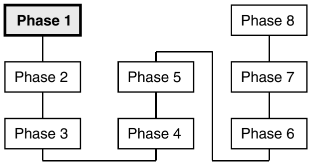
5

Performance and Specification in the Front-end Phase



5.1 Introduction

The front-end phase is phase 1 (stage-I, level-I) in Figure 2.4. The performance and specification in phase 1 were discussed in Section 3.6.1. In this chapter, we discuss this in more detail. The processes for defining the desired performance DP-I for standard and custom-built products differ slightly. When DP-I has been decided, the processes for deriving the specification SP-I and the predicted performance PP-I are similar.

The outline of the chapter is as follows: Sections 5.2 and 5.3 deal with standard products. We start with a discussion of the overall process in Section 5.2. It involves three sub-phases and each of these is discussed in more detail in the next three sections. Section 5.3 looks at data collection and data analysis, Section 5.4 deals with idea generation and screening, and Section 5.5 deals with product concept formulation and evaluation leading to defining DP-I, and deriving SP-I and PP-I. In Section 5.6 we look at performance and specification for specialized (custom-built) products. Section 5.7 looks at the reliability implications of the decisions made in the front-end phase and forms the link to the next chapter. In Section 5.8, we discuss issues related to the case study on cellular phones.

5.2 Front-end Process for Standard Products

The process for deciding on product performance and specification for standard products is shown in Figure 5.1 and involves the three sub-phases indicated below.

Sub-phase 1 – Data collection and analysis: Analysis of data may indicate whether or not there is a need for new product development (NPD). We discuss problems related to data collection and the tools and techniques for data analysis in Section 5.3 and illustrate some typical scenarios leading to new product development.

Sub-phase 2 – Idea generation and screening: Some of the basic concepts were discussed in Section 2.5.1. We build on this discussion and focus on the tools and techniques needed for carrying out this in Section 5.4.

Sub-phase 3 – Product concept formulation and evaluation: Some of the basic concepts were discussed in Section 2.5.1. We build on this discussion and focus on defining DP-I based on the outcome of the earlier two sub-phases and then deriving SP-I and PP-I. The process is iterative as shown in Figure 5.1. We discuss tools and techniques, and models that are needed in Section 5.5.

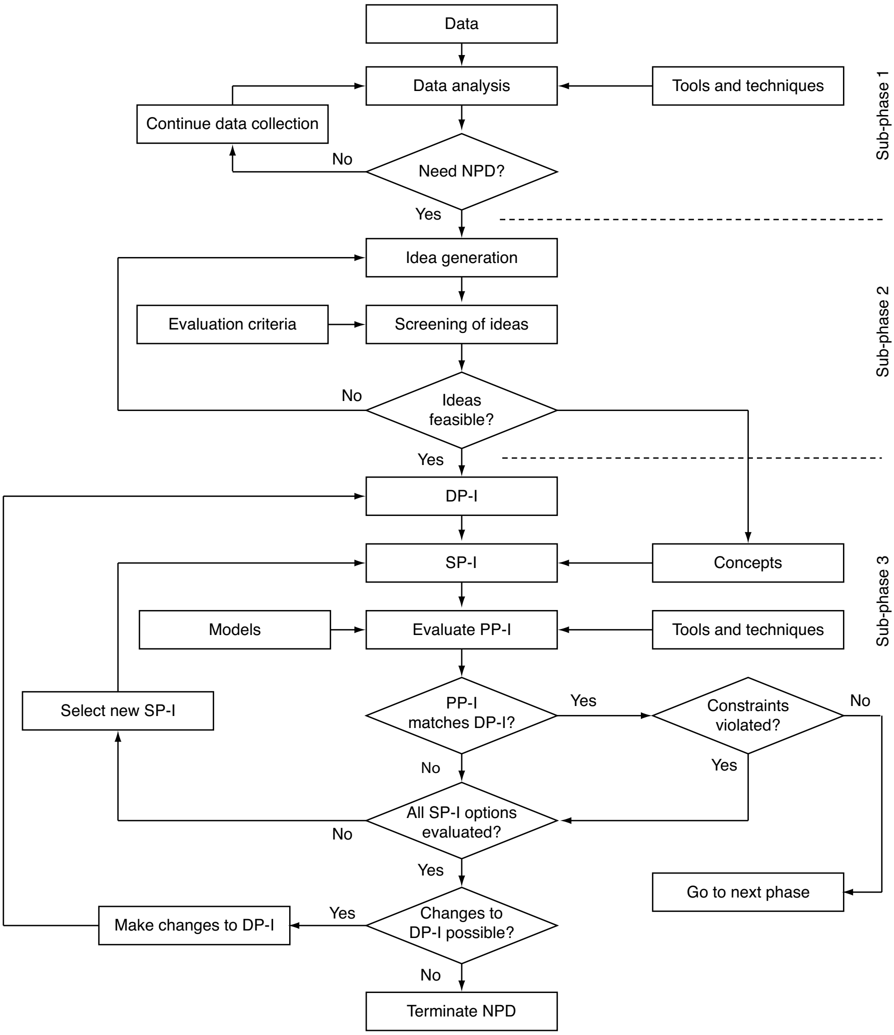


Figure 5.1. Front-end process for standard products

It is not possible to give the details of all the tools and techniques that are needed in each of the three sub-phases. Instead, we discuss a few important ones and give references where interested readers can get more details. Similarly, it is not possible to discuss all the different models that have been developed. Rather, we focus on some simple models to illustrate the use of models in decision making and cite references where interested readers can get details about other models.

5.3 Data Collection and Analysis [Sub-phase 1]

Many different kinds of data collected by manufacturers are relevant in the context of new product development. Data analysis transforms the data into information and this can be done at many different levels. The information forms the basis for decision making on whether to proceed with new product development or not. Figure 5.2 shows the links between data, analysis, information, and decision making.

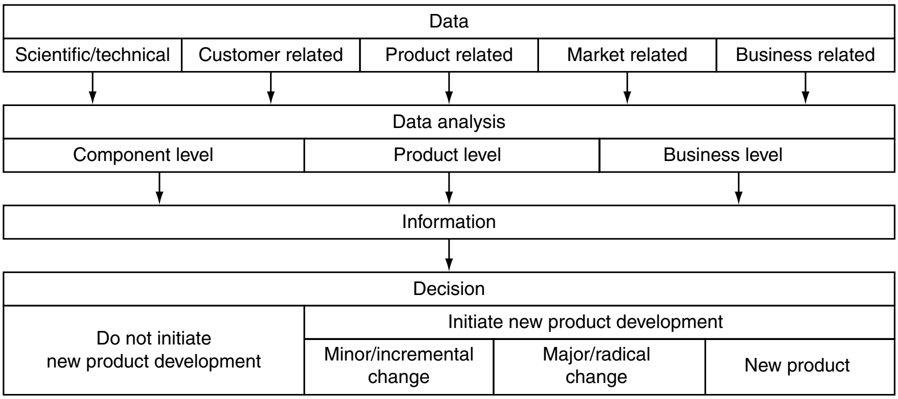


Figure 5.2. Data analysis in sub-phase 1

5.3.1 Data Collection

The data relevant for decision making in the front-end phase can be broadly grouped into the following categories:

- Scientific/technical data
- Customer related data
- Product related data
- Market related data
- Business related data

The main sources for the data are the following:

Management systems: Businesses use many different types of management systems. These, along with examples of the kind of data they provide, include: accounting systems (cost data); project management systems (product-related data during development); production systems (product-related data – e.g., conformance to specification during production); supply management systems (material flow data); customer support systems (customer-related data).

Market surveys: Market surveys are carried out to obtain commercial and customer-related data. This involves carefully designed questionnaires in order to obtain valid and reliable data.

Warranty servicing and field support: Data from warranty service and field support provide valuable information regarding product performance in the field. If the data are collected properly, it should also provide useful customer-related information such as usage mode and intensity, customer satisfaction and needs.

Data collection is discussed in more detail in Chapter 11.

5.3.2 Data Analysis

Data analysis is the summarization and presentation of the data. Summary values provide concise measures of the basic information content and graphical presentations give the overall picture. These are needed for effective decision making. The analysis depends on the type of data. The tools and techniques needed for analysis are discussed in Chapter 11.

The analysis can be done at three different levels as indicated in Figure 5.2 and we discuss each of these.

Component Level

The component level analysis deals mainly with technical data related to component performance. In the context of reliability, this includes failure modes and causes of failures (root cause analysis), times to failure, repair times (in the case of repairable components), cost of repairs, and so on. This kind of data is generated during the development and the post-sale phases of the product life cycle. The analysis provides estimates of the component reliability and this helps in deciding whether further development is needed or to replace the component with a more reliable one.

Product Level

The data at product level can be technical, economic, and usage related. In the context of reliability, the analysis provides information regarding product reliability in the field (technical), warranty costs per item sold (economic) or customer satisfaction (usage related). This can then be used for decision making, such as to improve the production process (if the problem is quality variations in production) or to improve reliability through design changes (e.g., reduce warranty costs, increase customer satisfaction).

Business Level

The business level data deals with product performance from the business viewpoint and changes in the market that can affect sales and revenue. As such, the analysis of market-related data yields information regarding trends and influence of competitors' actions; technical data provide information regarding the potential for new products, and so on.

5.3.3 Outcome of Sub-phase 1

The outcome of sub-phase 1 is a decision whether to initiate a new product development programme or not. In the former case, we proceed to sub-phase 2 and in the latter case we continue with data collection and analysis as indicated in Figure 5.1. We indicate four different scenarios for new product development and these correspond to the "opportunities" in Figure 2.2.

Scenario 1

Business level analysis indicates that customers are happy with the product, but the warranty costs are higher than expected and hence result in reduced profits. The driver for improvement is top management wanting to improve the overall profit by reducing the warranty costs. The aim of the product development is to improve the reliability of the product by minor changes to the design.

Scenario 2

Price is an important variable in the marketing of a product. The price needs to decrease with time unless there is periodic product upgrade to counteract the price erosion and ensure the desired profit margin. In this scenario, the product development is to improve the existing product (within the same product platform) and is driven by economic considerations.[1]

Scenario 3

A competitor has introduced a product that the customers consider to be better and this has affected the sales of the manufacturer's current product. One way for the manufacturer to counteract this is through a new and improved product (with better performance attributes) along with better product support (e.g., longer warranty period). In this case, the driver for the new product is a market factor and the new product needs to be significantly better than the existing product.

[1] Manufacturers of notebook computers based on the 486 CPU upgraded their products periodically, each time incorporating some combination of new screen, CPU, battery, hard drive or RAM. Eventually, the Pentium CPU made platforms based on the 486 CPU obsolete (Wilhelm and Xu, 2002).

Scenario 4

A new scientific breakthrough indicates the potential to develop a new breakthrough product.[2] However, it involves developing new technology that is costly and the outcome is uncertain. If the technology can be developed, the new product may have a significant impact and may result in very high returns on investment. In this case, the initial focus of the new product development is to develop the technology needed and come up with a prototype of the product. In this case, the product development is technology driven.

5.4 Idea Generation and Screening [Sub-phase 2]

In Section 2.5.1, we defined the notion of "idea" in the context of new product development. In this section, we look at idea generation, screening of ideas, and discuss the relevant tools and techniques needed for these. We start with customer understanding.

5.4.1 Customer Understanding

Customer understanding is very important in the context of new products. According to Ulwick (2002):

> "An often heard argument is that asking consumers what they want is useless, because they do not know what they want."

According to Flint (2002):

> "Many organizations do not know what kinds of customer information they ought to be collecting, do not have the skills to do so even when they do know, do not have formal processes designed to capture important customer information and/or are in too much of a hurry to move from ideation (i.e., idea generation) and screening to development phases of NPD.
> Many of the new products floating around firms these days may be unhelpful at best and harmful at worst because they are internally generated creative ideas not well founded in customer understanding that act more as distractions than sources of meaningful opportunities."

This indicates that understanding customer needs is a challenging problem. Some of the techniques and tools developed to assist in this process are the following:

Customer value determination process: This process is designed to capture deep customer knowledge.[3]

[2] For more on breakthrough products, see Deszca et al. (1999)
[3] For more details, see Woodruff and Gardial (1996).

> "It involves qualitative and quantitative research aimed at identifying customer value dimensions, determining strategically important value dimensions, determining satisfaction with value delivery, exploring value delivery problems, all within the target market segments" (Flint, 2002).

Ethnography and participant observations: Here the focus is on understanding the cultural and sociological meaning inherent in the product usage. This is done through spending extended periods of time with customers to gain deep insights into the customer needs and their usage of the products.[4]

> "These ethnographic approaches have yielded successful new product ideas because they tap into what we really mean when we say 'the voice of the customer' " (Flint, 2002).

Quality function deployment (QFD): This approach uses a multi-disciplinary team to determine customer needs and translate them into product design through a structured and well documented framework.[5]

5.4.2 Idea Generation

Sources

There are several sources for idea generation and these include:

- Suppliers, distributors, sales persons
- Trade journals and other published material
- Warranty claims, customer complaints, failures
- Customer surveys, focus groups, interviews
- Field testing, trial users
- Research and development
- Perceptual maps (visual comparison of customer perceptions)
- Benchmarking (comparing product/service against best-in-class)
- Reverse engineering (dismantling competitor's product to improve the product)

Tools and Techniques

There are many different tools and techniques that are useful for idea generation.[6] One of these, that is extensively used, is conjoint analysis.

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[4] For more details, see Atkinson and Hammersley (1994).

[5] For an interesting historical review of QFD, see Akao (1997). For an introductory discussion of the basic concept, see Hauser and Clausing (1988).

[6] These include category appraisal, conjoint analysis, emphatic design, focus group, free elicitation, information acceleration, Kelly repertory grid, laddering, lead user technique, Zaltman metaphor elicitation technique. Creativity enhancement techniques such as brainstorming, lateral thinking, synectics and innovation templates help in idea generation. For further details of these, see Kleef et al. (2005).

Conjoint analysis is a systematic approach for matching a new product with the needs and wants of customers. It is a way to understand and incorporate the structure of customer preferences into the new product development process. In particular, it enables us to evaluate how customers make trade-offs between various product attributes and is based on the following assumptions:

- Product/service is realistically decomposable into a set of basic attributes
- New product alternatives can be synthesized from basic alternatives
- Product/service alternatives can be realistically described, either verbally or pictorially

The method involves:

- A numerical assessment of the relative importance that customers attach to different attributes of a product category
- The value (utility) provided to customers by each potential feature of a product

5.4.3 Screening of Ideas

For a manufacturer to assess ideas, (i) they must first be defined to a level of detail that allows valid assessments to be made, and (ii) suitable criteria for evaluating the ideas need to be defined. The criteria involve several factors and these can be divided into several different broad categories as indicated below.[7]

Product related: Technical feasibility, type of technology involved, research and development needed, and fit with product platform and technology strategies
Market related: Demand, meet customer needs, sales, new and existing markets, and so on
Financial related: Investment needed, returns, risks
Business related: Fit with long-term business (corporate, technology, marketing strategies)

Tools, Techniques, and Models

Many different tools, techniques, and models have been developed to help the screening of ideas. Ozer (1999) surveys the different models and approaches for new product evaluation and some of them are given below.

Analogies: This method uses the historical data of similar products to assess the success of a new product.
Expert opinions: Here, experts provide their opinions about the prospect of a new product.
Purchase intentions: In this method, potential customers evaluate the product to state their intentions whether they will purchase or not.

[7] Udell and Baker (1982) suggest 33 factors grouped into several categories – societal factors, business risk factors, demand analysis factors, market acceptance factors, and competitive factors. See also, Brentani (1986) for further discussion on screening factors.

Multi-attribute models: Here, consumers evaluate a product based on description of its attributes to evaluate consumer preferences.

Focus groups: This involves a group of consumers (or experts) in an open and in-depth discussion about the new product with a moderator leading the discussions.

Some other well-known methods are (i) idea scoring methods (Kleef et al., 2005) and Analytical Hierarchy Process (Calantone et al., 1999).

5.4.4 Outcome of Sub-phase 2

The outcome of sub-phase 2 is a set of feasible ideas that form the basis for product concept formulation and evaluation.

5.5 Product Concept Formulation and Evaluation [Sub-phase 3]

The starting point for sub-phase 3 is a product strategy that is a part of the overall business strategy. This defines the desired performance DP-I at the business level. Each product concept defines product specification SP-I in the front-end phase. Models are required to derive the predicted performance PP-I for each SP-I. PP-I is then compared with DP-I to see if a concept is worth pursuing further. This is an iterative process as indicated in Figure 5.1. In this section, we discuss this process in more detail.

5.5.1 Defining DP-I

Once a decision is made to proceed with new product development, the starting point is formulating the new product strategy. This requires addressing the following questions:

- What portfolio of product opportunities should be pursued?
- What should be the timing of product development projects?
- Should any product platforms be shared across the products?
- What technologies should be employed in the products?

The choice of product variants (if there is more than one product) must balance heterogeneity in preference among consumers and the economies of standardization in design and production.

DP-I defines what the new product must achieve for the business and this is stated through business objectives. In other words, DP-I is the desired performance at the business level. The business objective involves several elements that can be broadly grouped into four categories as indicated in Figure 5.3. We discuss the salient features of each of these.

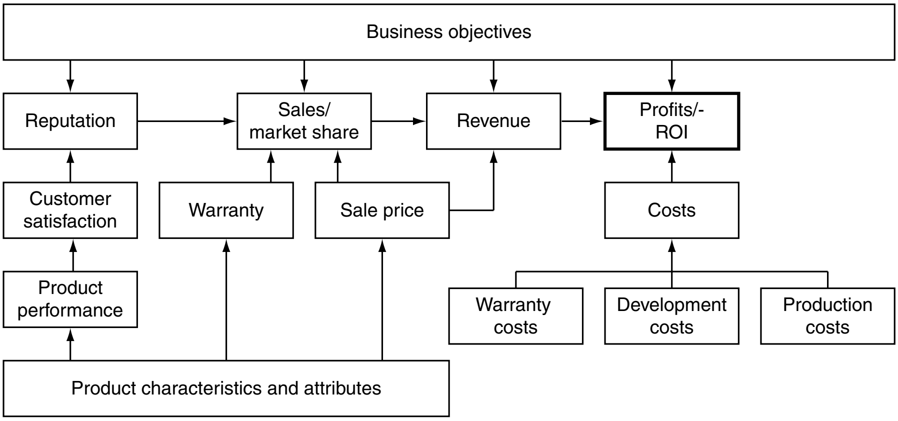

Figure 5.3. Key elements of DP-I and SP-I

Reputation

Reputation is a complex entity and relates to issues such as business reputation, product image, customer satisfaction and loyalty, and so on. These in turn have an impact on share value of the business and the sales of new products.

Customer Satisfaction and Loyalty

Satisfaction (or dissatisfaction) is linked to discrepancy between prior expectations and the actual (or perceived) product performance and product support. A customer is satisfied when performance exceeds expectations. The reverse situation leads to a dissatisfied customer.[8]

Consumers' perceived expectations regarding a product (performance and support) depend on several factors and can include different notions of product quality, value-price concept (a more costly product must perform better), manufacturer's reputation, product advertising, and so forth. This is important as customers do not buy products or services as much as they buy expectation.

> "As autos get better, consumers are getting pickier about what they identify as a problem. Many automakers have started to take consumer expectations into account when they set out to design a new model. As a result, new autos today are better vehicles than cars produced just a few years ago." (Evanoff, 2002)

Measuring customer satisfaction/dissatisfaction can be done through a properly designed questionnaire using a scale with discrete levels and ranging from strongly

[8] Most books on consumer behaviour (e.g., Neal et al. (1999)) discuss consumer satisfaction in detail.

satisfied to strongly dissatisfied.[9] Another approach is through critical incidents, that is, events that are out of the ordinary in the mainstream of events that may occur. Such an incident may cause a positive or negative adjustment to a customer's opinion of the product performance or its support services.[10]

The level of dissatisfaction depends on the timing of failure and the dissatisfaction decreases with time. Figure 5.4 shows four scenarios where W corresponds to the instant of warranty expiry.

(a) Failure occurring very soon after purchase resulting in high level of dissatisfaction
(b) Failure occurring within the warranty period but not very soon after purchase resulting in medium level of dissatisfaction
(c) Failure occurring very soon after the warranty has expired resulting in high level of dissatisfaction
(d) Failure occurring well after the warranty has expired resulting in low level of dissatisfaction

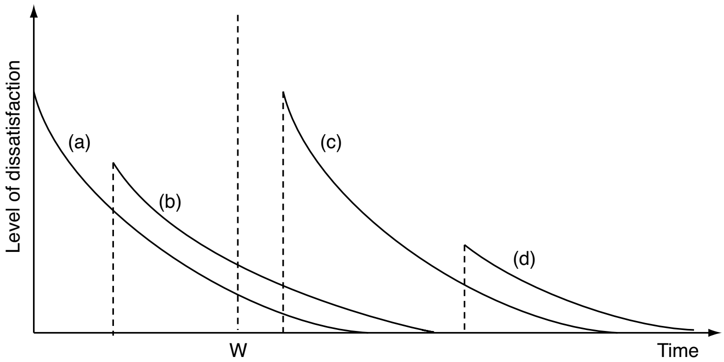

Figure 5.4. Dissatisfaction level versus timing of failures

The overall dissatisfaction is the cumulative sum of dissatisfaction from all the failures experienced. Satisfaction and loyalty are closely linked. Satisfaction is necessary, but not sufficient, for loyalty. Loyalty relates to repeat purchases and new purchases through referrals (word-of-mouth effect). According to Gitomer (1998),

> "The only way to measure loyalty is by the number of unsolicited referrals and re-orders received by the seller."

Customer loyalty impacts on profits:

9 Measuring satisfaction for consumer durables is different from that for industrial products. For more details regarding satisfaction with consumer durable products, see Oliver (1996). For industrial products, see Homburg and Rudolph (2001).

10 For more on critical incidents, see Flanagan (1954). Archer and Wesolowsky (1996) use this approach to study consumer response to product performance in the case of automobiles.

> "A 5% increase in customer retention leads to an increase in profits of 25–95% over 14 different industry sectors." (Reichheld, 1996)

If customers are dissatisfied either with the product or service quality, then they are more likely to switch.

Sales and Market Share

In a monopolistic market (with one single manufacturer), the total sales over the life cycle of a product depend on a number of marketing variables. Variables that have a significant impact on the sales are: warranty, sale price, advertising, product characteristics, quality of product, reputation of the manufacturer, and so forth. In a competitive market (with several manufacturers producing nearly similar products) the marketing variables of the other manufacturers determine the market sales and market share for a manufacturer.

Revenue

The revenue generated depends on the sales and the sale price. It is obtained as the product of total sales at different sale prices and summing over all different sale prices (in the case where the price changes over the product life cycle).

Profits and Return on Investment

The profit is given by the difference between the revenue and the costs. There are several kinds of costs and the main costs that are relevant to DP-I in the context of reliability are indicated in Figure 5.3. Other important costs include the marketing costs, financial costs, technology acquisition, and so on.

The investment is the initial capital needed to develop the product, the acquisition of technologies from outside, the setting up of the production facilities and the operating costs until the start of revenue income. The return on investment (ROI) is the ratio of the returns (revenue over the product life cycle) to the investment. We would need to use a proper discounting procedure as the investment is done at the start and the revenue is generated over the product life cycle.

The development and production costs are the costs involved during the development and the production of the product. The warranty costs are the costs associated with the servicing of claims under warranty.

Illustrative Scenarios

Defining DP-I requires linking product performance to business objectives and stating the constraints. In Section 5.3.3, we indicated four scenarios. In Scenario 1, the DP-I is to ensure that the warranty cost (as a fraction of the sale price) for the new product is below some specified value and that the product development must not exceed some cost limit and the project must be completed within some specified time limit. In Scenario 3, the DP-I is to achieve a certain market share subject to ROI exceeding some specified value.

5.5.2 Deriving SP-I

SP-I is defined in terms of target values for product attributes and features (including price) and for product support services (warranty, extended warranty, service contracts) that will achieve the desired business objectives (DP-I). In case of product variety, these need to be defined for each product type. We focus our attention on attributes and features that are relevant in the context of reliability design.

Warranty

A warranty is a manufacturer's assurance to a buyer that a product or service is or shall be as presented. It may be considered to be a contractual agreement between buyer and manufacturer (or seller) which is entered into upon sale of the product or service. A warranty may be implicit or it may be explicitly stated.

In broad terms, the purpose of a warranty is to establish liability of the manufacturer in the event that an item fails or is unable to perform its intended function when properly used. The contract specifies both the performance that is to be expected and the redress available to the buyer if a failure occurs or the performance is unsatisfactory. The warranty is intended to assure the buyer that the product will perform its intended function under normal conditions of use for a specified period of time.

There are many different types of warranty policies and a classification of these can be found in Blischke and Murthy (1994, 1996). Most standard products are sold with one of the following two warranty policies.

Free Replacement Warranty (FRW) Policy [Policy 1]

The manufacturer agrees to repair or provide replacements for failed items free of charge up to a time (the warranty period) from the time of the initial purchase. The warranty expires at time W after purchase.

Pro-rata Rebate Warranty (PRW) Policy [Policy 2]

The manufacturer agrees to refund a fraction of the purchase price should the item fail before time W (the warranty period) from the time of the initial purchase. The buyer is not constrained to buy a replacement item. The refund depends on the age of the item at failure, T, and the refund can be either a linear or a non-linear function of $(W - T)$, the remaining time in the warranty period. Let $\psi(T)$ denote this function. This defines a family of pro-rata policies which is characterized by the form of the refund function. The most common form is the linear function given by $\psi(T) = [(W - T)/W]P$ where P is the sale price.

Typical applications of these warranties are consumer products, ranging from inexpensive items such as plastic products to relatively expensive repairable items such as automobiles, refrigerators, and expensive non-repairable items such as electronic products.

Of particular interest in this context is warranty elasticity, that is, the ratio of relative change in total sales to relative change in the length of the warranty period.[11]

[11] Warranty elasticity for Chrysler is claimed to be 0.143 (Padmanabhan, 1996).

Sale Price

The total sales over the product life cycle depend on the sale price (for monopolistic market) and on the sale prices of the manufacturer and of the competitors (for competitive market). An increase in the price results in a decrease in the sales rate and the total sales over the product life cycle. The sale price can change over the product life cycle.

Linking to Concept Development

The notion of concept was discussed in Section 2.5.1. According to Krishnan and Ulrich (2001) concept development involves answering the following questions:

- What are the target values of the product attributes, including price?
- What is the core product concept?
- What is the product architecture?
- What variants of the product will be offered?
- Which components will be shared across which variants of the product?
- What will be the overall physical form and industrial design of the product?

Concept screening is similar to idea screening and is a process to ensure that concepts that are not feasible are screened out. Each product concept defines a SP-I.

5.5.3 Evaluating PP-I

PP-I is the predicted performance for a given SP-I and is needed for determining whether or not a selected SP-I (e.g., price, warranty) will achieve the DP-I defined in Section 5.5.1. It involves several elements and these are indicated in Figure 5.5. PP-I is obtained using appropriate models. Model building, in turn, involves data and information and model analysis needs a variety of tools and techniques.

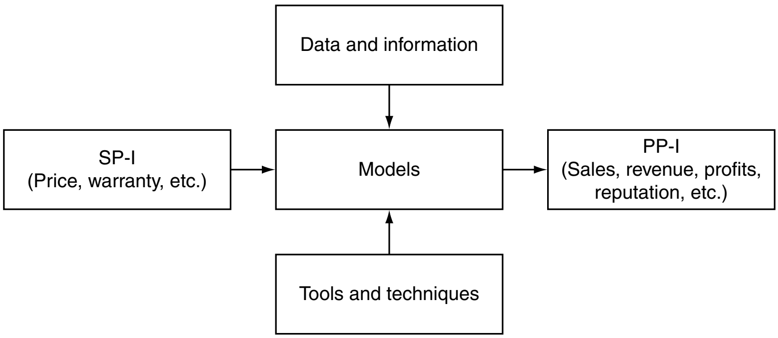

Figure 5.5. Linking SP-I and PP-I

A large number of models can be found in the literature and they vary in detail and complexity. We focus on some simple deterministic models. These are adequate for a crude analysis to get mainly qualitative and limited quantitative feel for the implications of different SP-I (the decision variables). We can use more refined (complex and/or stochastic) models to get better predictions and we cite some references where interested readers can get more details of such models. However, building such models requires a lot more data and information.

5.5.4 Models

Customer Satisfaction/Dissatisfaction Models

One of the roles of warranty is to provide assurance that the product will perform satisfactorily. As such, any failure during the warranty period leads to customer dissatisfaction.

Model 5.1: For non-repairable products sold with relatively short warranty period, a customer becomes dissatisfied should the product fail within the warranty period W. In this case the probability that a customer becomes dissatisfied is given by

$$P_d = \Pr(T \leq W) = F(W) \tag{5.1}$$

where $F(t) = \Pr(T \leq t)$ is the probability distribution function for the time to product failure.

Model 5.2: For repairable products sold with relatively long warranty period, the dissatisfaction depends on the number of failures encountered by the customer. If the failures are repaired minimally and the repair times are negligible, then failures over the warranty period occur with a ROCOF, $\lambda(t)$ so that the probability that a customer is dissatisfied with the purchase is given by

$$P_d = 1 - \sum_{k=0}^{n_0} \frac{[\Lambda(W)]^k}{k!} e^{-\Lambda(W)} \tag{5.2}$$

where $\Lambda(t)$ is the cumulative ROCOF and n_0 is some specified non-negative integer. *Comment*: When $n_0 = 0$, then $P_d = 1 - \exp[-\Lambda(W)] = F(W)$.

Sales Models

For certain products, there are no repeat purchases as the product life cycle is comparable to the useful life of the product. In this case, we only need to model the first purchase sales. However, when the useful life is much smaller then the product life cycle, then we need to model both first and repeat purchases.

The sale of a new product depends on product attributes (performance, price, warranty) and marketing efforts (advertising) and many different models have been developed.[12] We focus our attention on "diffusion type" models to model the effect of price and warranty on first purchase sales.[13]

Model 5.3: [Total first purchase sales with fixed price and warranty]
The total (first purchase) sales, $\bar{Q}$, over the life cycle, L, is given by

$$\bar{Q} = KW^{\alpha}P^{\beta} \tag{5.3}$$

where P is the sale price of the product, K is a constant, and α and β are the warranty and price elasticities given by

$$\alpha = \frac{\partial L/L}{\partial W/W} \quad \text{and} \quad \beta = \frac{\partial L/L}{\partial P/P} \tag{5.4}$$

α and β are obtained from the analysis of earlier (similar) products or based on expert (subjective) judgement.

Model 5.4: [First purchase sales with fixed price and warranty]
The sales rate is given by a first-order differential equation

$$n(t) = \frac{dN(t)}{dt} = \left(\bar{Q} - N(t)\right)(a + bN(t)), \quad N(0) = 0 \tag{5.5}$$

where $N(t)$ is the number of sales up to time t and a and b capture the advertising and word-of-mouth effects. The sales until time t is obtained by solving Equation (5.5) and is given by

$$N(t) = \frac{\bar{Q}\left(1 - e^{-\phi(t-t_0)}\right)}{1 + (b/a)\bar{Q}e^{-\phi(t-t_0)}} \tag{5.6}$$

where $\phi = a + b\bar{Q}$. Note that $\lim_{t\to\infty} N(t) = \bar{Q}$.

Model 5.5: [First purchase sales with changing price and warranty]
Often the price and warranty terms change over the product life cycle as indicated below.

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[12] The sales forecasting models include the following: Box-Jenkins, Customer/Market Research, Decision Trees, Delphi Method, Diffusion Models, Experience Curves, Expert Systems, Exponential Smoothing Techniques, Jury of Executive Opinion, Linear Regression, Looks-Like Analysis (Analogous Forecasting), Market Analysis Models (Atar Model, Assumption Based Models), Moving Averages, Neural Networks, Nonlinear Regression, Pre-Cursor Method (Correlation Method), Sales Force Composite, Scenario Analysis, simulation, Trend Like Analysis. See Kahn (2002) where references can be found to get more details of these models.

[13] This is the simple Bass-diffusion model first proposed by Bass (1969). Since then, the basic model has been extended to take into account other factors (e.g., advertising effort, price, negative and positive word-of-mouth effects) Details of these models can be found in Mahajan and Wind (1992).

Period	Interval	Price	Warranty period
1	$[0, T_1)$	P_1	W_1
2	$[T_1, T_2)$	P_1	$W_2 (> W_1)$
3	$[T_2, \infty)$	$P_2 (< P_1)$	W_2

The justification for this is as follows. Purchasers in the first period (also called "innovators") are willing to pay a higher price and take a higher risk. Purchasers in the second period need greater assurance (provided through longer warranty period) and those buying in the third period want a lower price.

The sales rates over the three periods are given by:

$$n(t) = \frac{dN(t)}{dt} = \left(\bar{Q}_1 - N(t)\right)(a + bN(t)), \quad N(0) = 0 \tag{5.7}$$

$$n(t) = \frac{dN(t)}{dt} = \left(\bar{Q}_2 - N(t)\right)(a + bN(t)), \quad N(T_1^+) = N(T_1^-) \tag{5.8}$$

$$n(t) = \frac{dN(t)}{dt} = \left(\bar{Q}_3 - N(t)\right)(a + bN(t)), \quad N(T_2^+) = N(T_2^-) \tag{5.9}$$

respectively with

$$\bar{Q}_1 = KP_1^{\alpha} W_1^{\beta}, \quad \bar{Q}_2 = KP_2^{\alpha} W_2^{\beta}, \quad \text{and} \quad \bar{Q}_3 = KP_1^{\alpha} W_1^{\beta} \tag{5.10}$$

Note that $N(T_1^-)$ is the total sales at the end of the first period and $N(T_2^-)$ is the total sales at the end of the second period. $n(t)$ is a discontinuous function (see, Figure 5.6) but $N(t)$ is a continuous function.

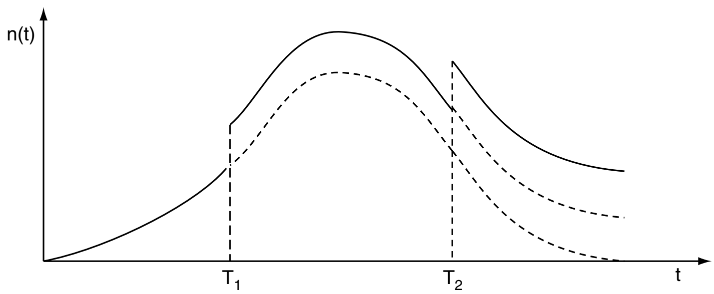

Figure 5.6. Sales rate versus time for Model 5.5

Model 5.6 [First purchase with customer dissatisfaction and negative word-of-mouth effect]
Dissatisfied customers can influence potential customers in not buying the product. This is captured through lost customers. Let $S(t)$ denote the number of lost customers by time t and let $s(t)$ denote the customer loss rate. Then

$$s(t) = \frac{dS(t)}{dt} = \left(\bar{Q} - S(t) - N(t)\right)(\zeta P_d N(t)), \quad S(0) = 0 \tag{5.11}$$

where ζ is a parameter characterizing the impact of negative word-of-mouth. The sales rate is given by

$$n(t) = \frac{dN(t)}{dt} = \left(\bar{Q} - S(t) - N(t)\right)(a + b(1 - P_d)N(t)), \quad Q(0) = 0 \quad (5.12)$$

The first purchase sales stop at time $\hat{t}$ given by

$$\left(\bar{Q} - S(\hat{t}) - N(\hat{t})\right) = 0 \quad (5.13)$$

The fraction of customers lost is given by $S(\hat{t})/\bar{Q}$ and the fraction of customers who have bought the product is given by $N(\hat{t})/\bar{Q}$. The critical parameters are (i) ζ, with larger value implying a higher loss of customers and (ii) P_d, reflecting the impact of product unreliability.

Model 5.7 [Repeat purchase sales]
This is relevant only when the useful life of the product is smaller than the length of the product life cycle. Let ν_j denote the probability that a customer who has bought the product for the jth time buys the product again when the purchased item reaches the end of its useful life. An upper limit on the number of repeat purchases is given by the largest integer less than L/T. Let $n_j(t)$ denote the sales rate for the jth purchase. Then

$$n_{j+1}(t) = \frac{dN_{j+1}(t)}{dt} = \nu_j n_j(t - T) \quad \text{for} \quad jT \le t < L; \quad j \ge 1$$

with the first purchase sale rate given by $n(t) = n_1(t)$.

Cost Models

The cost elements of relevance in the context of reliability design are (i) warranty costs, (ii) development costs, and (iii) production costs. The modelling of these costs poses challenging problems and a discussion of this can be found in Asiedu and Gu (1998) and Layer et al. (2002).

The warranty servicing cost depends on the product reliability and the warranty servicing strategy. We discuss two simple models. The development cost depends on the complexity and the degree of innovation needed and is discussed in Chapters 6 and 7. The production cost depends on the complexity of the product and the quantities produced, with the production cost per unit coming down as the quantity produced increases. This topic is discussed further in Chapters 6 and 8.

Model 5.8 [Warranty cost – free replacement warranty (FRW) policy]
If the failures are repaired minimally and the repair time is negligible, then failures over the warranty period occur according to a ROCOF with intensity function $\lambda(t)$. Let the (average) cost of a repair be C_r. Then, the expected warranty cost per unit is given by

$$c_W = C_r \int_0^{t_w} \lambda(t)\, dt = C_r\, \Lambda(W) \quad (5.14)$$

The total expected warranty cost (with total sales $N(L)$) is given by

$$C_W(\theta) = N(L) c_W = N(L)\, C_r\, \Lambda(W) \quad (5.15)$$

Comment: The cost changes if we use imperfect repair instead of minimal repair.

Model 5.9 [Warranty cost – pro-rata rebate warranty (PRW) policy]
The expected warranty cost per unit is given by

$$c_W = \int_0^W \psi(x)\, f(x)\, dx \tag{5.16}$$

where $\psi(x) = (W - x)/W$. The cost models for many other types of warranties can be found in Blischke and Murthy (1994).

The total expected warranty cost (with total sales $N(L)$) is given by

$$C_W(\theta) = N(L)c_W \tag{5.17}$$

Model Parameters

Numerical values must be assigned to the model parameters in order to carry out quantitative analysis. This requires appropriate data and information. Unfortunately, the data and information available in the front-end phase are rather limited. There are three approaches to determining the values to be assigned to the model parameters.

Approach 1 [Analogy-based]
Data for similar earlier products, past development programmes, and production costs is used to estimate model parameters. We can either use these estimates directly or after suitable modification to reflect the changed conditions for the new product.

The sales data for the current product are used to estimate the parameters of the diffusion model for the current product. The parameters for the sales model for the new product might need to be modified if the advertising effort differs significantly from that for the earlier product.

For the production and development cost model parameters, we can use data from several earlier or similar products. The cost versus the reliability can be plotted and extrapolated to obtain the cost estimates for the new models. For more on design effort costs, see Bashir and Thomson (2001) and the references cited therein.

Approach 2 [Expert opinion]
Here, information is sought from several experts using techniques such as the Delphi method. Most books on technology forecasting deal with this and many other methods (Martino, 1992). The costs to achieve different reliability targets or market sales under different price and warranty combinations can, for example, be obtained using this approach. The challenge is to identify a pool of experts who are qualified to provide sensible information.

Approach 3 [Subjective]
When data and information are very limited, the model builder has to make some guesses – either point estimates or interval estimates for some of the parameters.

5.5.5 Outcome of Sub-phase 3

The outcome of sub-phase 3 is the final SP-I (target values for the attributes characterizing product performance and product support) for which PP-I matches DP-I.

5.6 Specialized (Custom-built) Products

Characteristics common to almost all custom-built products include the following:

- Complex product (involving either existing or new technologies)
- Clearly defined product performance (reliability and non-reliability related) targets either specified by the customer or jointly negotiated by the manufacturer and the customer
- Evaluation of product performance during manufacture and in field operation
- Design changes if performance targets are not achieved in field operation
- A contract between the customer and the manufacturer (often referred to as "contractor")
- Cost to the buyer

The process for the front-end phase for custom-built products is shown in Figure 5.7, where PP-I(c) is the predicted performance from the customer perspective and PP-I(m) is the predicted performance from the manufacturer perspective. In this section we discuss briefly the different elements of the figure.

5.6.1 Performance Requirement

Deciding on the product performance requirements (also referred to as "customer requirements") is an iterative process as indicated in Figure 5.8. Typically, the customer (buyer) sends out a request proposal to one or more manufacturers indicating the performance requirements for the new product along with other information needed to prepare a bid on the project.[14] Manufacturers respond through an initial bid proposal that indicates how the new product can be realized and gives some indication of the performance levels and crude estimates of various costs (e.g., development, production, operation). This is done using crude models based on limited data. The buyer carries out an evaluation of the proposals and decides on which ones are to be rejected and considers possible revisions to the performance requirements based on the bid proposals. The proposals not rejected go through a second stage where the process is repeated. This iteration continues through one or more iterations until one manufacturer is selected and both buyer and the manufacturer are in agreement regarding performance and costs. The end outcome is the final contract for the manufacturing of the product.

[14] The manufacturer is often referred to as contractor when the manufacturer is awarded the contract to build the product.

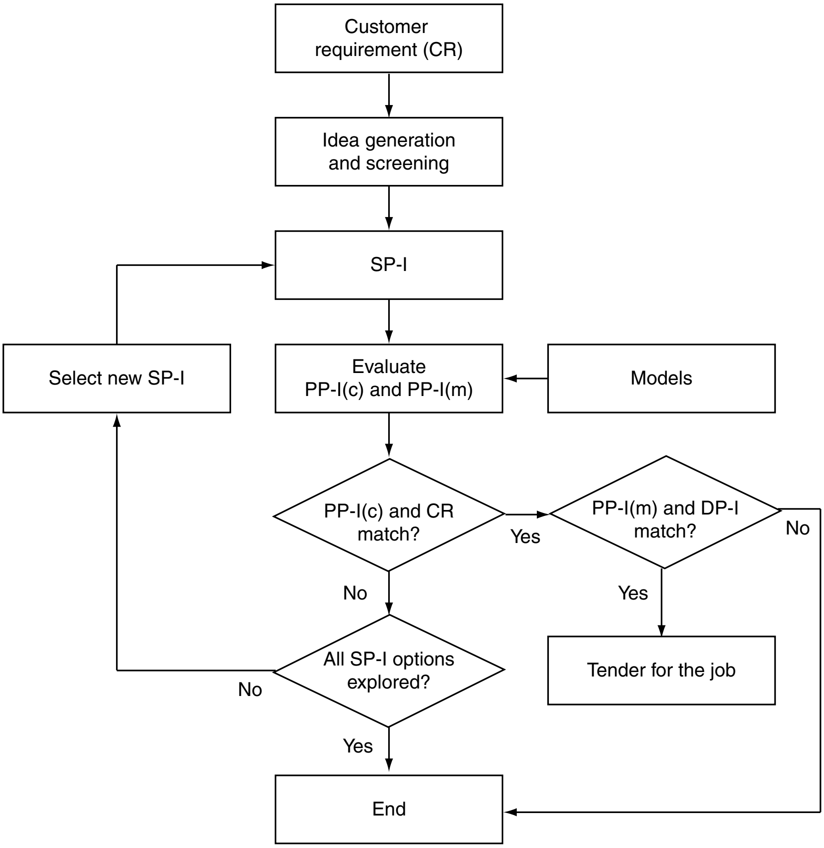

Figure 5.7. Stage I, level I process for custom-built products

Example 5.1 (Safety Instrumented System). Consider a separator on an offshore oil/gas platform in the North Sea. The hazards related to the separator are usually determined through a hazard and operability (HAZOP) study. For each significant hazard, protective features have to be considered. One such hazard is too high pressure in the separator. The risk related to this hazard can be reduced by installing pressure relief valves on the separator. If this protection is not sufficient, we may consider including an instrumented shutdown function on the inlet pipeline. This function is called a safety instrumented function (SIF) and this function has to be implemented through a safety instrumented system comprising one or more pressure sensors/transmitters, a logic solver, and one or more shutdown valves. The reliability requirements to the SIF are specified as a safety integrity level (SIL) that can take four different values. The SIL value may be determined from the overall risk acceptance criteria of the platform, and/or by different SIL allocation methods.

If, for example, SIL 3 is found to be required, a range of more specific requirements are specified in the standard IEC 61508. These imply that the probability of

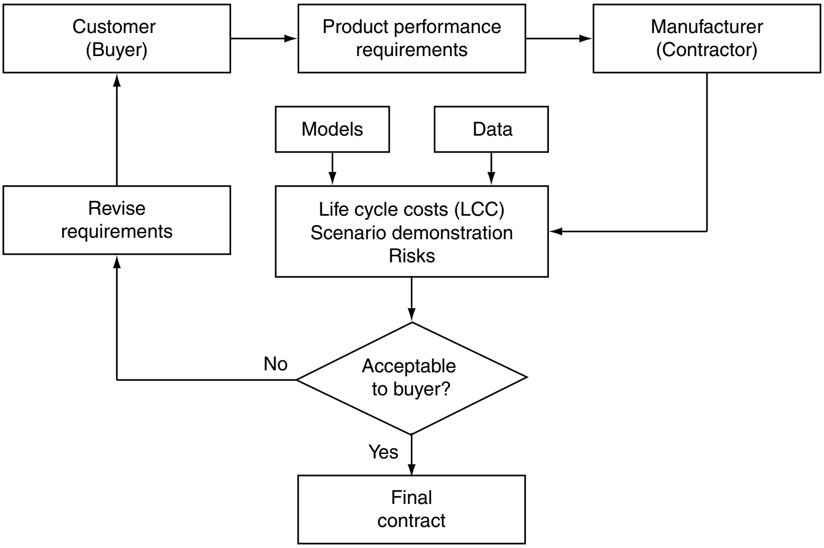

Figure 5.8. Performance requirements for custom-built products

failure on demand (PFD) must be less than 10^{-3} (see Chapter 4) and that the hardware fault tolerance of the system must be according to tables given in IEC 61508. In addition to the SIL 3 requirements, the customer (i.e., the oil company) will also have a set of additional requirements related to spurious trip rate, testability, space and cost constraints. Requirements are negotiated with the manufacturer and a safety requirement specification (SRS) is agreed.

As illustrated in Figure 5.8, detailed models and data need to be used to calculate the system PFD and the various other requirements. Some of these models are indicated in Chapter 4. ⊕

5.6.2 Contract

The contract defines the target values for the performance of the product and the constraints. These include both reliability- and non-reliability-related performances. If the objective of the contract is only to ensure that the product performance meets some minimum level, then it is an assurance contract. In this case, the aim of product development is to ensure that the specified level is achieved. In contrast, in some cases the buyer is interested in encouraging the contractor to exceed the minimum level and as such, the contract includes incentive features to achieve this. This is accomplished by tying the payment to the performance level achieved by the manufacturer. The customer is actively involved throughout the product life cycle and the focus is on the total life cycle.

The reliability, maintainability and supportability performance terms may include one or more of the following items:

- A guaranteed mean time between failure (MTBF)
- A guaranteed turnaround time for repaired or replaced units
- A supply of consignment spares for use by the buyer at no cost until the guaranteed MTBF is demonstrated
- Accuracy of testability (built-in test (BIT) and other tests)
- A guaranteed system availability (point availability and/or interval availability)

The performance of the product must be defined properly so that there is no scope for ambiguity. Reliability-related performance needs to include the time frame for data collection, the type of data to be collected, and the procedures to assess performance in terms of the data. In the case of MTBF, we must specify whether a point or interval estimate is to be used. Similarly, during development the contract needs to indicate the kind of testing to be carried out and how to translate the test data into assessing performance at component, sub-system or system level. If these are not done properly, it can lead to disputes and litigation at a later time.

5.6.3 Reliability Improvement Warranty

The reliability improvement warranty (referred to as RIW) is a class of warranty policies that are applicable for custom-built products. The intent of an RIW is to provide an incentive to the manufacturer to improve the reliability of the product, thereby reducing long-run repair and maintenance costs for the customer.

The first use of this type of warranty was in purchases of aircraft by commercial airlines.[15] In military procurement in the United States, the RIW was initially called a “failure free” or “standard” warranty (Trimble, 1974). Some versions of this warranty had been introduced at about the same time as the inception of the airline RIW (Gregory, 1964; Klause, 1979).[16] The RIW came into wider use during the next several years with a guaranteed MTBF as the predominant feature (Gandara and Rich, 1977) and is now firmly established as a factor in defence acquisition by the US Government. It is also finding greater acceptance in the context of complex industrial and commercial transactions.

The warranty statement addresses one or more of the following questions:

- What is the duration of the warranty period?
- Is it an assurance or incentive warranty?
- What are buyer and contractor obligations?
- What issues are covered?
- What are the exclusions?

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[15] The successful use of an RIW by Pan American World Airways in the purchase of Boeing 747s in the late 1960s is discussed in Hiller (1973) and Schmoldas (1977).

[16] The first actual use of an RIW, in 1967, was in procurement of a gyroscope for the F-111 aircraft. This warranty included a guaranteed MTBF provision, and it was apparently quite successful, with the target MTBF of 400 hours exceeded (the estimated actual MTBF was 531 hours) and a 40% reduction in maintenance costs per operational hour achieved (Schmidt, 1976).

- How are the spare parts issues addressed? Are they delivered at the start or over the operating life cycle of the product?

Note that this is not an exhaustive list and there may be many other questions. The following RIW policy is from Gandara and Rich (1977).[17]

> "Under this policy, the manufacturer agrees to repair or provide replacements free of charge for any failed parts or units until time W after purchase. In addition, the manufacturer guarantees the MTBF of the purchased item to be at least M. If the computed MTBF is less than M, the manufacturer will provide, at no cost to the buyer, (1) engineering analysis to determine the cause of failure to meet the guaranteed MTBF requirement, (2) engineering change proposals, (3) modification of all existing units in accordance with approved engineering changes, and (4) consignment spares for buyer use until such time as it is shown that the MTBF is at least M."

5.6.4 Idea Generation and Screening

The idea generation is similar to that for standard products discussed in Section 5.4. The screening would be different and needs to be done using criteria that involve customer requirements as well as the business objectives of the manufacturer.

5.6.5 DP-I

For the manufacturer, as with standard products, DP-I deals with the performance of the product from a business perspective. DP-I can involve one or more of the following variables:

- Costs
- Profits
- Risks
- Outsourcing
- Reputation

One needs to take into account various constraints such as

- Investment needed
- Time
- Expertise needed

We briefly discuss some of these.

[17] Blischke and Murthy (1994) discusses several other types of RIW policies.

Costs

There are several different types of costs involved. These include the following:

- Development cost
- Production cost
- Support cost (for spares, etc.)
- Warranty cost

The manufacturer needs to take into account all of these costs in the pricing of the contract. The warranty cost must include the provision of replacements, repairs, as well as upgrades. This depends on the duration and other terms of the warranty. Models are needed to predict these costs.

From the buyer's perspective, the cost of interest is the total life cycle cost (LCC). Figure 5.9 indicates the different elements of the LCC.

Risks

The manufacturer faces several kinds of risk. These include the following:

- Technical risk: This results from not achieving the performance levels stated in the contract and, as a consequence, incurring a large penalty through high warranty costs and/or high cost of engineering design modifications
- Project risk: This results from not delivering the product in time and/or cost overruns during development and production
- Risks associated with outsourcing

These risks can be assessed through a proper scenario analysis where we look at alternative scenarios and assess the probabilities of these occurring and the resulting consequences.

Outsourcing

Outsourcing can be defined as a process of transferring activities to be performed by others and its main advantage is conceptually based on two strategic considerations:

1. Use of internal resources mainly for the core competencies of the business.
2. Outsourcing of all other activities that are not considered strategic necessities and/or whenever the manufacturer does not possess the adequate competencies and skills.

Complex products require several different kinds of expertise and it is very rare that a manufacturer will have all the skills and competencies needed.

5.6.6 SP-I

SP-I defines alternative product concepts and options for building. Different concepts arise due to a multitude of factors and technologies, product architecture, and so on. The options can include outsourcing the design and/or manufacture of one or more of the sub-systems.

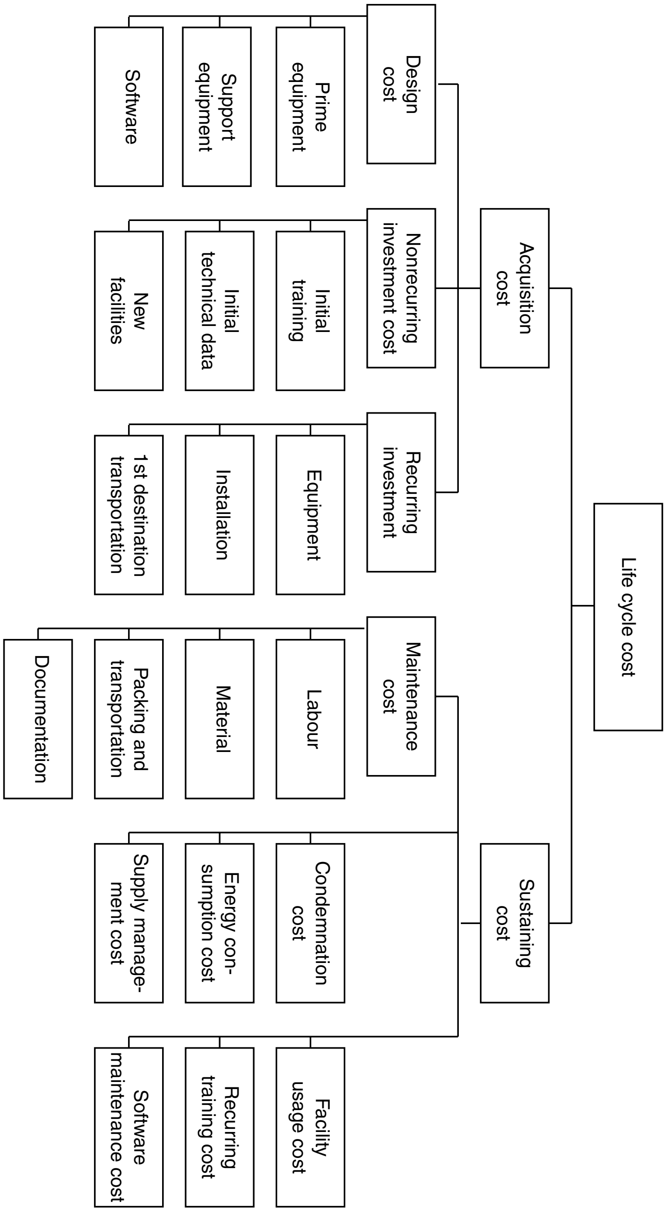

Figure 5.9. Components of life cycle cost

5.6.7 PP-I

There are two different types of PP-I. The first is PP-I (c) – the customer perspective and the second is PP-I (m) – the manufacturer's perspective.

PP-I (c): Here, we assess the predicted product performance in terms of the performance variable defined in the customer requirements. If PP-I (c) does not match the customer requirements, we must iterate back and consider a new SP-I. If there is no more SP-I options available, then the exercise comes to an end as the manufacturer is unable to come up with a concept to meet the customer requirements. If PP-I (c) matches the customer requirements, then we need to evaluate the match between PP-I (m) and DP-I.

PP-I (m): Here, we assess the predicted product performance in terms of the performance variables defined in DP-I. If PP-I (m) does not match DP-I, then the exercise is terminated as it is not in the interest of the manufacturer to proceed further. If PP-I (m) matches DP-I, then the manufacturer tenders for the job.

Many different types of models are needed to evaluate PP-I(c) and PP-I(m). Some of these (involving product reliability) are discussed in Chapter 6.

5.6.8 Outcome of Phase 1

If the tender is accepted, the manufacturer and the customer sign a contract. This forms the starting point for the next phase of the process.

Contract Document

This is a legal document between buyer and manufacturer to ensure that the manufacturer delivers the desired product. To prevent possible misunderstanding between the two parties (relating to reliability aspects) it is important that the contract deals with the following issues:

- Product performance requirements
- Definitions
- Documentation requirements
- Quality control requirements
- Work schedules
- Testing for reliability assessment and verification
- Data collection and analysis

These should be done in an unambiguous manner and should be complete. A proper drafting of such a contract requires a team comprising lawyers, engineers, reliability experts, and managers.

Dispute Resolution

In most cases, the product as well as the contract are complex. This implies that the contract might not address some issues that can lead to potential problems and disputes after the contract has been signed. Also, the interpretation of the contract (e.g., the testing conditions or operating environment) and other unverifiable factors (e.g., the cause of failure being either due to operator error or design weakness) can lead to possible conflicts. As such, both parties (buyer and manufacturer) need to look at alternative dispute resolution mechanisms as part of the contract.

5.7 Implications for Product Reliability

For standard products, product reliability does not appear explicitly in the decision making at the front-end phase. However, many of the variables (warranty costs, development costs, maintenance costs, customer satisfaction) are related to product reliability as will be indicated in the next chapter. In the case of custom-built products, product reliability appears explicitly through various performance measures (e.g., reliability, MTBF) and indirectly through variables such as development cost, LCC, and so on. SP-I and the elements of DP-I (and the constraints) are the inputs to stage II and define DP-II. From this we first decide on product reliability (at the system level) and then decide on component level reliability in the next chapter.

5.8 Case Study: Cellular Phone

As indicated in Section 1.1, the drivers for new product development can be one or more of the following:

1. Advances in technology
2. New (real or perceived) customer needs
3. Competitor's action

In this section, we look at the advances in technology and the changing customer needs.

Advances in Technology

The different elements of a cellular phone are indicated in Section 2.2.3 (Example 2.2).

Integrated circuits: Walsh et al. (2005, Table 1) defines seven epochs based on disruptive and sustaining technology changes in silicon ICs. The increase in the number of gates, bits, or transistors per device is from this source is given in Table 1.1. The changes in (i) device (SSI → MSI → LSI → VLSI → ULSI → UULSI), (ii) dominant design and production processes (Growth junction → Bipolar → Bipolar MOS

→ PMOS → NMOS → CMOS → BiMos), (iii) Technological substitutes for silicon (Germanium → FZ → GaAs SOS → Denuded silicon GaAs, SOI GaAs) (iv) semiconductor device product drivers (Transistors, diodes → Transistor amplifiers → A/D devices → Logic RAM → EPROM), diameter of silicone substrate (from < 2 inches to 6–14 inches) and (v) critical dimension in microns (going down from 10 microns to less than 1 micron).

Display technologies: In addition to the advances in the liquid-crystal display (LCD) there are new alternative technologies, such as the reflective bistable display technologies and the organic emissive displays (OEDs). Kimmel et al. (2002) deal with this topic and the drawbacks of OEDs in the context of cellular phones. From the reliability perspective, the main drawback is the variations in the lifetime of different colour emitters and the long-term reduction in quality.[18]

Batteries: Currently, cellular phones use batteries (lithium, cadmium, nickel, etc.) that need to be recharged (after usage of around 4 hours) and the life (defined through the energy capacity dropping to 80% of the rated) is typically around 2000–3000 hours. Atkinson (2005) reports that the advances in fuel cell technology give life lengths exceeding 5000 hours. This will likely result in batteries being replaced by fuel cells in the future.

Customer Needs

New features to satisfy the ever increasing customer needs have resulted in continuous improvements in the picture resolution, increase in memory for MP3 players and video downloading. A survey in 2005 reported that 53% are comfortable listening to music on their cellular phones and 38% are comfortable watching TV or movies.

Customer Choice

Given the wide range of cellular phones available on the market, the selection of cellular phone is a topic that has received some attention. Isiklar and Buyukozkan (2007) propose a multi-criteria decision making (MCDM) approach to model consumer evaluation of cellular phone alternatives. It uses an Analytical Hierarchy Process (AHP) to determine the relative weights of evaluation criteria and an extension of the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank the cellular phone alternatives. They look at two criteria (product related and user related) and three sub-criteria for each.

[18] Szweda (2006) discusses this topic and reports that the drawback associated with the blue colour emitter has been overcome. This implies that the organic light-emitting diodes (OLEDs) will impact on the sales of light emitting diodes (LEDs).