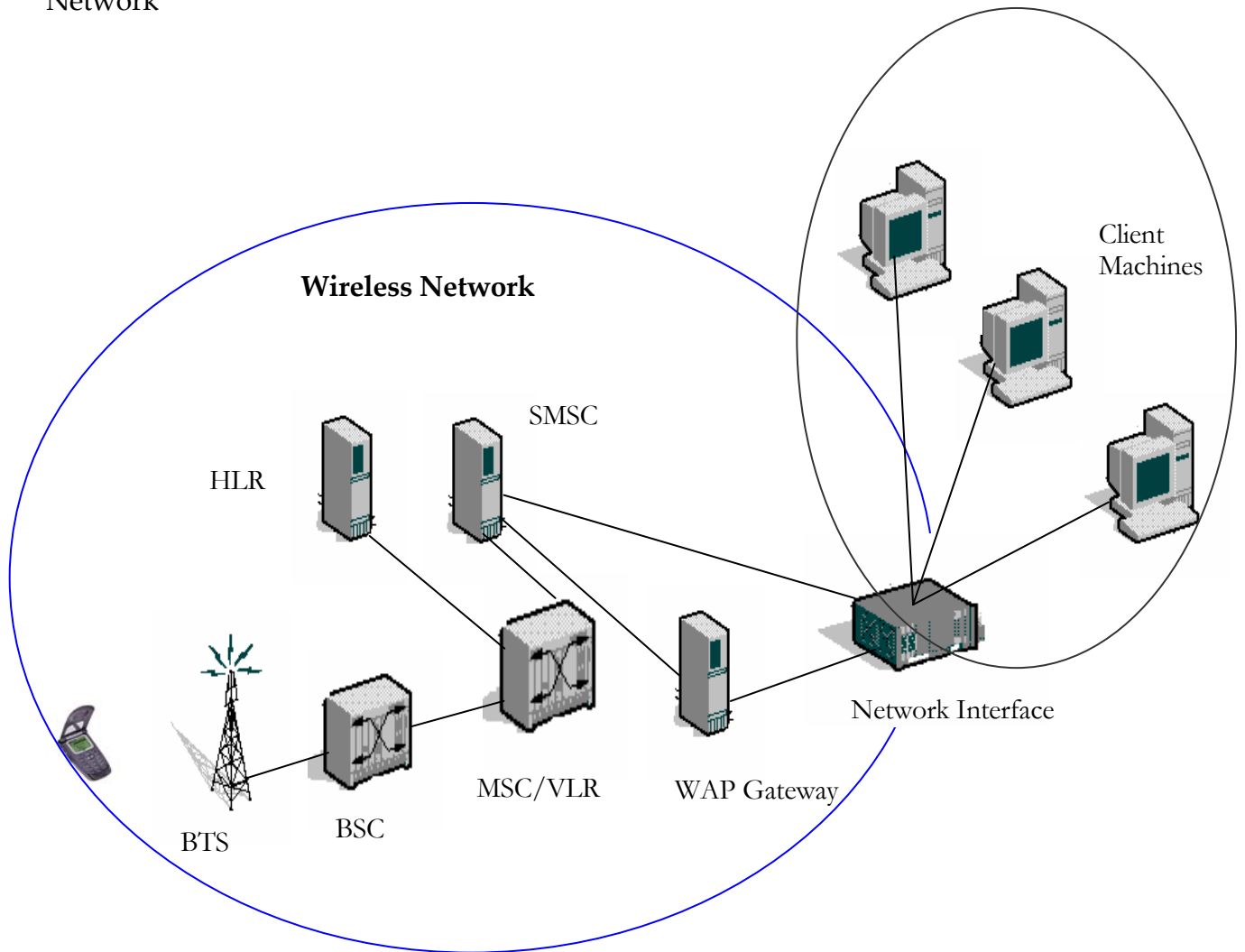


Figure 20 Simplified (2G) Wireless Network

**Cell** – is a geographical unit with a dedicated scheme of RF interaction with a wireless user. For GSM and TDMA networks, the adjacent cells have different operating frequencies. For CDMA networks they have a different code. Cells are typically visualized as hexagonal, but in actual practice my be of any arbitrary shape based on the desired coverage location (e.g. Highway) or call density (e.g. NYSE). The two key components of RF planning are the call volume (based on BTS-BSC capacity) and geographical extent of desired coverage. Networks are not designed based on only the peak call volume as it would lead to underutilization of the resources. The network design is usually based on the average and peak call volume in a cell, within the expected quality of service.

**BTS** – is the base station that provides the RF connection with the handset. It is a transreceiver. There is typically one BTS for a Cell.

**BSC** – is the bas station controller, having access to multiple BTS. In some networks the Base stations are directly connected to the switch.

**MSC** – is the Mobile switching center – which has access to multiple BTS and performs the switching function of a call and "hand-offs" between BSC's or between switches (if a user roams to a cell covered by a different switch.

**HLR –** Home Location Register is a database server that has subscriber information. There are other servers in the networks (not shown in the figure) e.g. EIR for Equipment Identification and authentication, VLR for visitor (roamers) data.

**SMSC** - The SMSC is the Short Message Service Center and interfaces with the internet using multiple schemes – one of them shown in the figure uses a Network interface server to interact with the users through internet (e.g. WEB based SMS).

## The Protocols/Standards

Within a wireless networks, there are two categories of standards *Access Standards* for example CDMA (IS-95) TDMA (IS-54,136), and *Network Standards[5]* for example (BSC - MSC (Proprietary, IS-631), and MSC to MSC, VLR, HLR, SMSC standard (GSM-MAP, IS-41, ISUP, TCAP). Modular Innovation [10] is common in the Network standards (Additions to ISUP, TCAP and upgrade of IS-41 from IS-41 B to IS-41C). The latest upgrade to 2.5 G networks in GSM-MAP, involved adding of two additional network nodes (GGSN and SGSN) and upgrading the GSM-MAP standard (equivalent of IS-41 for CDMA/TDMA) , as part of the  GPRS evolution as shown in

Figure 15 Evolution Paths of TDMA, GSM and CDMA.

## 4.4    The Dimensions

The application platform architecture used of our analysis, which can be used to represent the architecture of any of the nodes that are described in the preceding section,

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[5]  Access standards define the interface and protocols between the wireless handset and the wireless network. Network standards define the interface and protocols between the different nodes in a network.

has three layers as shown in Figure 21 Application Platform Layers. A State Machine (SM) is used to represent a deterministic finite state automaton.

1. Protocol interface – Provides active and passive[6] data to the Protocol SM's.
2. Protocol State Machine – Generates triggers for Application SM based on the events (messages) of on or many protocols.
3. Application State Machine – Performs functions based on the triggers received from Protocol state machine.
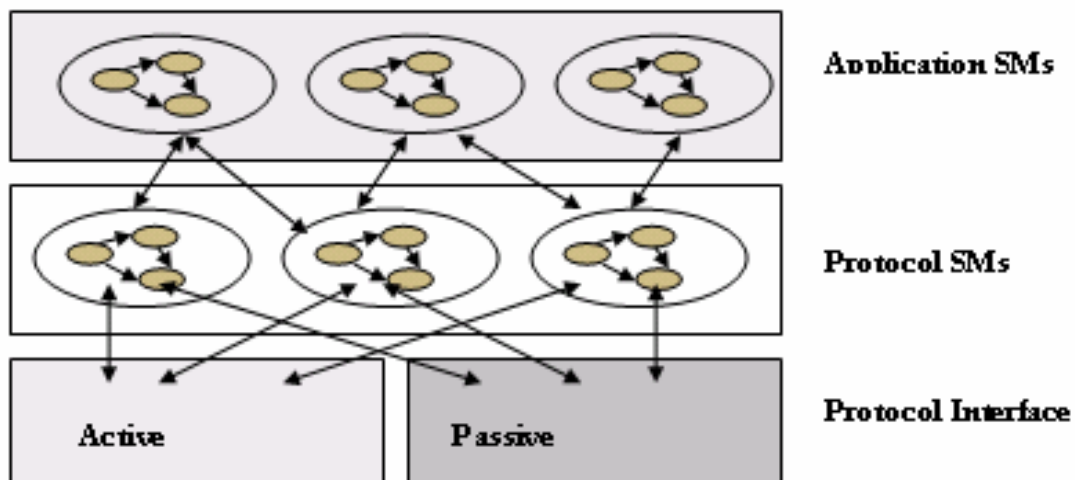


Figure 21 Application Platform Layers

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[6] The data in this case is the information exchanged as part of one or many protocols. If the node is an active participant in the protocol data , the data interface is called active data interface , else if the node gets this data in a passive or "monitoring" mode , the data interface is called passive data interface.

An application state machine can be visualized a standalone application doing a specific task. There would be specialized interfaces to these applications not shown in the diagram – like voice trunks in case of switches. We would include these interfaces in our generic description of systems in the next section.

Another example of a point solution can be "send e-mail to the charging network with call details for all abnormally terminated calls"

This configuration can be used to this platform to function as a MSC, HLR, VLR, EIR, and Application server , which were described in the previous sections.

**4.5    The State Machines**

In Figure 21 Application Platform Layers, we can theoretically extend the functional flexibility of the platform using one consolidated state machine that takes care of ALL possible application scenarios and ALL possible protocols. The two levels of state machine mitigates some of the issues that would be associated with a single state machine implementation -

**Complexity**: there are too many input events for a consolidated SM, which is a union of all protocol events e.g.

N = (ANSI ISUP Events) U (ITU-ISUP Events) U (MAP Events) …… U (IS634 Events)

If the total states is in the order of N. Total Number of Handlers to be implemented = $N^2$

Here N is in the order of 500 thus the handlers are on the order of 250,000.

If we add the number of states of the combined application – the solution becomes even more complex.

**Dormancy**: Many Handlers would not be used for current Point Solutions/ Solutions.

**Configuration**: In terms of a software realization, we can see this configuration as assigning a handler "function", for each state transition. Configuration of the Handlers becomes a big task because the total number of handlers is very large.

## 4.6    Flexibility Dimensions

Exploring these dimensions, a generic model was derived as shown in Figure 22 Flexibility Model of a System , which is the high level architectural realization of Network based Wireless Applications.

## 4.7    The Model

The model shown in Figure 22 Flexibility Model of a System  will be analyzed for a specific example a value added application[7], where the functionality of this application expanded and its capacity and performance are increased. The realization of this example would throw light on how the functional, capacity and performance flexibility can be "embedded" in similar network based wireless applications.

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[7] Value added applications were identified as one of the determinants of diffusion  for wireless networks in Chapter 3.
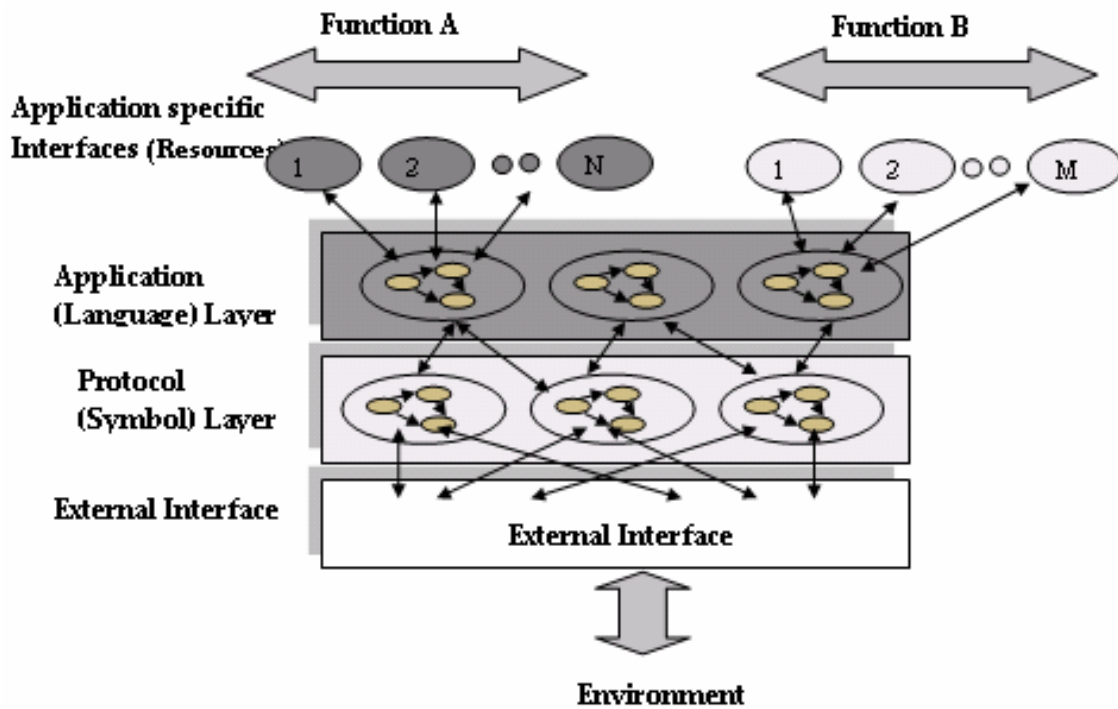
Figure 22 Flexibility Model of a System

Our example application, Application 1, re-connects dropped calls in a wireless network. A high level intent- process-concept diagram of the application based on Crawley's OPM framework [4] is shown in Figure 23 Intent-Process-Concept diagram of Application 1.

The intent of reducing the dropped calls is realized using the process of reconnecting such calls, by monitoring the signaling information and restoring the context of the dropped calls using Computer Telephony interfaces.
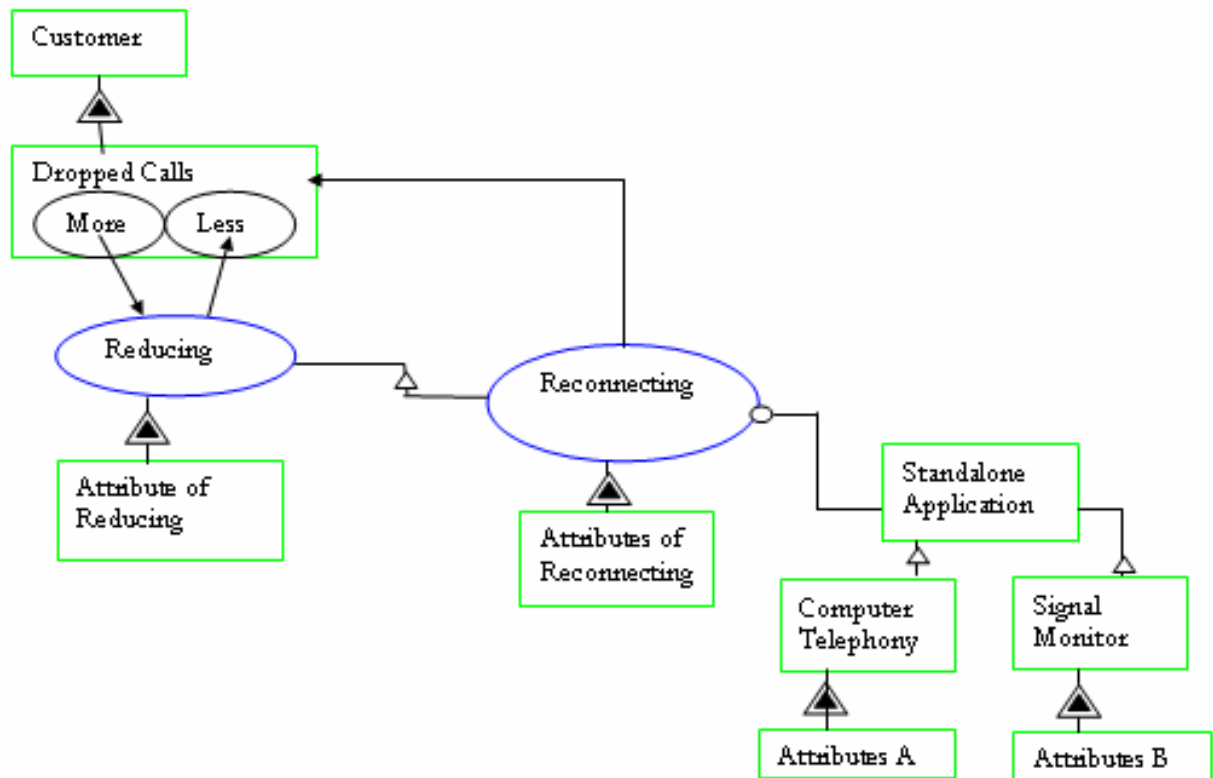
Figure 23 Intent-Process-Concept diagram of
Application 1

The Attribute of transforming in the primary intent (which in this case is reducing dropped calls) , the selected process (which in this case is re-connecting dropped calls), and the operating intent will drive the  form related attributes (Attributes A and Attributes B) as shown in  Figure 24 Application Attributes.

| Attribute | Category | Unit |
|---|---|---|
| Connection Latency | Performance | sec |
| Call Capacity | Capacity | Telephony Channels |
| Cost | Resource | $ |
| MTTF | Performance | years |
| *Maintenance cost* | *Performance* | *$/year* |
| Physical footprint | Resource | H x W x L and lbs |
| Power consumption | Resource | KW |

Figure 24 Application Attributes

The attributes compiled from the primary intent, process and operating intent for Application 1, and their units are shown in Figure 24 Application Attributes. The classification of the attributes in the three categories – Performance, capacity and Resource, provide an practical insight of the theoretical context presented in Chapter 3, Figure 5 OPD Representation of Flexibility: Capacity and Performance Flexibility.

It was interesting note that the attributes with a time component do conform to the traditional definition of performance.
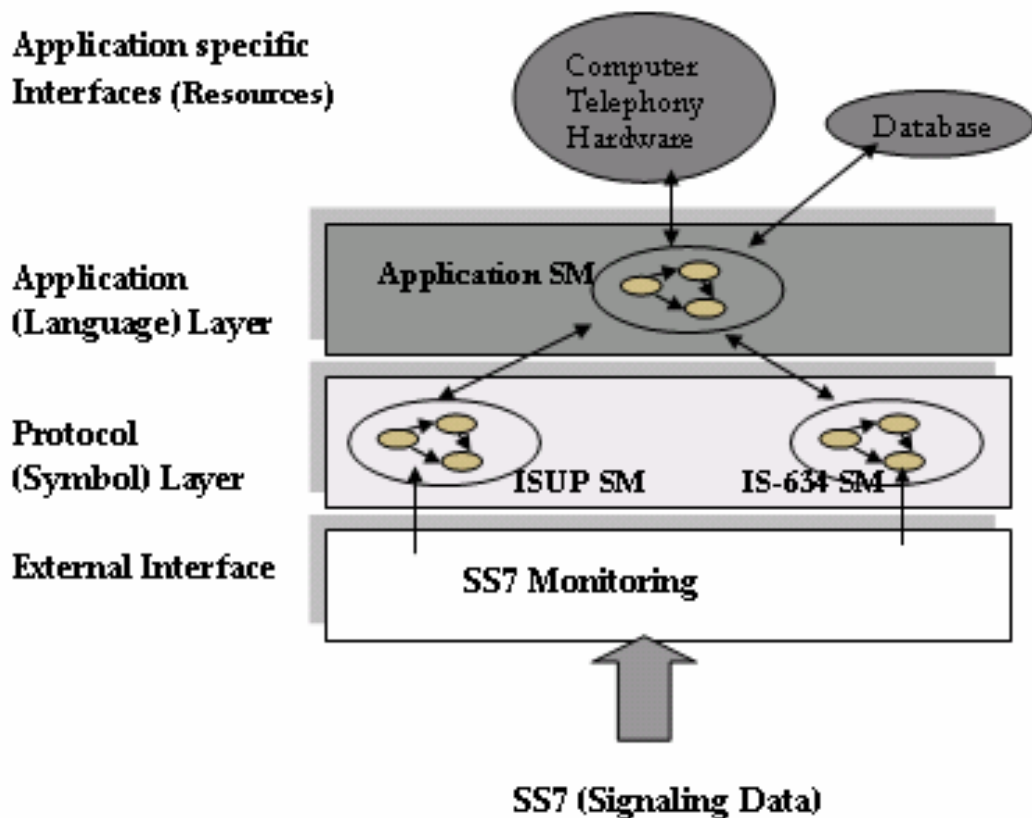
Figure 25 Architectural Form of Application 1

The connection latency, which is an obvious performance attribute, depends on the rate of primary attribute transforming (i.e. how fast the dropped calls are reduced. The Capacity attribute relates to the volume of the dropped calls. The architectural form of Application 1, based on the model described in Figure 22 Flexibility Model of a System , is shown in Figure 25 Architectural Form of Application 1.

Application 1 can be implemented by monitoring the IS-634 and ISUP Messages, which have the call termination information. The External Interface monitors the signaling link and extracts all the SS7 messages. The Protocol extracts the specific messages (Symbols) that are required by the application from the SS7 signaling data, which in this case are some specific IS-634 and ISUP messages.

The Application layer SM, correlates these messages and for the cases the call was abnormally dropped due to radio resource, initiates a two way call through the computer telephony interface to the caller and called party and patches the call. This is done when the wireless user re-enters the network (comes out of a blind spot). This restores the context of the call.

**Functional Flexibility** was defined as the ability of a system to perform additional tasks under a changing set of requirements or operating conditions. In Application 1, we can expand the functionality by sending an SMS with the dropped call details (called number and time the call got dropped) to the subscriber, who can follow up on the call at his convenience. This can be enabled by allowing dynamic addition of a new Application State machines, or enabling some dormant states of an existing state machine. An additional resource of SMSC connectivity is required for this added functionality as shown in Figure 26 Architectural Form of Application 1 with Functional. These "slots" have to be designed as part of the flexible system architecture and can be populated at a later time to achieve functional flexibility. This is similar to the extensibility "master plan" described in [9].

**Capacity Flexibility** could be defined as the capacity to address an *additional (or a range of) volume* of interactions. This would be defined by total number of simultaneous conversations taking place. In the example of Application 1, for example, if it takes 1Kb of data to store the context of the call of one subscriber, the database size would be 1GB for 1 Million subscribers and 2GB for 2 Million subscribers. To increase the capacity of the application from 1 Million subscribers, to 2 Million subscribers, the database has to be scaled accordingly.
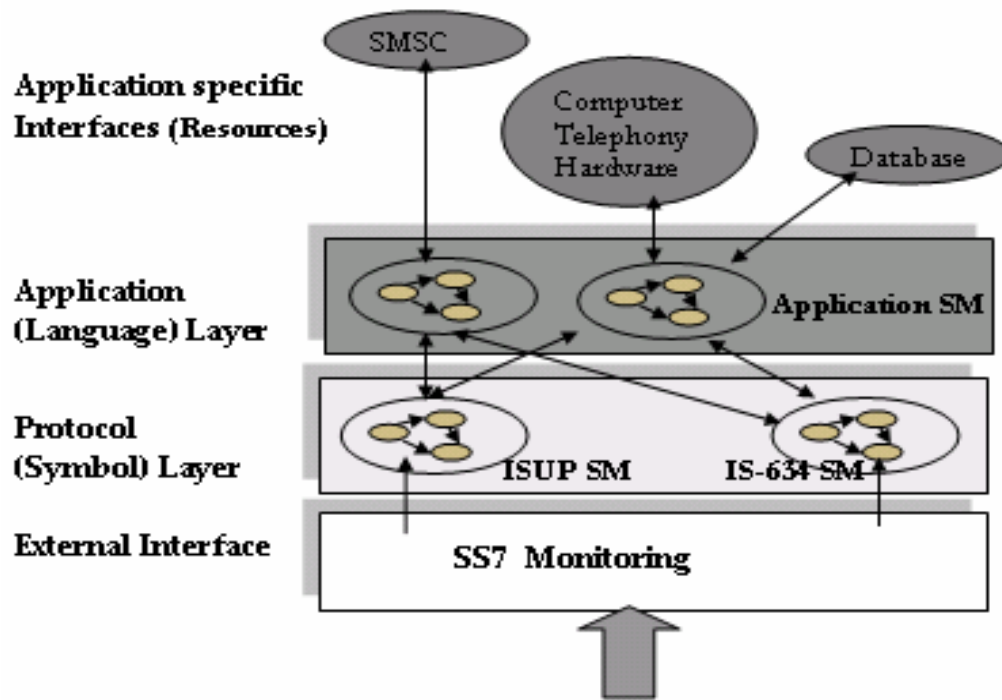
Figure 26 Architectural Form of Application 1 with
Functional Flexibility

This can be achieved by using a scalable data storage network as shown in Figure 27 Architectural Form of Application 1 with Capacity Flexibility.
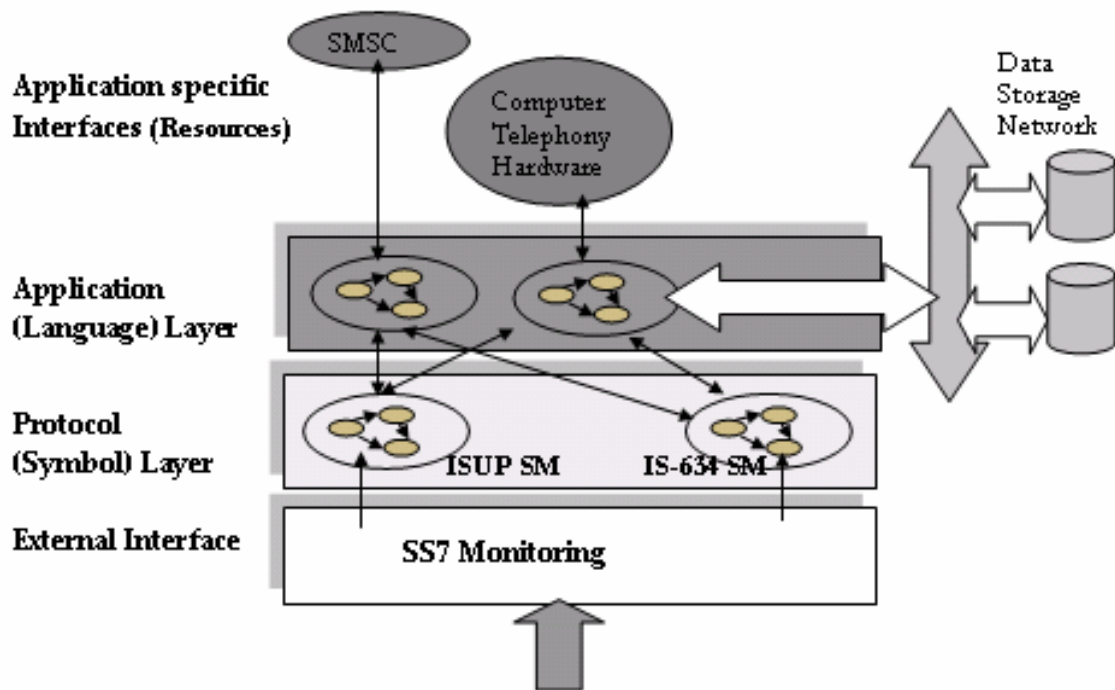
Figure 27  Architectural Form of Application 1 with
Capacity Flexibility

Thus, this dimension depends on the capacity of the persistent device that gives memory to the state machine – e.g. Enterprise Storage Arrays, Memory, and Flip Flops.  The interface to a scalable data storage network falls in the category of Extensibility as explained in [9].

**Performance Flexibility** could be defined as the capacity to address to *additional (or a range of) rate* of interaction. This would be limited by the rate and duration of the conversations taking place using the same amount of resources.  This dimension depends on the effective bandwidth of input and output from the system for an I/O constrained application and the CPU processing bandwidth for processing constrained applications.

In the example of Application 1, the connection latency, or the latency between the time the call is dropped and it is re-connected, was identified as a performance measure, based on the primary intent and process attributes in Figure 24 Application Attributes.

This latency will drive a lot of design parameter, but at a high level, this latency will depend on how "quickly" the application can acquire, retrieve, process and update the state information of a transaction (or call). This means, we have to plan for scalability across all these operations, to have performance scalability. Analyzing these operations in detail we find that:

**Acquire** operations depend on the Input/Output bandwidth. This aspect of the performance has to be resolved using a scalable I/O interface.

**Retrieve and update** operations depend on the database. For example it would take higher average time to query a database of 2 Million users, than 1 Million users (using the same indexing strategy). This aspect of the performance has to be resolved by using scalable databases with flexible indexing / partitioning schemes.

**Process** operations depend on the processing bandwidth of the machine the application is running on. This aspect of performance has to be resolved using a scalable application architecture, with multiple instances of the same applications "load sharing" to collectively scale the performance.

One method of implementing distributed applications is described in the Patent application [32], which describes a way of distributing the Acquire, Process and Database

function to achieve a flexible solution, which is limited only by the back-plane bandwidth.
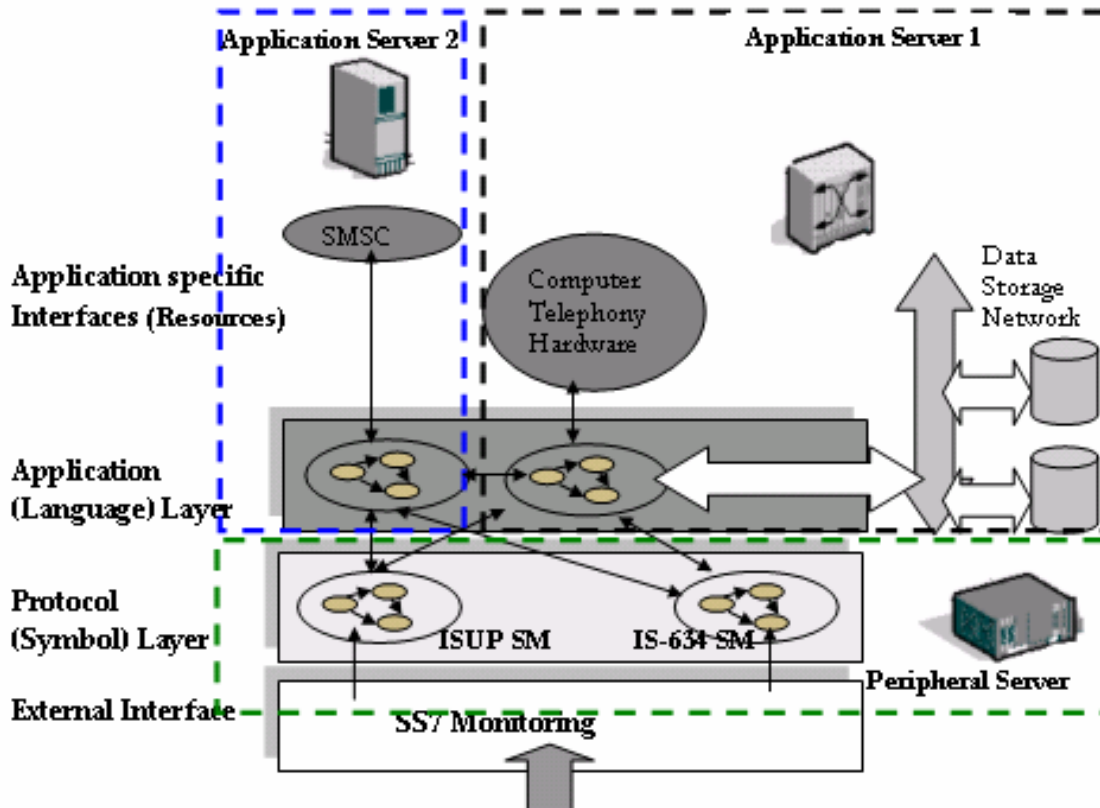


Figure 28 Distributed realization of Application 1

The application SM interface with the protocol SM through a distributed back-plane via distributed "adapters". These adapters allow us to distribute the layers and functional components of the Architectural form described in Figure 27 Architectural Form of Application 1 with Capacity Flexibility in different computation units (Machines/ Servers) as shown in

Figure 28 Distributed realization of Application 1.
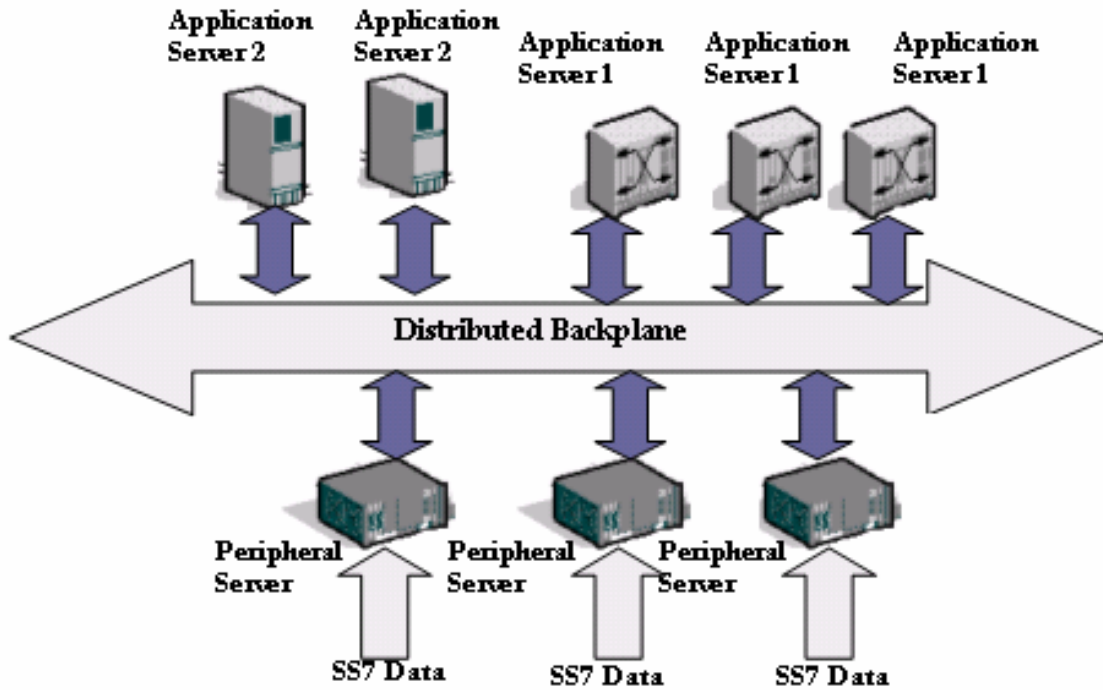
Figure 29  The Three Dimensions Realized

Capacity/performance flexibility is achieved by scaling the database dimension and adding more nodes to the network. The overall distributed architecture using the distributed adapters is shown in Figure 29  The Three Dimensions Realized. The different Application Servers enables functional flexibility. The different instances of one particular Application Server enable part of performance flexibility (Process). The scalable database interface enables the capacity flexibility and part of performance flexibility (retrieve /update). The different instances of Peripheral server enables part of performance flexibility (acquire).

**Conclusion**

It is shown by this analysis that the three dimensions of flexibility can be realized using a distributed architecture (for wireless network applications). This distributed architecture allows multiple applications, multiple instances of these applications and multiple network inputs to interact. , enabling all the three dimensions of flexibility. Using the example of Application 1, a network based wireless value added application; we found that Application Servers executing different Application SM enable functional flexibility. The different instances of one particular Application Server (Application SM) enable part of performance flexibility (Process). The scalable database interface enables the capacity flexibility and part of performance flexibility (retrieve /update). The different instances of Peripheral server enables part of performance flexibility (acquire). The example of the value added application was chosen to investigate the aspect of embedding flexibility as it illustrates all the three dimensions of flexibility. In the next chapter we will build the framework which would be used to identify and formally access the cost and value of implementing a flexibility design space (see Figure 8 Flexibility Design and Objective Space. Adapted from [6].), after the flexible objective space has been defined (as shown in Chapter 3) and its implementation feasibility verified (as shown in Chapter 4).

# *C h a p t e r   5*

# Valuing Product Flexibility (Mathematical Framework)

## 5.1   Introduction

In this chapter we explore the methods that can be used to model the payoffs associated with the flexible design options with respect to the costs incurred to implement design flexibility options in the face of uncertainty. In the subsequent sections, a framework is developed for assessing the cost and value of these design options.

The example cited in Chapter 3 describes the scenario where the on-chip cache size plays an important role in overall performance of the wireless handset from the context of different potential applications. Similarly, implementing a processor design optimized for only single threaded applications or multi-threaded applications leads to the constraint of meeting needs of only one market segment. There is uncertainty associated with how the application scenario, and with it the demand for higher single threaded performance or multi-threaded applications, will evolve.

The example of distributed network application explained in Chapter 4 (Embedding Flexibility), involves design and implementation of distributed adapters, which can enable scaling in terms of Functionality, Capacity and Performance. Similar to the example of wireless handset processors , by implementing these  flexible design features we can potentially maximize the net benefit by meeting new market needs which may

translate into a higher revenues when the Network application can scale for increased Functionality , Capacity and Performance requirements

This analysis illustrates the different ways of calculating the value of a flexible design option using the example of a hypothetical example of a Wireless Handset processor manufacturer.

## 5.2 Flexible Wireless Processor.

A processor design optimized for only a particular class of application, leads to the constraint of meeting needs of only one market segment.  There is an uncertainty associated with how the application scenario, will evolve. Implementing design features for a flexible feature (e.g. cache architecture), we incur a cost in terms of additional design effort, complexity and allocation of resources, which detract from traditional performance metrics (for example it may lead to higher power and die cost ).

By implementing flexible design features which enable optimization of  applications, by enabling of an additional on-chip cache at a later decision point in time we can potentially maximize the net benefit by meeting new market needs which may translate into a higher ASP (average selling price) for each unit when the new features are enabled.

### 5.2.1 Background

**PixelAirDSP** is a "fab-less"[8] DSP Company, and makes high performance Digital Signal Processors (DSP) for the wireless Handset segment.

It had a design win with **Smartest**, a major handset manufacturing company in Japan, which makes "smart" wireless handsets, customized for a large GSM based Mobile Network Operator (MNO) **CarryAll**, in Europe.

Currently the handsets that are being manufactured are for voice applications only. CarryAll wants to offer the 2.5G GPRS data services next year.

PixelAirDSP has been asked by Smartest to provide a DSP solution, which would provide a differentiated performance for digital video applications that would be based on GPRS Data services. The performance criterion is the total clock cycles expended by a low bandwidth codec (H.264), for a reference digital video sequence, for a standard resolution and frame rate.

Predicted handset diffusion data for next three years have been provided for different conditions.

PixelDataDSP's design simulations show that modification of two critical blocks would make their (under early design) 2.5 G DSP, perform satisfactorily for 3G bandwidths. One of the blocks is the on-chip cache architecture. Let us assume PixelDataDSP has two choices –

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[8] They outsource fabrication to a company in Taiwan.

**Option 1** -  Design a 2.5 G DSP for the handsets that would be required next year and Design 3G DSP, when there is a certainty of the 3G rollout. This will involve another development cycle , where most of the design would be shared but due to substantial "backend flow" costs , which are the costs of validating the processor design once it is put in silicon , it is estimated that the second development cycle would cost 50% of the first cycle cost of $20 Million.

**Option2** – Design a "flexible' cache architecture, which would cater to both 2.5G and 3G bandwidths. This would cause an additional design cost of $5 Million to the original design cost. The 3G cache features can be "enabled" at a later point of time, with an additional cost of $ 1 Million (primarily, a new production setup cost).

**Assumptions:**

1. There could be a reduction of the overall yield due to increased die size. This is the penalty in terms of the variable costs incurred due to the "additional" slots of a flexible design. For simplicity of the analysis, this is assumed negligible in our analysis.

2. It is assumed that the total design/production effort of PixelDataDSP is locked in to Smartest (and vice versa). This assumes there is no cost due to potential loss of market opportunity i.e. Smartest would not use an already available 3G DSP solution from  a PixelDataDSP's  potential competitor.

3. The Average selling price for both the 2.5G, 3G and Hybrid DSP is $30.

We will explore in the following section, using this example, the different ways PixelDataDSP can assess the flexible option.

## 5.2.2   Value of the flexibility option

This analysis is based on the Dual-Fuel Burner example [**Error! Reference source not found.**]. We start the analysis with an analogous assumption that the demand data is known with certainty and then introduce uncertainty to this data.

**Certain Demand – Development Cost scenario.**

In this scenario, CarryAll plans a 3G network rollout in year two and predicts a "certain" market diffusion data as shown in Figure 30   Market diffusion prediction. This data is considered to be "certain" demand at this point of time as most of the new handsets would replace the existing handset (which is a known data) and the market growth per year has been consistent for last five years.

This would necessitate introduction of new 3G handsets in the Year 2, supporting high bandwidth (2 Mbps) codec's like MPEG4.

**Cash Flows under certain demand**

The cash flows under certain demand are shown in Figure 31 Cash Flows under certain demand .
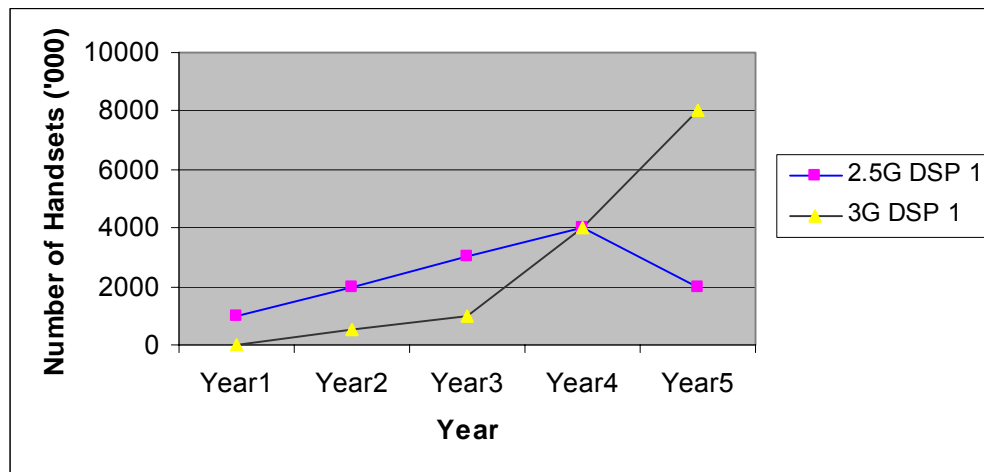
| | Probability | Year1 | Year2 | Year3 | Year4 | Year5 |
|---|---|---|---|---|---|---|
| 2.5G DSP | 1 | 1000 | 2000 | 3000 | 4000 | 2000 |
| 3G DSP | 1 | 0 | 500 | 1000 | 4000 | 8000 |

Figure 30  Market diffusion prediction

The Expected Cost of enabling the flexibility feature, as seen in the cash flow, is incurred in the year 3, when there is actual demand for the product (there is an underlying assumption that the feature can be activated with no delay). In the fixed case option, the cost of designing the 3G processor is incurred a year before the actual demand (which would be typical).

**CASH FLOWS ('000 $)          CERTAINITY**

**Discount rate**    5%

| | Year | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Option1** | Revenue | 30000 | 75000 | 120000 | 240000 | 300000 |
| **(Fixed)** | Cost | 20000 | 10000 | 0 | 0 | 0 |
| | R-C | 10000 | 65000 | 120000 | 240000 | 300000 |
| | Present Value | 9523.81 | 58956.92 | 103660.5 | 197448.594 | 235057.8 |
| | **NPV** | **604647.7** | | | | |

| | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Option2** | Revenue | 30000 | 75000 | 120000 | 240000 | 300000 |
| **(Flexible)** | Cost | 25000 | 0 | 1000 | 0 | 0 |
| | R-C | 5000 | 75000 | 119000 | 240000 | 300000 |
| | Present Value | 4761.905 | 68027.21 | 102796.7 | 197448.594 | 235057.8 |
| | **NPV** | **608092.2** | | | | |

Figure 31 Cash Flows under certain demand

**Recommendation**

Based on this analysis, (for this particular example) the flexible option is better than the fixed option even in the condition of certain demand. It has been widely published in the literature that flexibility is only valuable under uncertain conditions . This view, however, does not incorporate the engineering cost analysis and is based largely on uncertainty analysis of the benefits.

The hypothesis here is that flexible implementation can be a better option as compared to the fixed implementation due to differential development costs, even under the conditions of certainty. The flexibility option has a value in case of certainty when the

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cumulative fixed development costs exceed the cost of flexible implementation and activation of the flexible feature. This hypothesis is based on the simplifying assumptions that there are no variable cost penalty for the flexible implementation and that the diffusion curve is same for fixed and flexible solutions.

**Uncertain Demand – Flexible Activation Scenario**

There is a uncertainty in CarryAll's plans of 3G network rollout in the year two. This decision will be based on the observation of market response for 3G services for MobiKom and 3 (The two 3G based MNO's in Europe). This would necessitate introduction of new 3G handsets, supporting high bandwidth (2 Mbps) codec's like MPEG4.

The predicted units of units sold with their probabilities are shown in Figure 32 Predicted 3G units sold with uncertainty (delayed 3G rollout). We have retained the original 2.5 G , to facilitate easy comparison.

|  | Probability | Year1 | Year2 | Year3 | Year4 | Year5 |
|---|---|---|---|---|---|---|
| 2.5G DSP | 1 | 1000 | 2000 | 3000 | 4000 | 2000 |
| 3G DSP | 0.5 | 0 | 500 | 1000 | 4000 | 8000 |
|  | 0.4 | 0 | 0 | 500 | 1000 | 4000 |
|  | 0.1 | 0 | 0 | 0 | 500 | 1000 |

Figure 32  Predicted 3G units sold with uncertainty
(delayed 3G rollout)

This scenario illustrates a condition where there is a possibility of a delayed rollout due to unfavorable consumer response. The cash flows for the two options under this condition are shown in Figure 33  Cash Flow under uncertain demand. The Expected value of Revenue, Cost, Present Value and Net Present value are calculated based on the probabilities shown in Figure 32  Predicted 3G units sold with uncertainty (delayed 3G rollout). The Expected Cost of enabling the flexibility feature, as seen in the cash flow, is distributed in the years 3, 4 and 5 (immediate activation assumption). The cost for a fixed 3G design is similarly distributed across three years 2, 3 and 4 (design latency assumption).

| | CASH FLOWS ('000 $) | | UNCERTAINITY | | | |
|---|---|---|---|---|---|---|
| | Year | 1 | 2 | 3 | 4 | 5 |
| Option1 | E(Revenue) | 30000 | 67500 | 111000 | 193500 | 231000 |
| (Fixed) | E(Cost) | 20000 | 5000 | 4000 | 1000 | 0 |
| | E(R-C) | 10000 | 62500 | 107000 | 192500 | 231000 |
| | E(Present Value) | 9523.81 | 56689.34 | 92430.62 | 158370.226 | 180994.5 |
| | E(NPV) | 498008.5 | | | | |
| | | | | | | |
| Option2 | E(Revenue) | 30000 | 67500 | 111000 | 193500 | 231000 |
| (Flexible) | E(Cost) | 25000 | 0 | 500 | 400 | 100 |
| | E(R-C) | 5000 | 67500 | 110500 | 193100 | 230900 |
| | E(Present Value) | 4761.905 | 61224.49 | 95454.05 | 158863.848 | 180916.2 |
| | E(NPV) | 501220.5 | | | | |

Figure 33  Cash Flow under uncertain demand

### 5.2.3 Recommendation

The flexible option is better than the fixed option, even in the condition of uncertain demand. The simplifying assumptions that there are no variable cost penalty for the flexible implementation and that the diffusion curve is same for fixed and flexible solutions, that were made in the analysis of certain demand, applies for this case too.

**Analysis**

A comparative analysis of the relative advantage of the flexible product is shown in shown in Figure 34 Relative advantage of Flexible DSP.

| | Certainty | Uncertainty |
|---|---|---|
| **% NPV gain with Flexibility** | 0.569679 | 0.644957 |

Figure 34  Relative advantage of Flexible DSP

This can be substantiated by the fact that (all other things remaining constant) the cost of enabling the flexibility feature can be delayed based on the market scenario. This delayed cost increases the estimated NPV. Higher the activation cost, greater will the relative benefit under uncertainty as shown in Figure 35 NPV Gain with increased Activation Cost.

In this simplified analysis we assumed that the cost of designing a flexible product and activating the features is less than two cycles of fixed designs. We also assumed that the fixed designs and flexible design command the same price premium and incur the same costs.

**Costs (Million$)**

| Fixed Cost | Design | | Flexible Design Cost | | %NPV Gain |
|---|---|---|---|---|---|
| | | | 2.5/3G | | |
| 2.5G | 3G | | Design | Activation | |
| 20 | 10 | | 25 | 1 | 0.64495743 |
| | | | 21 | 5 | 0.73574185 |
| | | | 16 | 10 | 0.84922238 |
| | | | 11 | 15 | 0.96270291 |
| | | | 6 | 20 | 1.07618344 |
| | | | 1 | 25 | 1.18966396 |

Figure 35 NPV Gain with increased Activation

Cost.

In cases where the cost of the flexible design exceeds the cumulative cycle cost of fixed design, the differential cost has to be compensated by a price premium of the flexible product else Flexibility strategy should not be recommended.

In the cases where the Flexible design costs are "Front Loaded"(little or no activation costs) in addition to the overall cost disadvantage, this recommendation is especially important.

## 5.3   Quantitative Framework

In this section we build a quantitative framework to extend our initial analysis of one flexibility attribute – Processor performance for digital video codec, to multiple attributes.

### 5.3.1  Flexibility Attributes

Each one of the three dimensions of flexibility: Functionality, Performance, and Capacity, consists of many attributes, which can also be thought of as requirements. These requirements would define the form related design attributes and map into a part of the overall objective space, by defining the flexible objective space as shown in Figure 8 Flexibility Design and Objective Space. Adapted from [6]. However, we reserve the word "requirements" for concrete mandatory needs required for the delivery of the system, while these attributes are based on a prediction of what the system might morph into in the future. The attributes of the three dimensions are therefore:

Functional attributes:

$$Fa = [Fa_1, Fa_2, \ldots, Fa_l] \tag{1}$$

Where l is the number of Functional attributes.

Performance attributes:

$$Pa = [Pa_1, Pa_2, \ldots, Pa_m] \tag{2}$$

Where m is the number of Performance attributes.

Capacity attributes:

$$Ca = [Ca_1, Ca_2, \ldots, Ca_n] \tag{3}$$

Where n is the number of Capacity attributes.

In the example of wireless handset processors discussed in the previous section, the "Performance attribute" is the total clock cycles expended by a low bandwidth codec (H.264), for a reference digital video sequence, for a standard resolution and frame rate.

### 5.3.2 Time Window

These attributes may have different time windows associated with them, in our example, performance scaling in the wireless handset processors for digital streaming video applications, imposes a Performance attribute to handle 56Kbps – 2 Mbps data streams within a period of five years. Similarly, capacity scaling in the case of a wireless network application may have requirement to scale from 1 Million to 2 Million subscribers in a period of five years.

The time windows corresponding to the functionality attributes are therefore:

Functionality Time Window:

$$\mathbf{Tf = [Tfa_1, Tfa_2, \ldots, Tfa_l]} \qquad\qquad (4)$$

Where l is the number of Functional attributes.

Performance Time Window:

$$\mathbf{Tp = [Tpa_1, Tpa_2, \ldots, Tpa_m]} \qquad\qquad (5)$$

Where m is the number of Performance attributes.

Capacity Time Window:

$$\mathbf{Tc = [Tca_1, Tca_2, \ldots, Tca_n]} \qquad\qquad (6)$$

Where n is the number of Capacity attributes.

The functionality attributes that are mapped to design parameters have an overall time window Tw, which is the maximum of all individual time windows.

$$Tw = Max (Max (Tfa_1, Tfa_2, …, Tfa_l),$$
$$Max (Tpa_1, Tpa_2, …, Tpa_m),$$
$$Max (Tca_1, Tca_2, …, Tca_n )) \qquad\qquad (7)$$

### 5.3.3   Flexibility Design Space

Through various existing systems engineering methods, like QFD [1673] these functionality attributes (similar to requirements) can be related to design parameters. These parameters constitute the flexibility design trade space.

The flexibility design parameters vector is therefore:

$$Dp = [Dp_1, Dp_2, …, Dp_k] \qquad\qquad ( 8)$$

Where k is the number of design parameters that map to the flexible design space. It contains all the flexibility design parameters. In the example of the wireless handset processor, if the performance flexibility is realized using a 2X on-chip cache AND an enhanced  Direct Memory Access (DMA),

$$Dp = [Dp_1, Dp_2 ] \qquad\qquad (9)$$

Where,

**Dp₁** - 2X on-chip cache.

**Dp₂** - Enhanced DMA.

### 5.3.4 Current Costs

The Dp vector is associated with current implementation cost. This cost is comprehensive, and should include the costs resulting form various aspects of the implementation:

- Cost of design
- Cost of manufacturing
- Cost associated with product delays to accommodate for the flexibility design
- Cost associated with the incremental risk added to the system as a whole as a result of the flexibility design

The result is a flexibility cost vector:

$$Cf = [Cf_1, Cf_2, \ldots, Cf_k] \tag{10}$$

Where k is the number of design parameters.

### 5.3.5 Future Costs

There is a cost vector (in the future) for implementing the flexibility option, in other words activating the built-in flexibility features. Note that this is different from the cost of designing flexibility which was described in the previous section. This cost is

dependent on the design decisions made at t0, i.e. on the flexibility design parameter vector Dp.

**Ci(Dp) =[Ci$_1$, Ci$_2$, ..., Ci$_k$]** (11)

Where k is the number of design parameters.

### 5.3.6 Value

Along with the cost, there is a value associated with implementing the flexibility. This value can be represented by the vector Vi. This value is dependent on the state of the future F(t).

**Vi(F(t), Dp) = [Vi$_1$, Vi$_2$, ..., Vi$_k$]** (12)

Where k is the number of design parameters.

In the example of wireless handset processor, we estimated this value under certain and uncertain future and found that the value of flexible options increases with increasing uncertainty.

### 5.4 Real Option Approach

The traditional method that companies use to select which projects or designs to invest in, Discounted Cash Flow analysis (DCF) or Net Present Value (NPV) calculations, does not always accurately represent the actual value of the projects under study [14]. That is because DCF assumes that we will follow a predetermined path.

In reality, uncertainty and investment choices exist together and these choices are spread over time. As uncertainty changes, downside losses can be avoided by not investing more funds into projects which have poor performance [15]. In our case, this investment relates to the cost of embedding flexibility in the product.

We use the concept of real options to calculate the call value of the option, based on the earlier work of Black and Scholes. In our case this is the value of embedding flexibility in a product design.

This section provides a mechanism to compute the value of the flexibility option Vf (Eq. 12), that is, the value of embedding multi-attribute flexibility in the design. There are multiple methods to compute Vf using Real Option Analysis. Amram and Kalutilaka[17] propose three high level solutions:

- The PDE approach, by solving a partial differential equation to obtain the value of the option from a tracking portfolio.
- A dynamic programming approach that lays out the future and folds back the optimal strategy.
- A simulation approach that picks the optimal value strategy by simulating all possible outcomes.

We will look at two of these solutions and map them to our problem.

### 5.4.1 Black-Scholes Model (PDE)

The Black-Scholes model is simple to implement once all the variables have been identified. It consists of an equation that computes the value of the option given the following variables:

Cost of exercising the option,

Current value of the underlying asset,

Risk free interest rate,

Time to expiration, and

Volatility of the underlying asset

Other than ensuring a proper mapping, one needs to verify the boundary conditions of the formula. The Black-Scholes formula [1676] for the valuation of financial stocks is the following:

$$V = N(d1) \, A - N(d2) \, X \, e^{-rT} \tag{13}$$

Where

V  =  Value of call option

A  =  Current value of underlying asset

X  =  Exercise price

T  =  Time of expiration

r  =  Risk free interest rate

$\sigma$  =  Volatility of underlying asset

N(d) =   Cumulative value of normal distribution at d

$$d1 = \ln(\sigma/X) + (r + 0.5\,\sigma^2)T)/(\sigma.\text{Sqrt}(T)) \qquad (14)$$

$$d2 = d1 - \sigma.\text{Sqrt}(T) \qquad (15)$$

This formula models European call options. European options can only be exercised at the expiration time T. On the other hand, American options can be exercised at any time between t0 and T. In modeling flexibility using real options, although the most accurate model is the American one, we can justifiably use the European model by assuming that at the time of the valuation of the flexibility (design phase), one can predict to a degree of certainty the time at which this flexibility would be activated . This time is Tw as shown in Eq.8.Moving forward with the European model, we can then map the flexibility real options parameters to the financial parameters as shown in Figure 36 Mapping Design Flexibility Options to Financial Options.

| FINANCIAL CALL OPTION PARAMETERS | | FLEXIBILITY OPTION PARAMETERS | | COMMENTS |
|---|---|---|---|---|
| Option value | V | Value of designing flexibility | Vf | |
| Option price | P | Cost of designing flexibility at time 0 | Cf | |
| Exercise price | X | Cost at time T of implementing the flexibility | Ci | |

| Current stock price (price of underlying asset) | A | Current value of implementing flexibility | Vi | The mapping of this variable still needs some careful manipulation to ensure that it matches the boundary conditions of the Black-Scholes model |
|---|---|---|---|---|
| Time to expiration | T | Time at which the flexibility would be implemented | Tw | To fit the Black-Scholes model, there is an assumption that the time between incurring cost Ci and getting value Vi is zero. In reality, this time is not zero and the equation would have to be adjusted to account for it by time shifting either Ci or Vi. |
| Risk free interest rate | r | Risk free interest rate | R | |
| Volatility of the stock price | σ | Volatility of the expected benefit of implementing the flexibility | σ | This is estimated in Chapter 7. |

Figure 36 Mapping Design Flexibility Options to

Financial Options

In order to successfully utilize this model, we need to identify a method for computing the risk free interest rate as well as the volatility of the expected benefit of implementing flexibility. Moreover, we need to be able to determine and quantify Vi. A proposal for how to accomplish that is presented in the Chapter 6 [Assessing Flexibility: Option Parameters and Cost].

**Limitations of Black-Scholes**

The Black-Scholes formula assumes the existence of a replicating portfolio and no arbitrage [33]. The absence of data on replicating portfolio for flexible options makes the estimation of the value of the underlying asset less accurate. Since flexible product options in innovative industries are not traded on open security markets it is difficult – and often impossible – to find a replicating portfolio for assessing the value of a particular, flexible product feature as a European or American Call Option. The value of the underlying asset can be subjectively estimated [16], but the results of the Black-Scholes formula would not be accurate [39]. The formula, however, can be used for qualitative comparison between different flexibility options and in cases where a similar flexible product is already in the market and the value of the flexibility (and volatility) is known.

**Black Scholes Valuation of Flexible Processor Architecture**

The following example illustrates the application of Black Scholes option model to calculate the economic value of flexible system design for handset processor architecture. The traditional CPU architecture can be enhanced during the concept engineering phase to incorporate flexible features which have a potential market and economic value. The flexible design variants which are enabled in this case are:

| Option | Flexible design variant |
|--------|-------------------------|
| A | integrates multi-threaded architecture |
| B | integrates high performane graphics core |
| C | integrates encryption hardware |
| D | integrates memory controller |
| E | integrates ultra low power mode to conserve battery life |
| F | integrates support for 64 bit applications |

Figure 37 Flexible Design Variants for a  Processor

As discussed earlier we can determine through Conjoint Analysis which features present the greatest utility to the end customer, what combination of features constitute a viable design variant and also the price differential represented by higher ASP we can expect by enabling some of the latent features in a given CPU architecture at a later point in time. We can estimate the potential market by looking at the future growth trends for some of the features in a stand alone component and by estimating the projected diffusion curve of capturing a certain market segment share of integrating some of these features into an existing CPU architecture. Specifically, we can easily get market research data for the discrete graphics market share for high end graphics card in the future. By using appropriate diffusion curves we can make predictions for the adoption of an integrated design as a function of time. The cost of enabling a flexible design feature can be estimated on a case by case basis. For example, integrating a high end graphics engine would result in die size increase, yield impact, higher power consumption leading to higher cooling costs and additional design and validation costs. All these can be ascertained and quantified. The delay in time to market due to higher complexity can also be translated into lost revenue which is factored into enabling any one of the design variants.

In applying the Black-Scholes model, the hardest parameter to estimate accurately is the variance associated with future returns of a flexible design variant. To determine this we can identify the returns with the new product to the variance of a similar feature in the past. One consideration if we use this approach is to look at the variance at least as far back in time as the period in the future for which we are calculating the real option value.
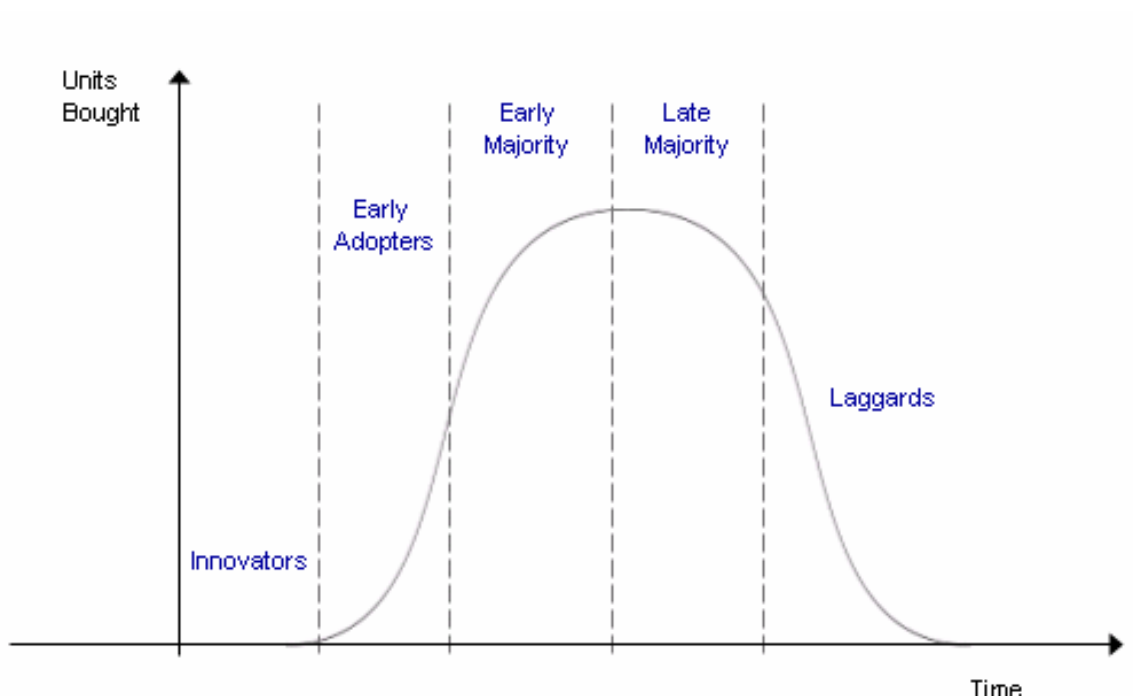


Figure 38 Diffusion Curve

As illustrated in Figure 39  Black Scholes Valuation of Flexible CPU Architectures, the design variant which integrates a high performance graphics core has a NPV of $25 million but the real option value is $48.14 million. This is due to the large time to expiration of 5 years and standard deviation of 30%. Similarly design variant which integrates support for 64 bit application has NPV of -$25 million but the option value of $10.15 million due to 3 years to expiration and a standard deviation of returns of 40%.

The combined option on the portfolio has a value of $98.75 million whereas the NPV is $0. This example illustrates the key differences in using an option framework in valuing flexible design variants versus using NPV (which does not model uncertainty).[9]

| All costs in million $ | | A | B | C | D | E | F | Portfolio Value |
|---|---|---|---|---|---|---|---|---|
| Variable | | | | | | | | |
| | | | | | | | | |
| S | Value of Underlying Asset | $ 300 | $ 300 | $ 100 | $ 100 | $ 250 | $ 250 | |
| X ($millions) | Exercise Price | $ 300 | $ 275 | $ 90 | $ 110 | $ 250 | $ 275 | |
| t | Time to expiration (years) | 0 | 5 | 0 | 0.5 | 5 | 3 | |
| $\sigma$ | Std. Deviation | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.4 | |
| $r_f$ | Risk Free Return | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | |
| | | | | | | | | |
| PV(X) | Present Value | $ 300.00 | $ 205.50 | $ 90.00 | $ 106.84 | $ 186.81 | $ 230.90 | |
| NPVq | Value to Cost Metric | 1.000 | 1.460 | 1.111 | 0.936 | 1.338 | 1.083 | |
| $\sigma$*sqrt(t) | Cumulative volatility | 0.000 | 0.671 | 0.000 | 0.141 | 0.671 | 0.693 | |
| | call value | $ - | $ 48.14 | $ 5.00 | $ 3.06 | $ 32.40 | $ 10.15 | $ 98.75 |
| S-X | Conventional NPV | $ - | $ 25 | $ 10 | $ (10) | $ - | $ (25) | $ - |

Figure 39  Black Scholes Valuation of Flexible CPU Architectures

## 5.4.2   The Binomial Solution (Dynamic Programming)

As described by Amram and Kulatilaka [17], the Binomial solution of valuation of options is implemented in two stages.  The goal is to compute the value of Vf.  In the first stage, the current value of the underlying asset (*A* from the previous table) is rolled forward from t=0 to t=T at intervals dt.  At each time interval, each node bifurcates into

two probable outcomes, up and down, each with an associated probability. The coefficients by which *A* increases or decreases are *u* and *d* respectively, as shown in Figure 40 Asset value change using the Binomial model (Adapted from [17]).
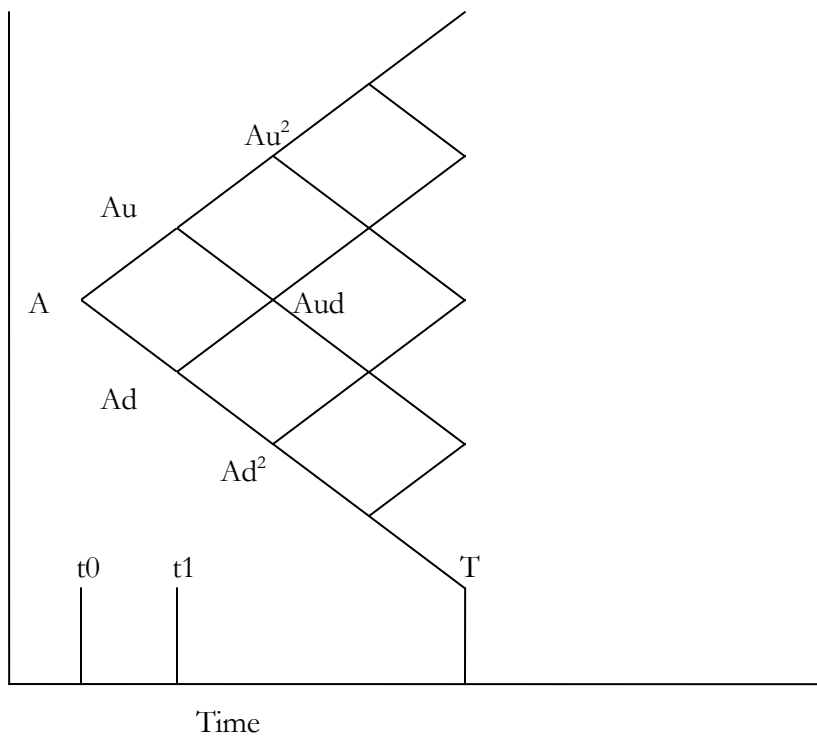


Figure 40 Asset value change using the Binomial
model (Adapted from [17])

The change in asset value as described above is therefore dependent on u and d, as well as their associated probability P and (1-P). Amram and Kulatilaka relate these to the volatility and the risk free interest rate, and solve the equations for a normal distribution and for the particular case where the up and down movements are symmetric: u = 1/d. The equations obtained are the following:

**u = e^r** (16)

$$u = e^r$$

**d = 1/u** (17)

$$d = 1/u$$

**P = (e^r -d)/(u-d)** (18)

$$P = (e^r - d)/(u-d)$$

Where:

r is the risk free interest rate.

In the second stage, the values obtained at the end nodes of the resulting tree are folded back. The option to exercise is reflected using the following rule at the end nodes

**$A_{Tn}$ = max[$A_{Tn}$-X, 0]** (19)

Where:

$A_{Tn}$ is the value of the asset at time T and end node n

X is the cost to exercise the option

The values are folded back according to the equations shown in Figure 41 Binomial method (stage 2). Rolling back to obtain the value of flexibility.

$$= ((P.A_{T1}) + ((1-P).A_{T2})).e^{-r}$$
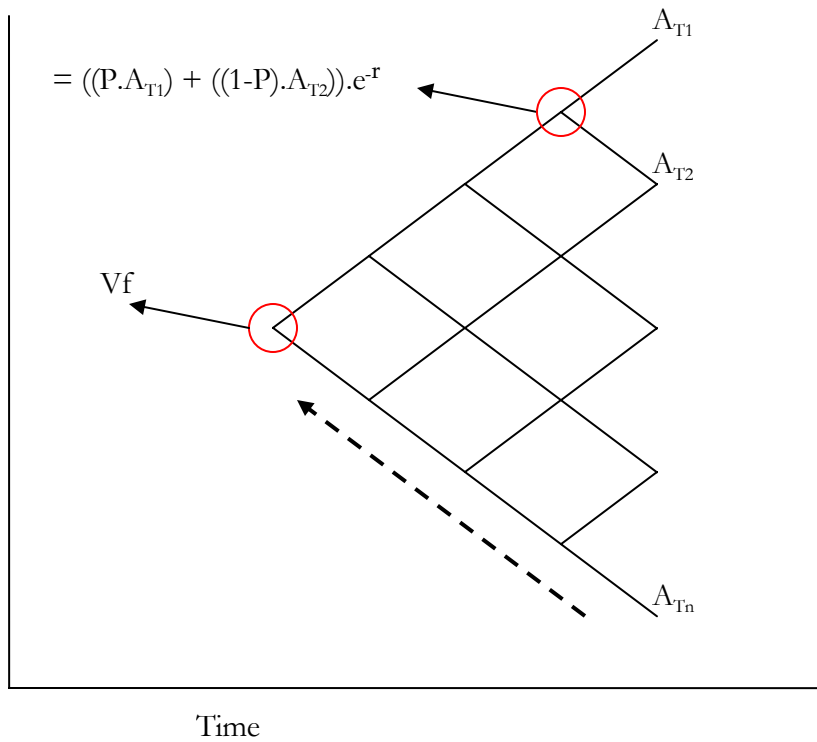
Figure 41 Binomial method (stage 2). Rolling back
to obtain the value of flexibility

Rolling all the way back to time t0 yields Vf, the value of embedding the flexibility in the design. Similarly to what was mentioned in the Black-Scholes model, this computation is dependant on the value of the underlying asset (A or Vi) as well as the volatility and time to expiration. Unlike Black Scholes , however , it does not assume the existence of a replicating portfolio and thus the quantitative results using Binomial method would be more accurate than Black Scholes in cases where the assumption of existence of a replicating portfolio does not hold.

## 5.5    Conclusion

The value of embedding flexibility can be assessed using the real options approach.  The Black-Scholes model and the Binomial model can be used to compute the value of flexible design options. The decision of implementing the flexibility is analogous to the financial decision of exercising the option, and the cost of implementing the flexibility is analogous to the exercise price of the option.

We found in the case study of a flexible mobile handset processor that the value of flexibility does increase with increasing uncertainty. We also found that by moving the cost of embedding flexibility to the later or "activation" stage, the value of the flexible option increases as compared to a "front loaded" flexibility cost.

We established a mathematical framework for a multi-attribute flexible product and mapped these attributes to flexible design options. The parameters used in option calculations - value of the underlying asset, time to expiration and cost of embedding flexibility, have been defined under a mathematical framework in this chapter. The next chapter would describe some of the methods that can be used to compute these parameters.

# *Chapter 6*

## Assessing Flexibility – Option Parameters and Cost

### 6.1  Introduction

We have modeled the present situation vis-à-vis flexibility, its dimensions, its attributes, the design parameters to implement these attributes, as well as the costs associated with these design parameters.  We now take a look at the future market potential of a flexible product. This analysis is to determine the value of the underlying asset, and the volatility of this value. This, by far, are the most difficult parameters to access in the flexibility analysis.

Our intention is to calculate the mean value of the underlying assets (Eq. 12) and it's volatility over the time to expiration. At a given point of time, the mean value can be seen as the product of the number of units of the product and the incremental price a customer is willing to pay for the flexible features. Since both these distributions can be assumed to be normally distributed, the effective distribution will be a convolution of these two normal distributions.

Let P be the normal distribution of the price a customer is willing to pay for a flexible feature (we describe two methods to do this in later sections),at a given time  where:

$$P = N\ (\mu_P\,,\sigma_P{}^2) \tag{20}$$

Where $\mu_P\,,\sigma_P{}^2$ are the mean and variance of the distribution.

Let U be the normal distribution of the units expected to be sold in the same time the Price was determined[10] (we describe two methods to do this in later sections),  where:

$$U = N (\mu_u, \sigma_u^2) \tag{21}$$

Where $\mu_u, \sigma_u^2$ are the mean and variance of the distribution.

The resultant distribution of Value, V , which is the product  of these two distributions at a given time , will have the mean $\mu_u$,

$$\mu_u = \mu_u * \mu_p \tag{22}$$

The resultant distribution will not be normally distributed [41] . If we use this mean value of "Value" and plot this over time, we can calculate the Mean of this distribution over time (mean value of the underlying asset) and the volatility (variance over time) , as shown in Figure 42  Components of the Value distribution over time.

---

[10]  In this example we assume that  "Price' and  "Number of units sold"  are independent random variables , for illustrative simplicity.

$$\mu_v{}^T = \mu_{nT} * \mu_{pT}$$
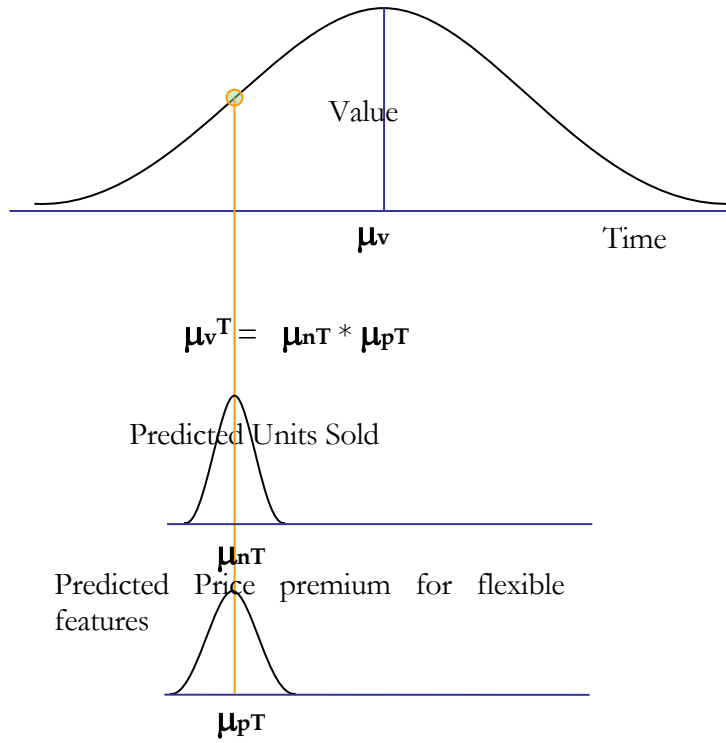
Figure 42  Components of the Value distribution
over time.

## 6.2    Future Demand

The future can be modeled by a Future demand vector, comprised of several types of elements: needs element, technology element, strategy element, market element, competitor element, and economy element.  For example, the needs elements represent customer needs at any point in time in the future.  Similarly, technology elements represent technology availability at any point in time in the future.  This vector can be written as a function of time:

**F(t) =[Nf, Tf, Sf, Mf, Cf, Ef]**                                                        **(23)**

*(N=need, T=technology, S=strategy, M=market, C=competitors, E=economy)*

The F(t) vector represents the state of environment , with respect to a product demand, at a given time. "Environment" is loosely used to refer to the immediate environment in which the system under consideration will operate.  Given the uncertainty of the future, the F(t) vector can be modeled by a set of predicted states, along with their associated probability distributions P.

**F(t) =[N, Pn ;   T, Pt;   S, Pf;   M, Pm;   C, Pc;   E, Pe]**                    **(24)**

.



Units Sold

Time

Effective Predicted Units Sold

No

Predicted Units Sold

½   1.2   2.0

Effect of Economy on Units Sold
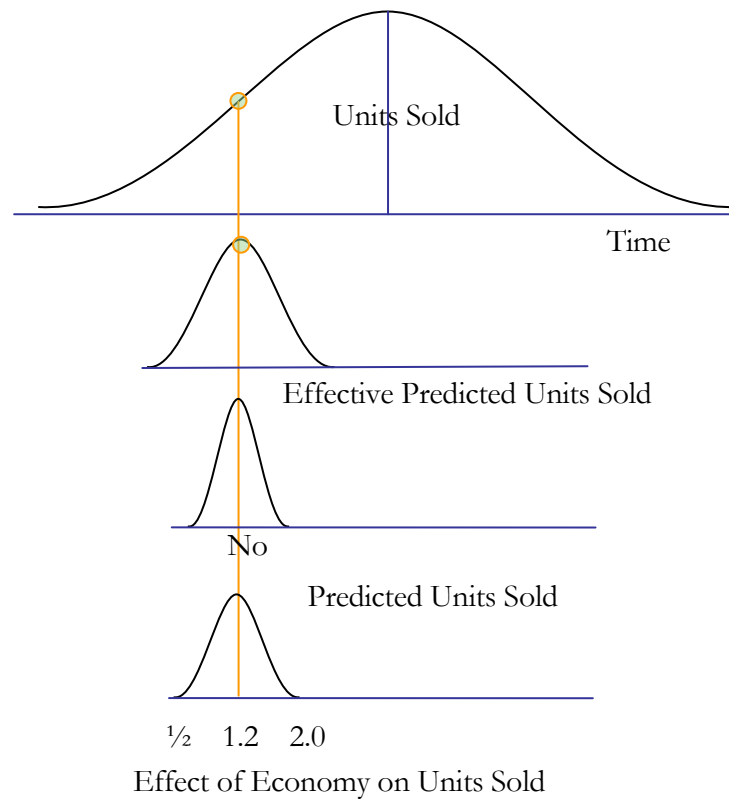
Figure 43 The effect of uncertainty dimensions

This vector represents the cone of uncertainty. There would ideally be probability distributions (discrete or continuous) for the effect of a particular component on the normalized demand of a product.

This is shown in Figure 43 The effect of uncertainty dimensions , where the convolution of the effect of the economy on the demand distribution and the predicted unit sold distribution at a given time, gives the effective predicted units sold distribution, mean value of which is represented in the overall product diffusion curve over time. The effective distribution will not be normally distributed (as shown in the figure, for simplicity) but the mean of this distribution will be the product of the means of the two distributions [41]. The effect of all the other factors described in Eq. 20, can also be factored in a similar way.

### 6.2.1   System Dynamics Model

Systems dynamics model has been successfully used to predict the future market and can be used in conjunction with the other tools to predict the future penetration of a product.
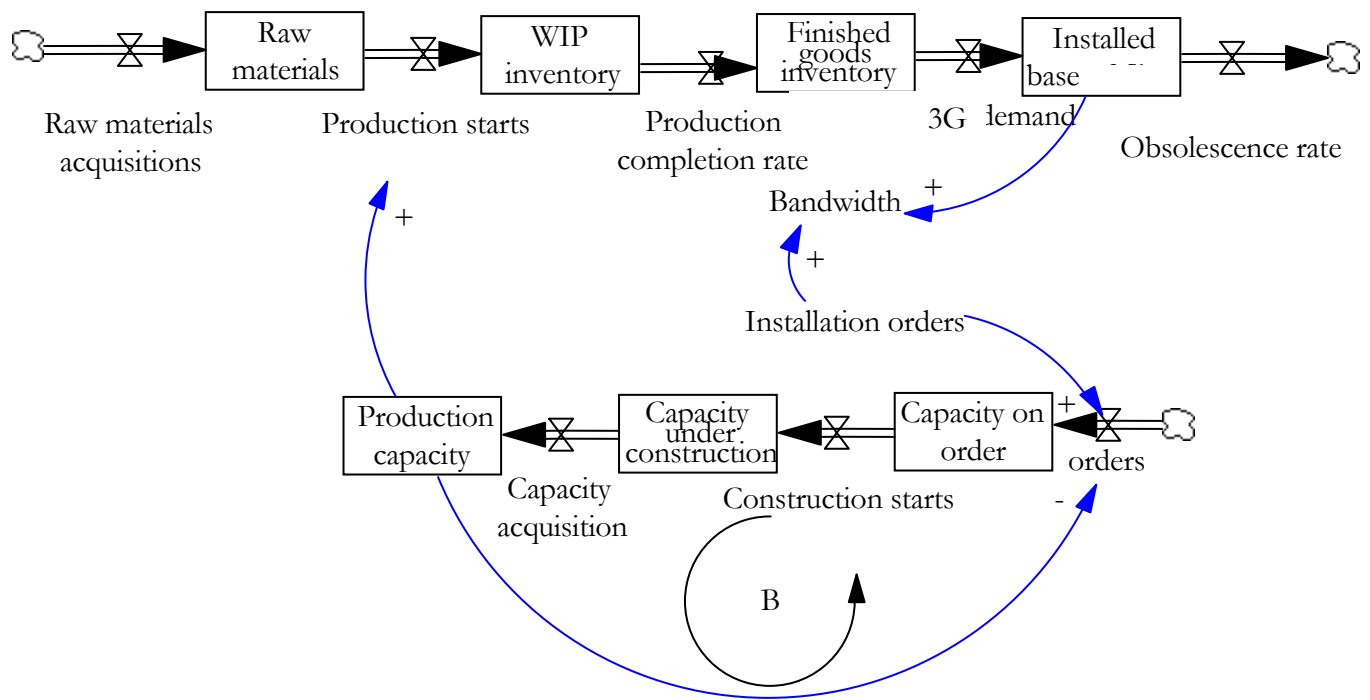
Figure 44 Causal Diagram of 3G Capacity [11]

One of the determinants of diffusion for wireless networks identified in Chapter 3 was the network capacity. 3G Networks provide a higher capacity than traditional 2 G networks, an illustrative causal diagram of the manufacture and deployment of 3G networks, with a higher capacity, is shown in Figure 44 Causal Diagram of 3G Capacity .

When the carrying capacity of the system based on demand saturates, the orders for new 3G rollout declines. Due to time delays in the system, overcapacity results which are followed by rapid decline in new orders leading to even more unutilized capacity. These characteristics of the system lead to the expected slow rollout and underutilization of the 3G Networks.

---

[11] This diagram is based on the Fiber Capacity boom-bust causal diagram illustrated in 15.874 (System Dynamics for Business Policy)

## 6.3    Value to Customers

In order to determine the estimated market potential of different flexible design features which are embedded in a product platform, extensive market research is required with lead users. Value Benchmarking [21] is used to determine how the product attributes contribute to the value differences. Conjoint analysis is used to value the utility of the product features. Contingency analysis is used to comprehend the value of social and environmental factors on value. Direct value methods use a combination of both conjoint and contingency analysis for assessing feature value to customers.

In the subsequent section, we review the applicability of Conjoint analysis and Kano analysis methods, in determining which product features to enable and also to ascertain the incremental cost customers are willing to pay for a product with the flexibility features enabled. A critical factor to consider in this regard is the correlation between stated preference and actual action in terms of purchase.

### 6.3.1    Conjoint Analysis

Conjoint analysis is a quantitative method used to identify and prioritize the preferences of multiple product features. A convenient aspect of this method is that the price a customer is willing to pay for a product feature can be embedded as one more variable in the analysis. This method uses a customers ranking of a combination of global product attributes and then decomposes it into a scale of utility attribute for each attribute or a group of attributes. It uses orthogonal arrays in the design of the market survey

responses to minimize the explosion in the number of potential product variants presented to the customer [22].

We have used the example of flexible handset processor that was described in Chapter 5 to illustrate this method. Consider a flexible design which has an option to optimize either single threaded performance or multi-threaded performance but not both. Higher performance along either one of these attributes results in increased die size and higher power (reduced battery life). It also translates into higher system costs. If we want to find the preferences of the consumers to enable any one of the design options we can rely on conjoint analysis.

If the single threaded performance has three levels (ST-, ST0, ST+) where ST0 corresponds to baseline performance, Multi-threaded performance has similar three levels (MT-, MT0, MT+). The -/+ suffix indicate lower or higher performance from baseline. Let's assume we impact the battery life by two levels (BAT-, BAT+). Expected increase in CPU ASP (average selling price) due to improved performance is categorized as (Pr-, Pr+, Pr++) where Pr+ is higher performance and Pr++ the highest performance. The mobility vector is again specified by two levels corresponding to increased thermal requirements for higher performance leading to additional thermal system volume denoted by (Mob-, Mob0).

The complete combination of all product attribute, (each level is correlated to a product architecture choice), results in 3x3x3x2x2 = 108 combination. Using Orthogonal arrays as described in [21] we can reduce the possible design variations presented to the consumers to 18.

| Design Variant | Multi_Threaded Performance | Single-Threaded Performance | Price | Battery Life | Mobility |
|---|---|---|---|---|---|
| 1 | MT- | ST- | Pr0 | Bat- | Mob- |
| 2 | MT- | ST0 | Pr+ | Bat- | Mob0 |
| 3 | MT- | ST+ | Pr++ | Bat+ | Mob- |
| 4 | MT0 | ST- | Pr+ | Bat+ | Mob0 |
| 5 | MT0 | ST0 | Pr++ | Bat- | Mob- |
| 6 | MT0 | ST+ | Pr0 | Bat- | Mob- |
| 7 | MT+ | ST- | Pr++ | Bat- | Mob0 |
| 8 | MT+ | ST0 | Pr0 | Bat+ | Mob- |
| 9 | MT+ | ST+ | Pr+ | Bat- | Mob- |
| 10 | MT- | ST- | Pr++ | Bat+ | Mob- |
| 11 | MT- | ST0 | Pr0 | Bat- | Mob0 |
| 12 | MT- | ST+ | Pr+ | Bat- | Mob- |
| 13 | MT0 | ST- | Pr0 | Bat- | Mob- |
| 14 | MT0 | ST0 | Pr+ | Bat+ | Mob- |
| 15 | MT0 | ST+ | Pr++ | Bat- | Mob0 |
| 16 | MT+ | ST- | Pr+ | Bat- | Mob- |
| 17 | MT+ | ST0 | Pr++ | Bat- | Mob- |
| 18 | MT+ | ST+ | Pr0 | Bat+ | Mob0 |

Figure 45 Orthogonal Array for Processor Design

using Conjoint Analysis

The ranking of the customer preferences from the survey group for each design variant is used to translate into a utility scale [0<=utility<=1] for each product attribute and for each level of the attribute. The boundary condition for the utility is that the summation of the utility for each design variant (as a function of the sum of the utilities of the individual attribute level) matches the ranking average of the particular design variant based on the survey response.

Using the conjoint analysis data, we can extract the following information:

1. Product feature which has the highest value

2. Combination of design features which have the greatest utility

3. For a set of design features, the expected increase in ASP we can expect

4. Product features which have no value for the customer and hence we need not enable in a product

It should be noted, however, that for real-option analysis we need the value of the flexible feature in the future, which can be estimated using Conjoint analysis and use the methods described in section 6.2 to predict the future value of the flexibility options.

### 6.3.2 Concept Engineering

During the front end design cycle, it is very hard to forecast the market needs or identify lead customers in order to identify the flexible attributes and determine the value of these attributes. If we rely solely on the surveyed customer base and optimize along identified customer attributes, we may end up eliminating design features which may become critical as the design progresses. Hence, we need to rely on the collective intuition of the development team, past experiences in specifying engineering attributes and the operating range of these variables. This approach also increases the pitfall of falling into the innovator's dilemma wherein all the development resources are allocated in developing product features which satisfy needs of current customers who may not be able to articulate the needs for disruptive technologies which may create a market which may expand at a much more rapid pace in the future. Nonetheless, a systematic framework in needed for any front end design cycle for complex systems.

A useful method in identifying new customer needs and aligning optimization of engineering attributes is Concept Engineering as espoused by Prof. Shoji Shiba [24]. It builds on the prior work of Kawakita which uses a W-V model.
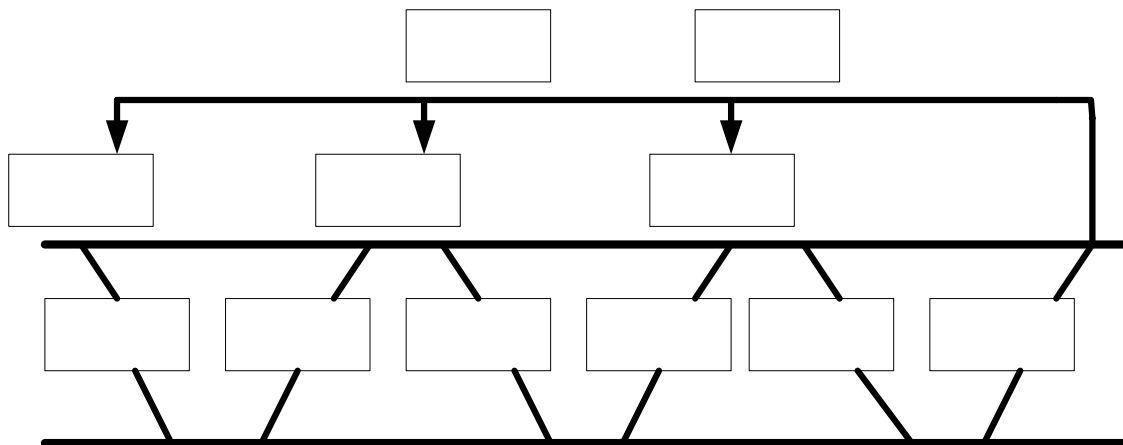


Figure 46 W-V Model (Source [24])

This approach can be used in conjunction with the QFD [23], since it introduces a key step in the process which is alternating between levels of thought (analysis) and experience (prototype development) and also reinforces the need to rely on intuition and contextual experiences. It also relies both on qualitative and quantitative data during the process of breakthrough system definition.

The concept engineering method relies heavily on the Language Processing method to translate the voice of the customer into a key requirement. It also uses the Kano Analysis

Sense Problem                                    Se

to classify each customer requirement into- Attractive, One dimensional (meeting the result in increasing satisfaction), Must be, Indifferent, Reverse (result in dissatisfaction when fulfilled and satisfaction when fulfilled), Questionable (error in input data).

Using Kano Analysis [24], we can understand the relationship between the fulfillment and non fulfillment of a requirement – in this case this requirement would be the flexibility option. Using Kano Analysis; we can classify the customer requirements into four categories (ignoring the categories that arise due to faulty questionnaire)-

**A - Attractive**: These are requirements that create satisfaction when fulfilled, but the product is acceptable without these features. These requirements cause the "Wow" factor in a customer. The flexibility features that typically fall in this dimension will command a good premium. Functional flexibility would be more likely to be perceived along this dimension.

**O - One Dimensional:** These requirements cause rising satisfaction as they are satisfied more and vice versa. Performance and Capacity flexibility are more likely to fall along this dimension.

**C –Must-Be:** These are requirements that do not lead to satisfaction when fulfilled, but lead to dissatisfaction if not fulfilled. These feature will typically be defined by the basic attributes of the Intent and Process as described in Chapter 1.

**I- Indifferent:** User is indifferent to these requirements. This is a very important dimension. Flexibility features that have no value to the customer should not be considered.

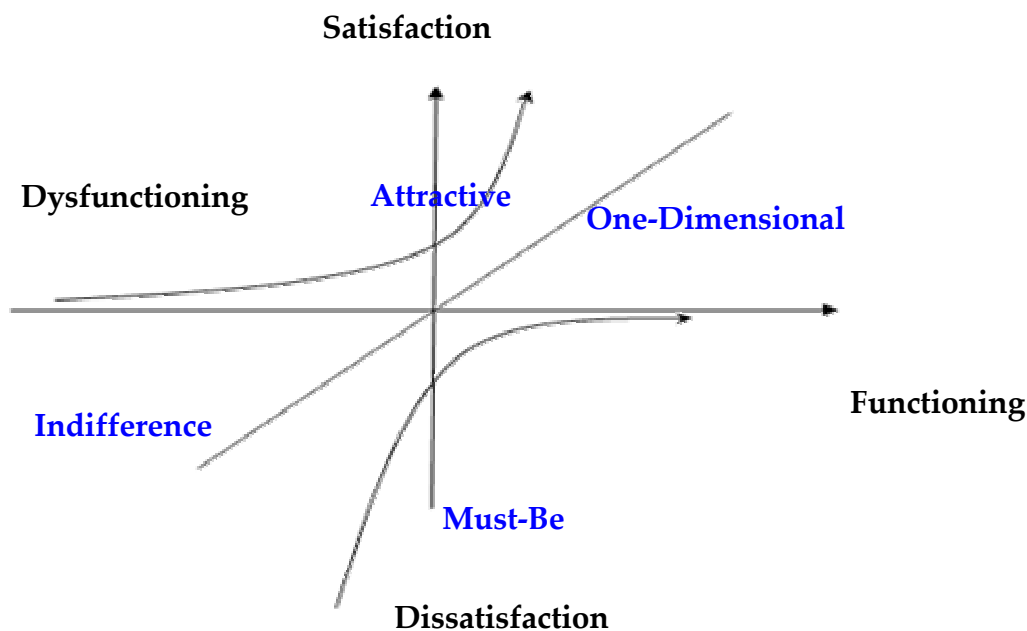These dimensions are shown in Figure 47.



Figure 47 Kano Requirement Dimensions (Source

[24])

The response analysis of the Kano questionnaire is then converted into a tree diagram which is an analytical tool for generating the process for defining right metrics for measuring customer requirements. Each metric is ranked based on its effectiveness, feasibility and rank.

This process is followed by the concept generation phase. The system is decomposed into sub systems and solution interdependence is analyzed. It is followed by structured reflection using DeBono's (PMI-Plus, Minus, Interesting) method. The solution concepts are then ranked relative to a reference design concept against the metrics which reflect customer preferences as identified earlier.

| Concept Solutions | | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 | +2 | NA | 0 | -2 | -1 |
| 2 | +2 | NA | 0 | +1 | -1 |
| 3 | +2 | NA | 0 | -2 | -1 |
| 4 | +2 | NA | 0 | -2 | -1 |
| 5 | +2 | NA | 0 | -2 | -1 |
| 6 | +2 | NA | 0 | -2 | -1 |
| 7 | +2 | NA | 0 | -2 | -1 |
| 8 | +2 | NA | 0 | -2 | -1 |
| 9 | +2 | NA | 0 | -2 | -1 |
| 10 | +1 | NA | 0 | -2 | -1 |
| | | | | | |
| | | | | | |
| | | | | | |

1,2      Superior Performance
0      Reference Performance
-2,-1      Inferior Performance

Figure 48 Alternative Screening Matrix

The alternative screening matrix is then scored using the weights from the Kano results and the final concept is then selected after due deliberation.

In high clockspeed [20] industries is quite rapid and it is very hard to predict requirements 5-10 years out, it is critical to draw both on intuition and experience to identify key operating points in the flexibility objective space and incorporating these features in the product development process.

## 6.4  Time to Expiration

The time to expiration for a flexible design option is shown in Figure 49  Flexible Design Time Line. This timeline is based on two generation of products – Gen1 and Gen2. The flexibility option is based on the decision to embed flexibility in Gen1, to have the Gen2 Features.
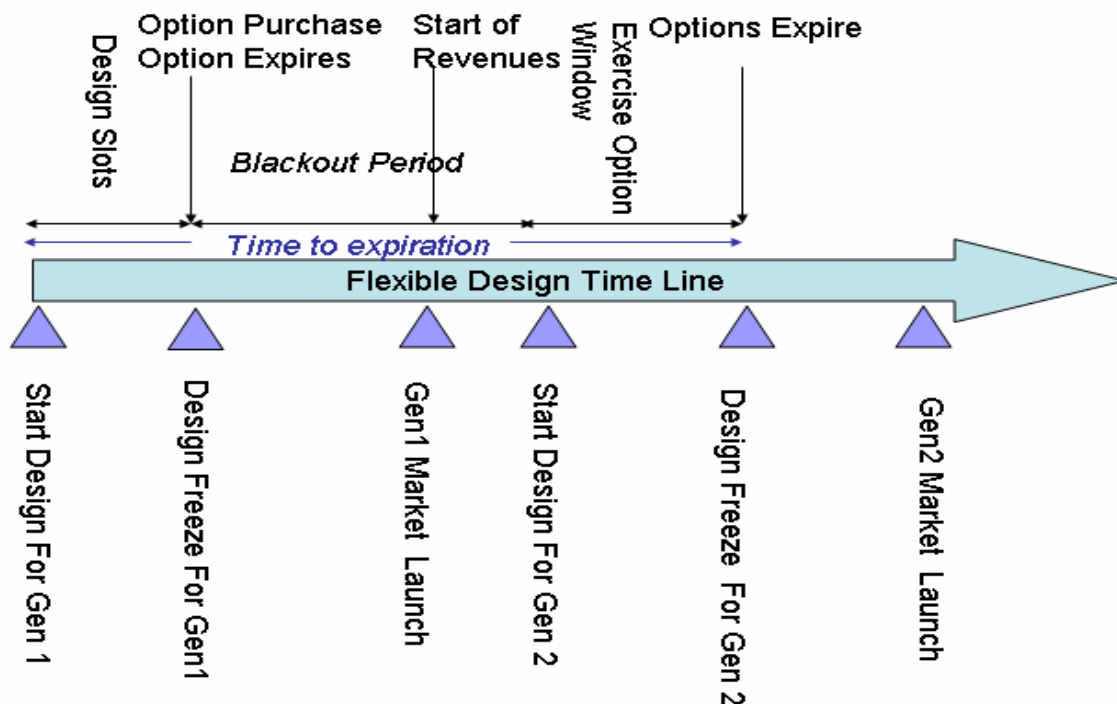


Figure 49  Flexible Design Time Line

The flexibility "slots" have to be designed before the design of Generation 1 is frozen. This is the time when the window to purchase the flexibility option exists. If these slots are designed (based on the cost and value analysis described in the preceding chapters), the decision to "populate' or leverage from this slots can be done at any time before the scheduled freezing of the design of the Generation 2 product. This defines the time to expiration of the flexible design.

These timelines can be quantified on a case to case basis, based on the product and industry dynamics. The time window between the market launch of Generation 1 and Generation 2 can be determined using Christensen's Model [11] as described in the next section.

**Macro Analysis**

The time window between the market launch of Generation 1 and Generation 2 can be estimated by the window of opportunity for the flexible product. Using Christensen's Model [11] to determine the lower bound of this window of opportunity as for a majority of high clockspeed products, this window will be determined by the area where the existing performance[12] exceeds the actual market demand in a high clockspeed industry [20]. This will be the lower bound of the window, assuming there is no perceived performance difference between the Generation 1 and Generation 2 designs as a worst case scenario. The bounds of this window will expand based on how well the performance due to the "slots" designed in the flexible product conform to the actual market perception at a later point in time.
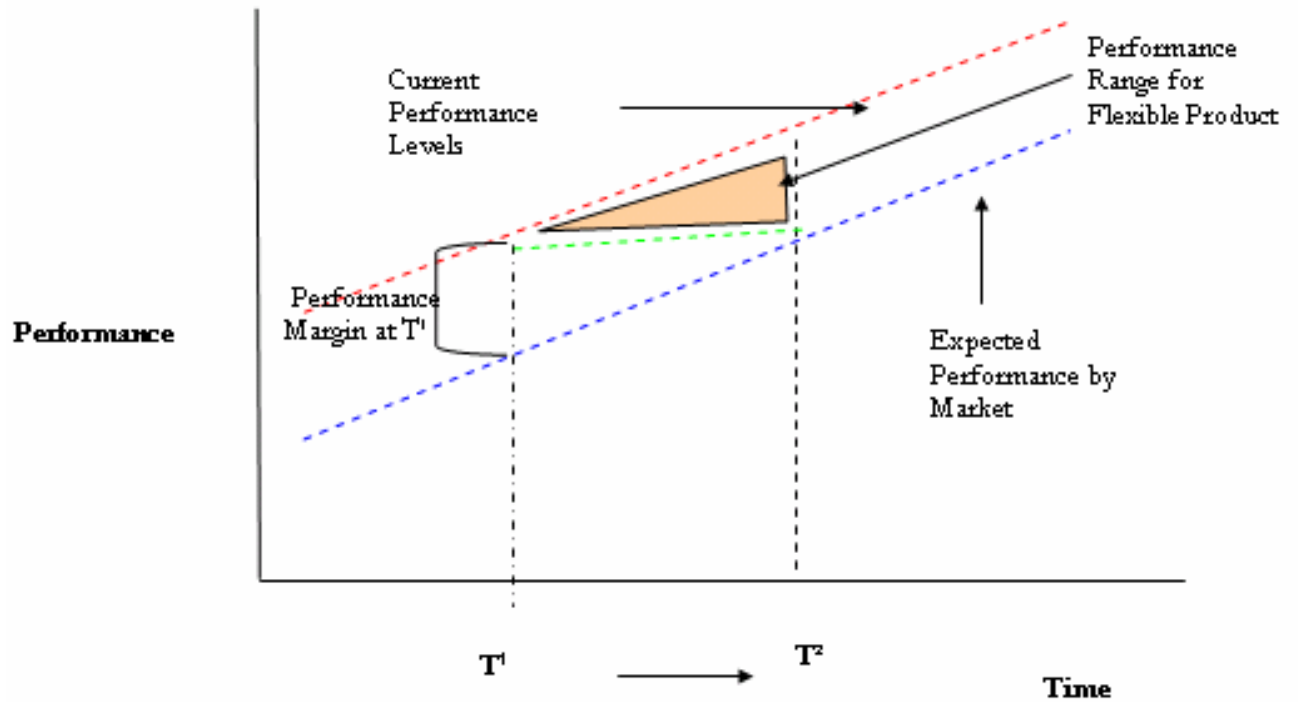
Figure 50 Boundary for Time to Expiration for Flexibility Strategy

for an established product

A guideline to determine the time to expiration is described in product. The shaded area shows the approximate performance range of the flexible product. The boundary of the time to expiration,

$$T^{ExpMax} = T^2 - T^1 \tag{25}$$

---

[12] Performance in this section is used from a less rigorous context and would include functional , capacity and performance aspects described in the earlier chapters.

Where $T^1$ is the current time and $T^2$ is the time where the existing performance becomes the projected expected performance.

In the case where the expected performance is more than the product's performance, future strategies have to be made, based on the projected expected performance. This is shown in Figure 51  Boundary for Time to Expiration for Flexibility Strategy for a disruptive product. This method can be applied for estimating the time to expiration of (typically) disruptive products which have a lower traditional performance to start with, but have a higher ancillary performance, for example a low performance (e.g. Clock cycles for a certain operation), but less expensive and smaller processor can use the ancillary performance (chip - size) to get market share. Once the product has a substantial market share, it can compete on the (traditional) performance metrics.
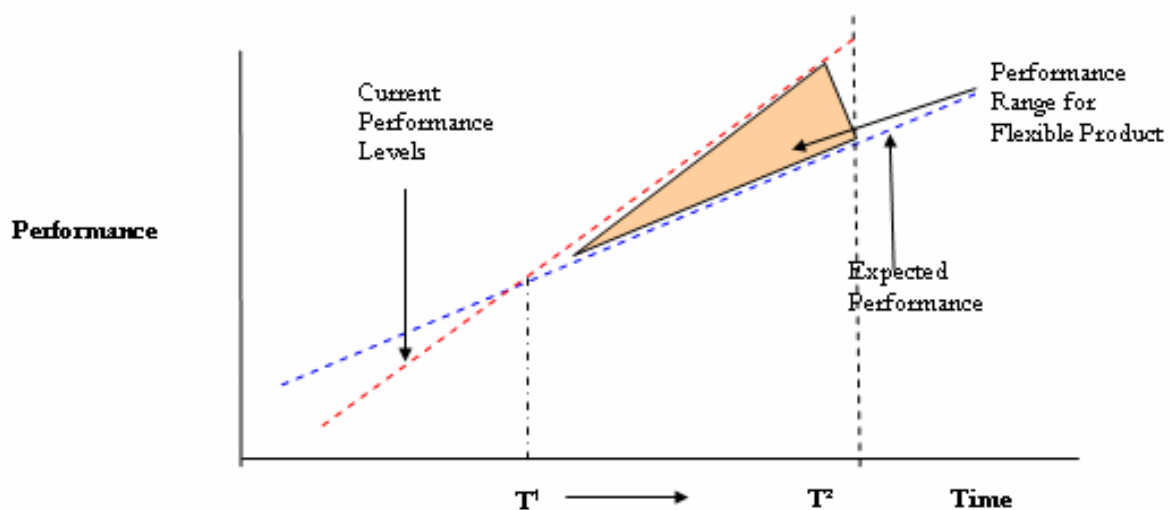


Figure 51  Boundary for Time to Expiration for

Flexibility Strategy for a disruptive product

The effective bound of this window would typically be the minimum of the time to market of the individual performance attributes as described in section 5.3.2 .The actual range should be dermined factoring in the competitive scenario which would dynamically make the expected performance front to shift upwards reducing the window.

The dynamics of this window with respective to the competitive scenario and the expected performance, can be studied in further detail.

## 6.5    Cost

The cost of embedding flexibility includes the cost of designing the flexible feature 'slots' and the cost of populating these slots at a later point in time. We investigate these cost from the context of functional , capacity and performance flexibility using the example of the wireless network application, Application 1, which we used as an example for "embedding flexibility' in Chapter 4.

### 6.5.1   Functional Flexibility

If the flexible objective space cover the whole functional objective space (see Figure 8 Flexibility Design and Objective Space. Adapted from [6]. ), we would have an unconstrained flexibility where we turn a feature off or on in the complete functional

objective space (assuming a constant capacity and performance). As we saw in Chapter 4, in this case there would be cost implications as increased complexity will amount to increased development and operating cost. Another aspect uncovered in Chapter 4 was that configurability of such a system will be very difficult.

This indicates that functional complexity might be optimally handled using discrete operating points from the objective space in case of functional flexibility as shown in Figure 52 Functional Flexibility.
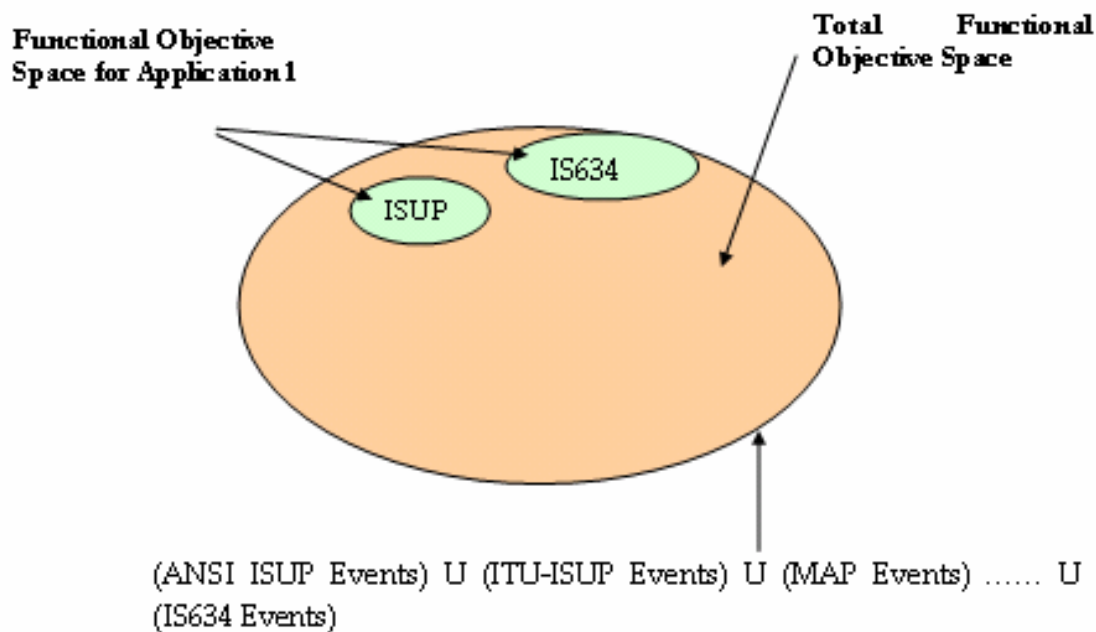


Figure 52 Functional Flexibility as part of the

overall Functional objective space

In the example of the network based wireless application in Chapter 4 , we showed that the functional objective space for an application that can respond to all combination of network events would require that this fully flexible application handles N events , where:

N = (ANSI ISUP Events) U (ITU-ISUP Events) U (MAP Events) …… U (IS634 Events)

Application 1, described in Chapter 4, handled the IS 634 and ISUP events.

The discrete operating points can be enabled by allowing dynamic addition of diverse Application State machines (using an architecture similar to that described in Chapter 4), or enabling some dormant states of an existing state machine. This assumes that flexible functional operating space can be achieved using the existing interfaces with the application specific resources. These "slots" have to be designed as part of the flexible system architecture and can be populated at a later time to achieve functional flexibility. The cost of implementing functional flexibility is the cost of designing the dormant states and "slots" for application resources and some amount of testing of potential future applications.

The cost for populating these slots will be an additional dimension of cost that would be incurred while activating the feature at a later point of time. In the example of flexible handset processor described in Chapter 5, this cost will be the cost of activating the additional cache. In the example of Network based wireless application described in Chapter 4 , this cost will be the cost of interfacing Application 1 with a SMSC.

### 6.5.2   Capacity Flexibility

As described in the previous chapter, this dimension depends on the capacity of the persistent device that gives memory to the state machine – e.g. Enterprise Storage Arrays, Memory, and Flip Flops.  We described in Chapter 4 that how the storage requirement

changes as an application scales from the capacity of 1 Million subscribers to 2 Million subscribers. This additional storage would have a cost implication (see Appendix B for an estimate of cost implications for capacity scaling)

We start with the analysis of a point solution (iso-function and performance) to see the impact on capacity. Once we have suitably explained the behavior of an iso-function/performance capacity flexibility we would build up the framework for the interaction between these dimensions.

### 6.5.2.1 The Platform Strategy

Typically in these applications, the application capacity is represented by total number of subscribers that are supported and is directly linked to the database configuration and the Hard Disk Drive (HDD) capacity. An example of such a system could be -

**Low End Configuration** -

- Less Than 50,000 Subscribers  ( Capacity)
- Less Than 40 calls/second Peak Network Traffic  (Performance)
- 1-2 MSC in the Network. (Capacity)

    Server used –

        CPU (UltraSparc II)

        2@450 MHz Sun Ultra 60

        10 GB HDD

**Medium Configuration** -

- Less Than 200,000 Subscribers

- Less Than 50 calls/second Peak Network Traffic

- 2-4  MSC in the Network.

Server used –

    CPU (UltraSparc II)

    2@450 MHz Sun Ultra 60

    20 GB HDD

**High End Configuration** -

- 250,000 – 2 Million Subscribers

- 50-100 calls/second Peak Network Traffic

- 5-16 MSC in the Network.

    CPU (UltraSparc III)

    4@450 MHz Sun Ultra 80

    2x20GB HDD

Note that in this example the server configuration is same for low and medium configuration (Market driven). The High end configuration has a different server (Technology driven).
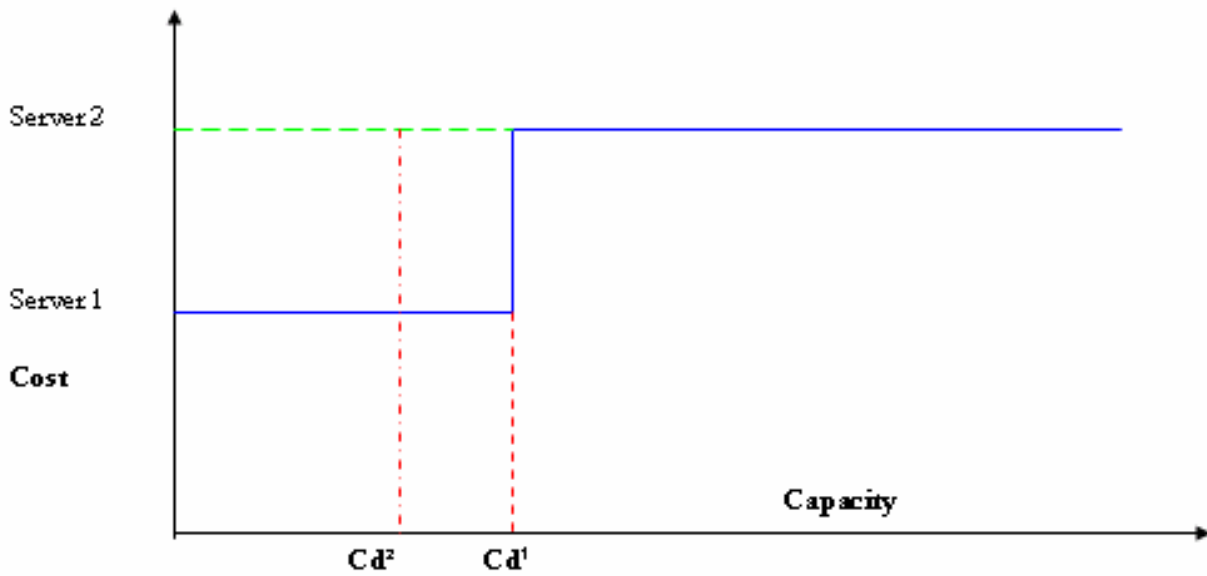
Figure 53  Capacity vs. Cost

If we plot the capacity vs. cost as a graph (Figure 53  Capacity vs. Cost) we see that the cost transitions are discrete (see Appendix B for actual server configuration and cost data).

The capacity is flexible within $Cd^1$ within the same cost objective, however for Capacity > $Cd^1$ there is a discontinuity in the objective space - thus indicating the discrete behavior of Capacity flexibility similar to Functional flexibility. Similar observation is made in flexibility analysis of communications satellites via orbital reconfigurations and staged deployment [40]. The discontinuity will intuitively shift left to $Cd^2$ if we increase the number of functions in the application – increasing the CPU load.

### 6.5.3   Performance Flexibility

As described in the Chapter 4, this dimension depends on the effective bandwidth of input and output from the system for an I/O constrained application and the CPU processing bandwidth for processing constrained applications. The processing and I/O bandwidth is usually limited by the server (or processor board) configuration. A particular configuration would be able to support capacity flexibility to the limit where its resources get constrained.

The plot of Performance vs. cost as a graph is shown in Figure 54 Performance vs. Cost.
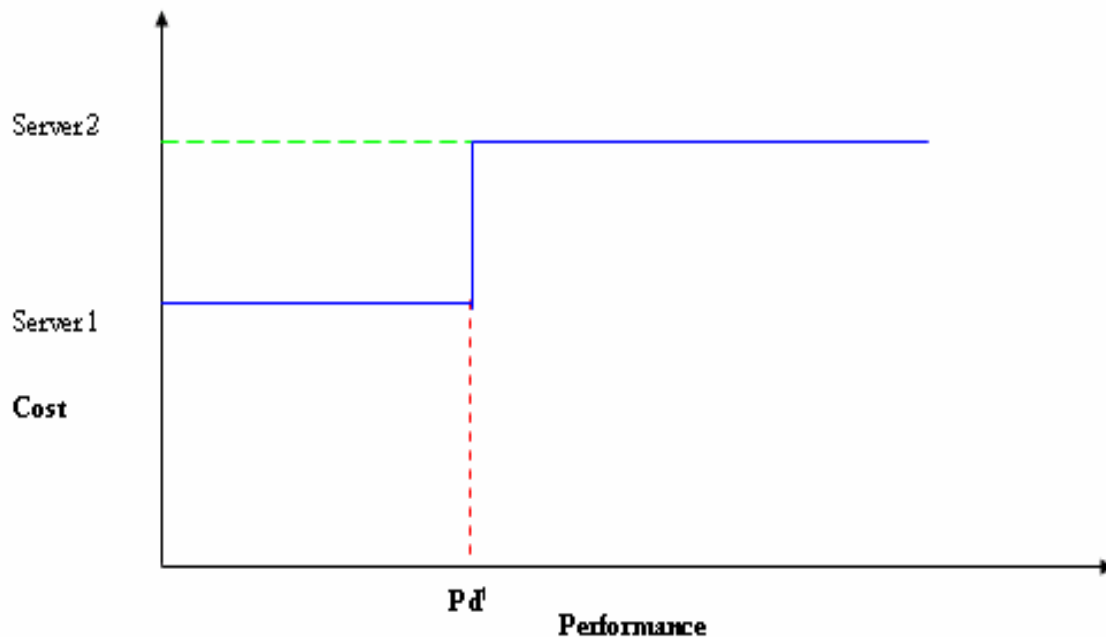


Figure 54 Performance vs. Cost

The Performance is flexible within $Pd^1$ within the same cost objective, however for Performance $> Pd^1$ there is a discontinuity in the objective space. The point of discontinuity shifts with increased functionality.

## 6.6   Conclusion

Methods to determine market volatility, value of the underlying asset and time to expiration were presented in this chapter.

In order to determine the value of the underlying asset, which is one of the terms needed for the valuation of flexibility, two approaches are presented: conjoint analysis and concept engineering. The bounds of time to expiation are explored using Christenson's Model [11] and analysis of the timeline of product life cycle based on two generations of a design. The time to expiration was defined as time window between the start of the first generation design and the planned design freeze date of the second generation design.

We found that Functional flexibility might be optimally handled using discrete operating points from the objective space. The cost of implementing functional flexibility is the cost of designing the dormant states and "slots" for application resources. The cost for populating these slots constitute to an additional dimension of cost that would be incurred while activating the feature at a later point of time. Performance flexibility depends on the effective bandwidth of input and output from the system for an I/O constrained application and the CPU processing bandwidth for processing constrained applications. The processing and I/O bandwidth is usually limited by the server (or processor board) configuration. A particular configuration would be able to support capacity flexibility to the limit where its resources get constrained. This leads to a discrete

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change in cost of the system at this boundary. Capacity flexibility, in way similar to performance flexibility, causes a discrete change in system cost as the database/persistent device capacity is constrained.

*C h a p t e r   7*

# Flexibility Strategy and Conclusions

## 7.1   Introduction

The Flexibility Strategy for a product involves the analysis of the cost and value of embedding flexibility in a product and selecting the optimum flexible design options. Once these options have been selected, the portfolio of real options has to be tracked over time to decide which of these have to be nurtured, exercised or discarded.  Nurturing could involve creating market awareness or demand for a feature that has been designed in flexible product. Exercising the option would mean implementing these features or filling the 'flexible slots'. Discarding the option would mean not exercising the option.

Figure 55 Option Steps for a Flexible Design shows the steps in the comparison of a fixed design versus a flexible design. The cost of designing flexibility or the 'flexible slots' is determined by the cost of the steps $\alpha$, $\beta$ and $\gamma$.  These steps could be combined as one for products where these options cannot be separately purchased.. The cost of implementing flexibility or populating the flexible slots is determined by the cost of step $\delta$.

If the value of the module described in Figure 55 Option Steps for a Flexible Design is $V^{C}_{M}$, where:

V is the value for the product configuration C, for the party M.
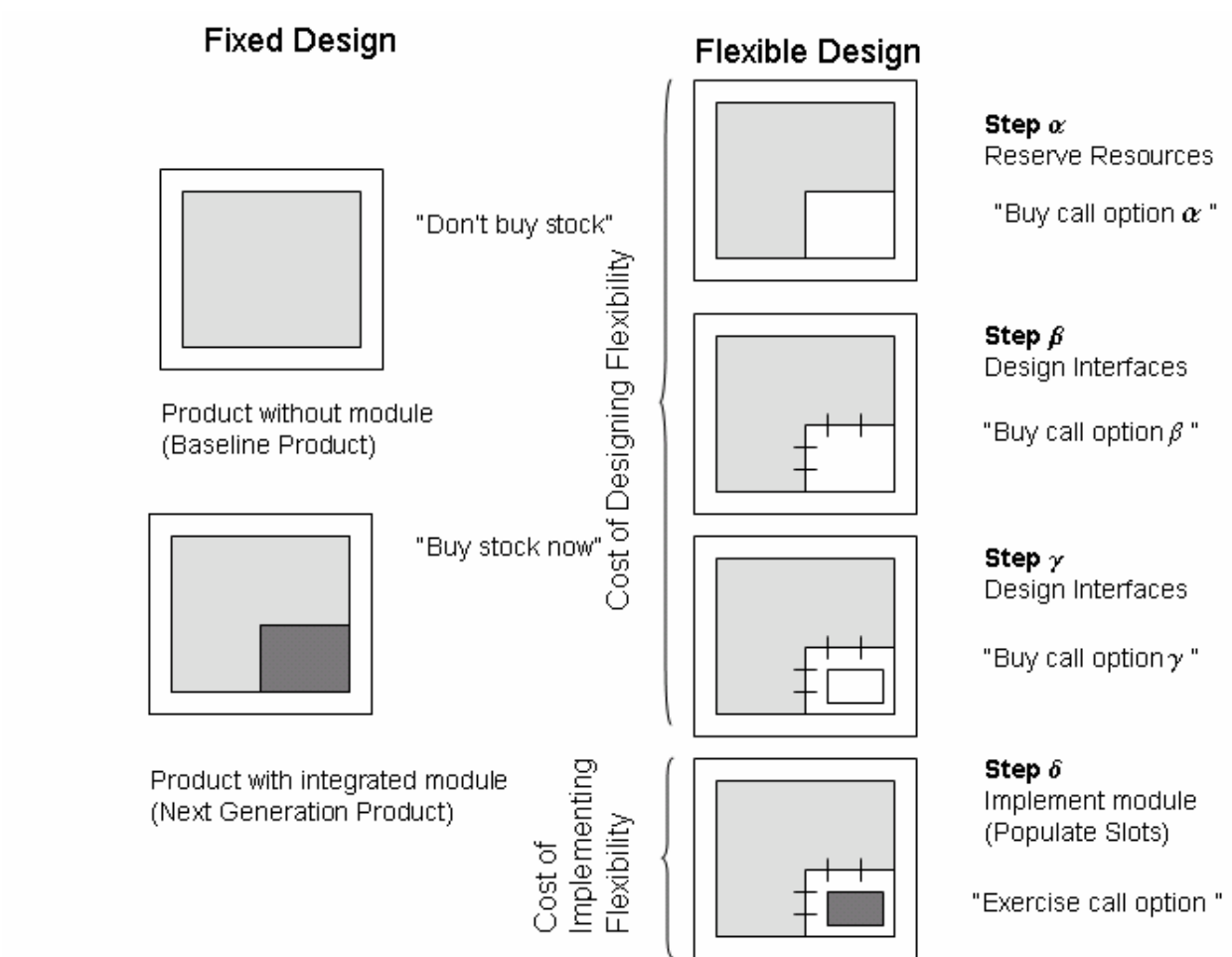
Figure 55 Option Steps for a Flexible Design

M can be customer "C" or enterprise "E" (for this analysis).

C is the product configuration, which can be :

0 : without the module

1: with integrated module

α :with reserved resources for module

β : with interfaces with module

γ : with designed module

δ : with implemented module

Value of the module to the customer, Vmod can be expressed as:

$$V_{mod} = V^1_C - V^0_C \tag{26}$$

The cost of the module to the Enterprise is:

For fixed design option, the cost to the enterprise $C_{Fixed}$, for two generations of the product is -

$$C_{Fixed} = C^0_E + C^1_E \tag{27}$$

For the flexible design option, the cost to the enterprise is $C_{Flex}$,

$$C_{Flex} = C^\alpha_E + C^\beta_E + C^\gamma_E + C^\delta_E \tag{28}$$

The baseline module (first generation only) is recommended when:

$$V_{mod} < Minimum(C_{Fixed}, C_{Flex}) \tag{29}$$

Fixed design is recommended when:

$$C_{Fixed} < Minimum(C_{Flex}, V_{mod}) \tag{30}$$

Flexible product strategy is recommended when:

$$C_{Flex} < Minimum\ (C_{Fixed}\ ,\ V_{mod}) \tag{31}$$

Once Flexible product strategy is found to be the optimal strategy, for different features or 'modules', we need to choose the portfolio of options which are optimal and which we would then embed in the product architecture. These options are for *different* flexibility features.

## 7.2    Option Analysis

To make the optimal decision, we have to choose an optimal set of design options from the flexibility design vector Dp (Eq. 8).  This vector has an associated cost Cf (Eq. 9) along with an associated value of embedding flexibility as computed using the Real Options approach, Vf (Eq. 11).  Figure 56   Flexibility Design Space presents the possible Dp vectors, each with an associated Cf and Vf values. The Y axis represents the cost of flexibility, and the X axis its value.

The choice of flexibility options is different from the choice of financial options because the choice of design options would be done at the time of "embedding" flexibility. Once the initial set is chosen, we are restricted to this portfolio of options for all future product strategies. The choice initial set of design vectors would depend on the decision maker's utility profile and external constraints. We provide the recommendation for choosing these options under three different scenarios.

## 7.2.1    Rate of Return Scenario

In this scenario, the option set with maximum rate of return is chosen, irrespective of other factors. All the points that fall above the y=x line in Figure 56  Flexibility Design Space, have a cost to value ratio greater than 1, and therefore should not be considered as valid flexibility design options.

Let the Cost Vector Cv,

$$Cv = \{C_0 , C_1 .... C_n \} \tag{32}$$

Where,

n is the number of design options,

$C_i$ is the cost Cf of the ith design vector.

The Design Option Vector Dv,

$$Dv = \{D_0 , D_1 .... D_n \} \tag{33}$$

Where,

n is the number of design options,

$D_i$ is  ith design vector.

The Option Value Vector Vv,

$$Vv = \{V_0 , V_1 .... V_n \} \tag{34}$$

Where,

n is the number of design options,

$V_i$ is the real-option value of the ith design vector.

The strategy for maximizing the rate of return scenario would involve choosing the design options from the Design Option Vector, with the maximum return ratio Rmax

Ramax can be also be represented by the minimum slope of the line that corresponds to a valid Design Vector , represented by the normalized value and cost as shown in Figure 56 Flexibility Design Space for maximizing rate of return .

The optimal design options are shown in the figure Figure 56 Flexibility Design Space for maximizing rate of return , which include the design options that have the rate of return between Rmax and Rc , which is the cut off rate of return value.

$$R\max = Min(\frac{C_i}{V_i}), \forall V_i \in V_v, \forall C_i \in C_v \tag{35}$$

Thus the Flexibility Design Option vector, Dfv can be defined as

$$\mathbf{Dfv} = \{\mathbf{D_0}, \mathbf{D_1}....\mathbf{D_m}\} \ \forall \ \mathbf{D_k} \in \mathbf{Dfv}, \ \mathbf{Rc} > \mathbf{C_k}/\mathbf{V_k} > \mathbf{Rmax} \tag{36}$$
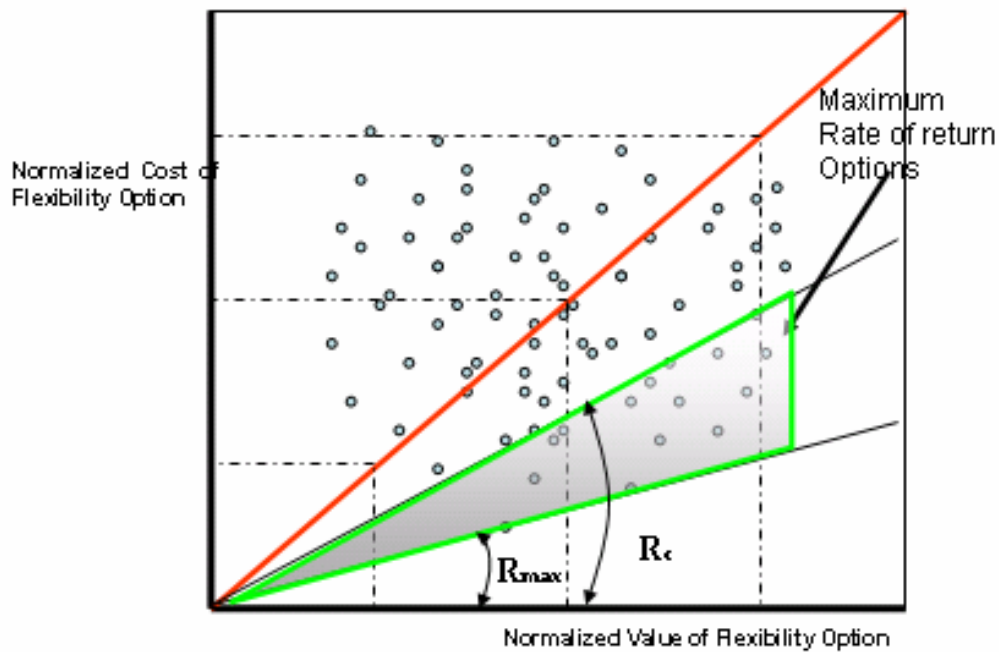
Figure 56  Flexibility Design Space for maximizing
rate of return

## 7.2.2  Unconstrained Scenario

If the only constraint for the choice of Flexibility Design vector is increase of the
incremental value of the investment (without being constrained by the amount of
investment), all the flexibility options, which are below the diagonal in the flexibility
design space can be chosen as shown in Figure 57 Unconstrained Flexibility Options. All
these options provide greater value than cost and thus will increase the incremental value
of the investment.

Net Incremental value of Investment is Inv where :

$$\mathbf{Inv} = \sum\nolimits_{i=0}^{n} (\mathbf{C_i \cdot V_i})\tag{37}$$

To maximize Inv , we have to choose the Design vectors Dv from the Design Option vector , where, $\mathbf{V_i > C_i}$

Thus the Flexibility Design Option vector, Dfv can be defined as

$$\mathbf{Dfv = \{D_0, D_1 \ldots D_m\},\ \forall\, D_k \in Dfv,\ (V_k - C_i) > 0}\tag{38}$$

Where m <= n, the total number of design options. This set is shown in Figure 57 Unconstrained Flexibility Options.

In the unconstrained scenario, some of the options which have a marginally higher cost than value, but have a high volatility, can also be chosen as the value of such options can change favorably in the future.
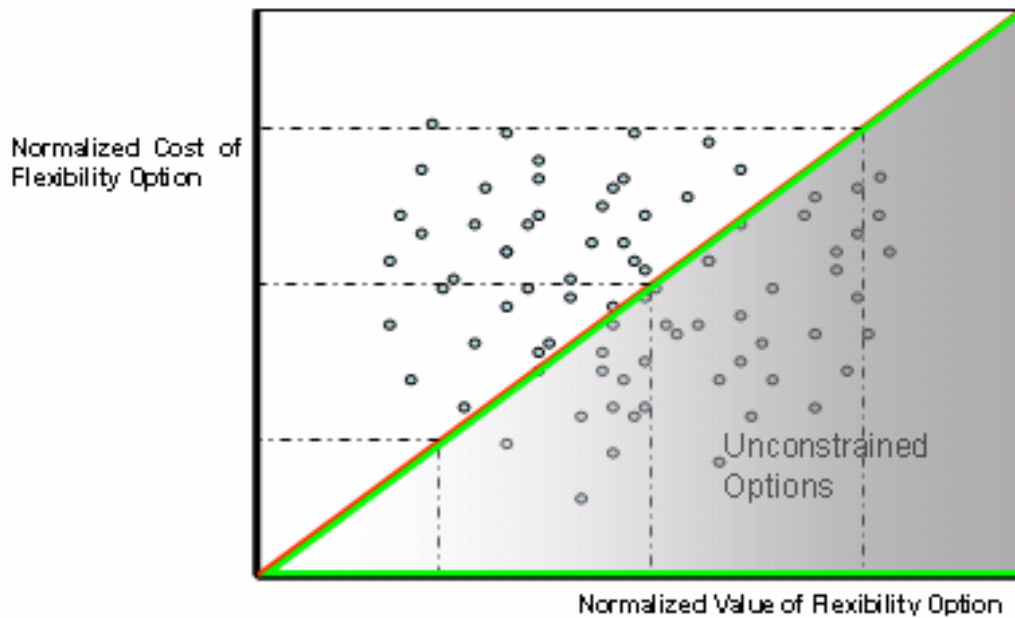
Figure 57 Unconstrained Flexibility Options

### 7.2.3   Constrained Scenario

In the constrained scenario, there could be investment constraints. These constraints can be in the form of limit on the total investment, maximum investment for a single design option, among others. One strategy is to select the optimum design options, with a total investment limit.  The portfolio of optimum design options are selected from the Design Vector, based on their individual rate of return. Design options that have the maximum rate of return are selected till the total cost exceeds the maximum investment limit.

## 7.3 Portfolio of Real Options

Using the cost and value(s) of embedding flexibility, we recommend a Portfolio of Real Options based Flexibility Strategy in this section, which is based on earlier work by T.A Luehrman [25].

The main concept of this approach is that once we ascertain the value, cost and the volatility of the optimal design front identified in the previous section, we have to devise a strategy to activate these options at a future point of time.

We can make the flexibility strategy based on the value-to-cost and volatility dimensions that exist at a given point of time. The first in the chain of this option is the value of the optimal design Pareto front as a whole. This will drive the decision to invest in the R&D and design cost for this portfolio. This decision would be linked with "activating" the individual features at a point time in the future. As we mentioned in the last section , the design parameters optimum design parameters would change with time and some of these would turn out to be really profitable , others not. Doing this analysis would help us to determine the investment we could make in "nurturing" a particular type of design option, or "write off" another. The nurturing costs could include advertising expense, costs to make strategic alliances etc. The key point of this method is to see the portfolio of optimal design parameters identified in the previous section as a chain of options rather than static NPV based decision.

## 7.4    Conclusion

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The flexibility of a system is its ability to meet a changing set of requirements after it has been fielded under new modes of use or changes in its environment. The purpose of this research was to provide a framework for estimating the *value of embedding flexibility* in the design of a system and to recommend a strategy based on this value that would enable us to make decisions to choose the flexible attributes and the resources to invest in these attributes for optimum value capture.

Real Options analysis was used to model the payoffs associated with the flexible design options in the face of uncertainty. This approach is more suitable than the Net Present Value (NPV) based analysis which assumes a static view of the market, when in reality, uncertainty and investment choices exist together and these choices are spread over time. As uncertainty resolves, downside losses can be avoided by not investing more funds into projects which have poor performance.

The Real option Analysis of Flexibility, which was explored in detail in this thesis can be summarized using de Weck's general real option reasoning framework [40] as shown in Figure 58 General Real option reasoning Framework (adapted from [40]).
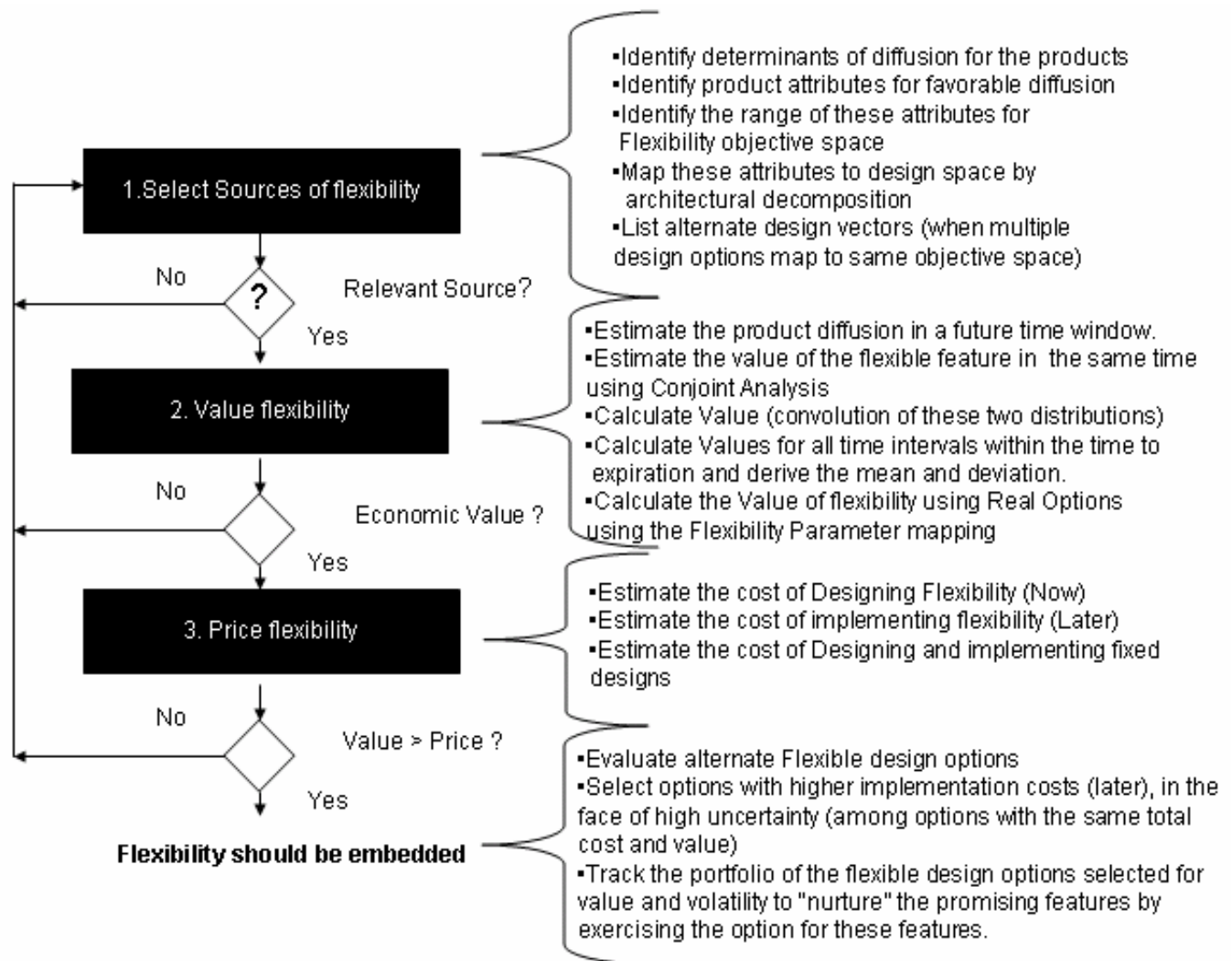
Figure 58 General Real option reasoning
Framework (adapted from [40])

## 7.5    Future Work

Beyond the work done in this thesis, research avenues could include more accurate
quantitative methods for computing volatility for flexible design variants in the face of
uncertainty for breakthrough products.   Furthermore, a comprehensive methodology

could be developed for determining the bounds of the expiration time for exercising flexible design options.

The comparison of fixed and flexible design options which was done in this thesis can be extended to develop quantitative models of  the tradeoffs between the flexibility design costs and flexibility implementation costs and  how moving the costs from design to implementation , affects the relative attractiveness of a flexible design option as compared to a fixed design.

The tradeoff between the flexibility dimensions - functional flexibility, capacity flexibility and performance flexibility can be quantitatively analyzed within given resource constraints.

# *A p p e n d i x   A*

## GSM, TDMA & CDMA Overview

### GSM – Global System Mobile

**Frequency Bands**

GSM operates in three frequency bands – Cellular, PCN and PCS. The frequency allocations in these bands are –

Cellular -  890-915MHz and 935-960MHz

PCN –      710-785 MHz and 1805-1880MHz

PCS -      1850-1910 MHz and 1930-1990MHz

The first half of the bands is used for transmitting and the other half is used for receiving.

**Modulation Scheme**

Each band is subdivided into 124 FDM channels spaced 200KHz apart. Each of these carrier frequencies is further subdivided into .577 ms TDM channels which are used for control messaging and voice traffic. The traffic channel burst of 156 bits of data has two blocks of 57 bit data and a 26 bit training sequence.

### TDMA – IS-136

**Frequency Bands**

IS-136 operates in the Cellular and PCS frequency bands (900 and 1900 MHz).

**Modulation Scheme**

TDMA uses differential quadrature phase shift keying and provides an across air bit rate of 48.6 Kbps. The TDMA frame is of 40 mS duration with six 6.67 ms slots per frame. Two slots are allocated for full rate voice channel.

# CDMA – IS-95

**Frequency Bands**

Uses AMPS band (Analog). 824-849 MHz for uplink and 869-894 MHz for downlink. 1.2 MHz bands with frequency spacing of 45 MHz.

**Modulation Scheme**

Code Division Multiple Access, uses a spread spectrum modulation scheme. The signal is spread using a pseudo random noise sequence. Offset Quadrature Phase Shift Keying (OPSK) is used for reverse channel and Quadrature Phase Shift Keying (QPSK) for forward channels.

# *Appendix B*

## Cost Implication for Capacity Scaling of Database Applications

The Capacity scaling considered here is based on the size of the storage (hardware cost) and the database license (software). These costs are based on the pricing information available in the public domain at the time this appendix was written. The hardware and database configurations are based on the analysis of Application 1 storage requirement described in Chapter 5.

| CAPACITY (SUBSCRIBERS) | CONFIGURATION | COST ($) | TOTAL COST ($) |
|---|---|---|---|
| 100,000 – 500,000 | **Hardware**<br><br>Sun Fire B100s SPARC Blade Server w/1-GB Memory<br><br>**Database**<br>In Memory Database (1GB limit) | 6,590<br><br>10,000 | **16,590** |
| 500,000 – 1 Million | **Hardware**<br><br>2 x Sun Fire B100s SPARC Blade Server w/1-GB Memory | 8,385 | **18,385** |

| | | | |
|---|---|---|---|
| | **Database**<br><br>In Memory Database (1GB limit) | 10,000 | |
| 1 Million – 2 Million | **Hardware**<br><br>4 x Sun Fire B100s SPARC Blade Server w/1-GB Memory | 11,975 | **29,975** |
| | **Database**<br>In Memory Database (2GB limit) | 18,000 | |

Figure B-1 Capacity Scaling

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