Functional Guarantees – A New Service Paradigm

Aparna Gupta

Department of Decision Sciences and Engineering Systems

Rensselaer Polytechnic Institute, Troy, NY 12180

Norman K. Sondheimer

School of Management

University of Massachusetts, Amherst, MA

and

William A. Wallace

Department of Decision Sciences and Engineering Systems

Rensselaer Polytechnic Institute, Troy NY 12180

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Abstract

The United States equipment service sector supports the nation's infrastructure and accounts for a significant portion of the nation's economy. Availability of improved diagnostics technologies and prognostics methodologies has enabled aggressive equipment producers to offer a new service. They provide a long-term guarantee on the operation of a product in exchange for a fixed annual fee. However, since a rigorous framework for managing the delivery of such a guarantee does not exist, the producer can be exposed to extensive risks. This can result in serious losses to the producer, which can carry over to the customer and the society. In this article, we develop a rigorous framework for the design and delivery of a new service paradigm, Functional Guarantees. In a Functional Guarantee, the producer sells a service of providing 'functionality' from a physical equipment. An integrated risk management approach forms the core of the framework, enabling a viable delivery of the required quality of service from the equipment. The framework will allow the producer to meet the customer's needs and help eliminate potential losses, while constantly looking towards improving profitability.

Keywords: Service operations management, integrated risk management, service design, service quality

Section I. Introduction

The United States equipment service sector supports the nation's infrastructure and accounts for a significant portion of the nation's economy. Industries that consume equipment services include airlines, power generation, railways, trucking, construction, and military. Forty percent of U.S. Navy and Air Force personnel are assigned to maintain and repair the military equipment (Ryan (1999)). Today the world's commercial airlines carry approximately \$60 billion worth of spare parts inventory for aircraft service activities (Sondheimer (2002)). Maintenance of a Boeing 777-200 commercial aircraft absorbs 20% of the plane's operating costs (Alex Brown (1999)). The cost of servicing and repairing America's automobiles and truck fleets is 9.8% of all operating expenses (GE (2003)). This does not include 13% of overall operating costs incurred due to accidents resulting from equipment failures or the excess capacity required to allow for failures. Using a conservative estimate of 10% of total operating costs, maintenance of equipment is easily over a \$250 billion expense for maintaining productivity of the nation's economy. It is, in effect, one of America's largest industries.

Technologies continue to develop that promise to reduce these costs now and in the future. Manufacturing quality initiatives, such as Six Sigma, are gaining larger popularity. New generations of sensors and actuator systems, such as micro-accelerometers, micro-gyroscopes, and nano-thermal probes, are being introduced, as are ever-less-expensive robust embedded processors. Improved diagnostic techniques provide failure isolation, and remote monitoring and prognostic techniques identify future maintenance needs, with a goal of avoiding failures.

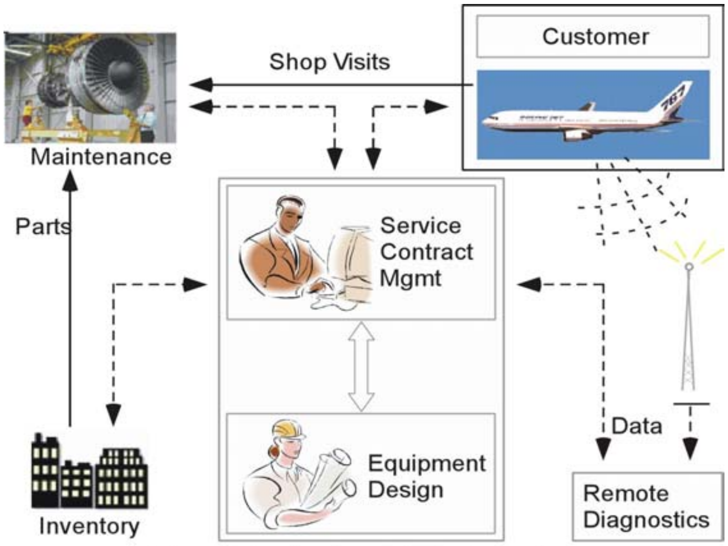


Figure I. Service Guarantee Infrastructure

Taking advantage of these developments, aggressive producers have moved to offer new services to the customers of their equipment. Major equipment producers are offering a long-term guarantee on the operation of their products in exchange for a fixed annual fee. The customers must accept constraints on how they may operate the equipment, allow the producer real-time access to the sensor data from the equipment, and give the producer the right to maintain the equipment. Caterpillar offers its customers tracking and management of some aspects of their field heavy equipment (CAT (2002)). General Electric (GE) Medical Systems and many others have 'call centers' that offer customers many direct services tied to remote monitoring. Service infrastructure visions, as seen in Figure I, are common in many industries. GE offers for its jet engines 10-to-15-year service guarantees under GE's "Maintenance Cost Per Hour" product. United Technologies Corporation's Pratt & Whitney (P&W) offers service guarantees under the brand name of "Fleet Management Programs." Boeing and Airbus also offer service guarantees on their aircrafts. Other GE businesses offering service guarantees include GE Transportation Systems and GE Power Systems. GE Transportation Systems provides guarantees of 25 years' duration on many of its locomotives and has contracts in place for almost all the nation's major railroads. GE Power Systems sells many of its gas turbines with service guarantees. Informal estimates indicate GE Power Systems has over $70 billion of contracts in place.

In providing service guarantees, producers capitalize on their knowledge of the operations of their equipment in a variety of settings. Producers use their advantages to price the service profitably, while recouping the large investments for service infrastructure from several customers. Customers do not have to acquire and update the technical knowledge required to maintain and repair the equipment. Their objective is to minimize the cost of the service by significantly reducing or even eliminating the cost of maintenance and repair. By taking advantage of the producer's technical knowledge and service infrastructure, the customers of the service guarantees hope to better serve their consumers. For instance, GE Power Systems provides long-term service guarantees for the electricity-generating gas turbines to Niagara Mohawk, a New York-based utility company. Taking advantage of the services provided by GE, Niagara Mohawk can improve its capability for better meeting its consumers' needs.

Service guarantees hold great promise; however, in absence of a rigorous framework to support the delivery of the service, both the service producer and the customer can miss out some vital information and knowledge required to maintain long-term functionality of the equipment (Blischke (1996), Lutz (1998)). In the contractual agreement of a service guarantee, services provided based on partial information and analysis can result in losses not only to the producer, but losses that can also carry over to the customer. Often the customers of the equipment in turn sell services to end-consumers, such as, traveling by air, electricity, and medical services. Therefore, this creates a possibility of serious losses to not only the producers and the customers, but can expose the end-consumers to harm. For instance, an aircraft being maintained under a service guarantee with imperfect information of its potential flight conditions or usage characteristics exposes the passengers to the risk of potentially fatal accidents.

In this article, we present a rigorous framework to support the design and delivery of service guarantees from the producer's perspective. In the producer-customer-consumer relationship for a service guarantee, the producer plays the critical role of making the service guarantee happen; hence, the framework presented is producer-centric. The framework requires the customer to stay closely involved in service definition and delivery process in order to guard its interests. The government needs to protect the consumers by setting relevant regulations and standards.

The producer can replace any part of the equipment or almost the entire equipment in order to maintain its operational level. Therefore, really the producer sells not merely a physical piece of equipment, but the 'function' provided by the equipment. We will refer to this arrangement as a **Functional Guarantee**. The 'functionality' delivered by the equipment to the customer is the service the producer sells. The physical equipment is only a facilitating component of delivering the service, hence is the **physical component** of the service. In order to illustrate the setting, we present the following case.

Section II. A Case

A large conglomerate, HF Corporation, consists of a division that manufactures power-generating gas turbines. The gas turbine division has been selling Functional Guarantees on five different models of gas turbines it produces. In the past five years, over 30 Functional Guarantees have been extended to nine different utility companies in 6 different states. Each Functional Guarantee service is at a different level of maturity, 5 are five years old, 15 are three years old, and the remaining are in their first year. Differential maturity of the physical components in these Functional Guarantees poses as both a challenge and an opportunity to the gas turbine division. The aircraft division of HF Corporation has been selling Functional Guarantees for longer. It is a more mature business, where a lot more information and data are available for design and delivery of Functional Guarantees. Most Functional Guarantees last 10-15 years and four of the nations leading airlines are the aircraft engines division's customers. The division has so far successfully delivered Functional Guarantees based on the engine models from previous generation. Their major challenge is to create Functional Guarantees for the new generation aircraft engines, which are based on a substantially different technology. The locomotive division to-date has only provided maintenance services to its customers, but looking at the success of the aircraft engines and gas turbine division, is actively considering selling Functional Guarantees. The challenge for HF Corporation is to view all the Functional Guarantees extended by each division as a part of the whole and manage them. The framework developed in this article will allow HF to meet the challenge.

Organization of rest of the article is as follows. We begin with presenting the framework for the Functional Guarantee paradigm. Following this, we will briefly compare Functional Guarantees with other services and place it in the classifications for the service industry. We will then describe the integrated risk management core of the framework in detail and conclude with the research challenges for the framework.

Section III. Framework for Functional Guarantees

We present a rigorous framework to support the design and delivery of Functional Guarantees from the producer's perspective. The primary objective of the producer is to maintain long-term viable profitability of its business. Since most of the physical components in this framework provide critical infrastructure to the country, the government will want to protect the consumers of the equipments by creating standards and regulations. The framework has to allow the producer to meet its objectives while following the relevant governmental standards and regulations.

At the core of our vision for the Functional Guarantee paradigm is **integrated risk management**, which combines the management of three dimensions of risks – **strategic**, **operational**, and **extreme-events**. To support integrated risk management, the paradigm will employ technological advances in remote monitoring and sensing. Collected data will enable constant diagnostics and prognostics for the equipment performance. The integrated risk management approach will use these data to gain a global perspective of the business and in turn feed information for improved design of the physical component and service. Combining all the above with a close interaction between the producer and the customer will help meeting the producer's objective while adequately responding to the customer's needs. We now describe the framework for the Functional Guarantee paradigm; Figure II gives an overview of the proposed framework.

Inputs: The quality of service depends on the quality of effort of the producer and the usage characteristics of the customer. In order to deliver the guaranteed service, the producer of the service will need to develop a thorough understanding of the physical component and the environment in which it will operate. Various factors that make up the business setting for providing a prospective Functional Guarantee constitute the inputs of the paradigm. These are the characteristics of the service defined in terms of the required operations of the physical components, the environmental conditions surrounding these operations, both within a facility and external to the platform used to deliver the service (for instance, the airframe holding the aircraft engines as well as the anticipated flight conditions), and the real and perceived preferences of the customer as well as the consumers. All these are largely uncontrollable factors from the producer's perspective, and sufficient knowledge of them will need to be gathered and compiled in order to design and develop the service.

Controllables: The producer can control and steer several aspects of the service process to its advantage. Under the Functional Guarantee paradigm, service delivery begins with the **design** of a physical component with a desired functionality. Based on the **manufacturing** and **reliability** characteristics of the physical component, the producer also enjoys freedom in **defining the service process**. In order to successfully deliver Functional Guarantees, the producer will need appropriate **service infrastructure** to perform diagnostics, monitoring, and prognostics of the equipment in operation.

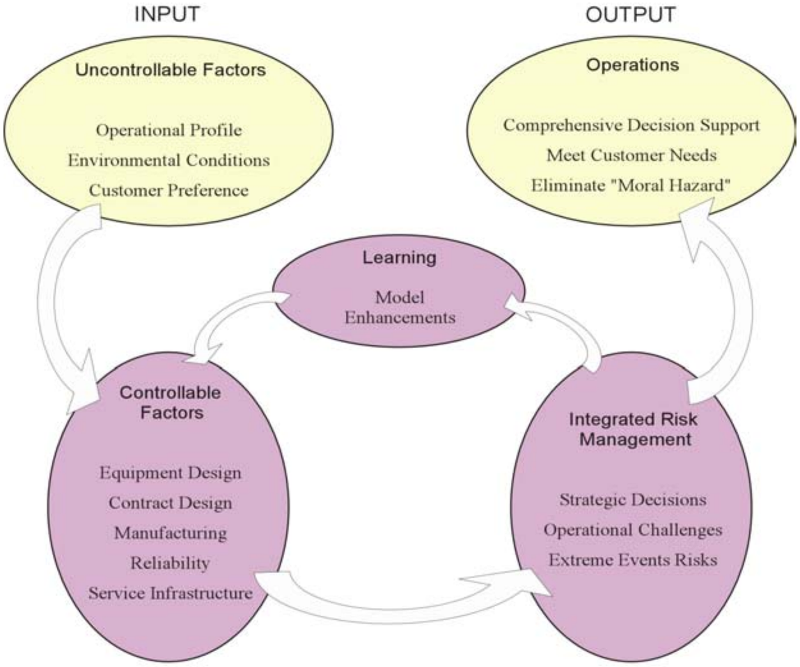


Figure II. Functional Guarantee Framework

Managing Risks: The producer is exposed to several risks in the delivery of a Functional Guarantee. Following Knight, we define 'risk' as the measurable uncertainties of a system (Knight (1921)). A thorough understanding of a Functional Guarantee business requires a comprehensive formalization of these risks, the cost of the risks, and a plan for managing them. We identify **strategic**, **operational**, and **extreme-events** risks as three major categories for the risks. Risks in each category should be analyzed in depth and interrelated in order to develop an **integrated-risk-management** framework for the service. Establishing a connection between management of risks and the controllables (e.g., design, service infrastructure) of the business is a primary goal of **strategic risk management**, a key component of integrated risk management. Thus, a risk-management-based approach along with profit considerations becomes a rigorous, conceptual core of the framework for delivering a Functional Guarantee.

Learning: Gaining insights and improving operations is an on-going process. The role of learning techniques is to make that happen. Constant methodological improvements and model enhancements will be necessary to bring in greater efficiencies from the insights gained, and information acquired.

Outputs: The paradigm will deliver a consistent and coherent decision-making process that will better meet customer needs, help eliminate potential losses, while constantly looking towards improving profitability.

Before describing the paradigm's integrated risk management core in detail, we make a brief digression for fully characterizing a Functional Guarantee, while establishing and relating it with service classifications.

Section IV. Functional Guarantees Characterization

A Functional Guarantee service is a guarantee of a level of output from the physical component providing the service. For instance, for a power-generating turbine, this may be a certain amount of electricity produced per year, or for a fleet of aircrafts, it could be total length of flight, landings, and take-offs per year. Under the Functional Guarantee paradigm, service delivery begins with the design of a physical component with a desired functionality. Typically, the physical component has a long life and a high capital cost for manufacturing and maintenance, when compared with labor costs. Subsequently, the equipment is manufactured, installed, and operated at a customer site under a **contract** that delineates the specifics of the Functional Guarantee service the producer will deliver to the customer and the specifics of the operating conditions under which the customer will use the equipment.

The producer of the service is required to have a high degree of technical knowledge, since sophisticated, high-capital equipment is involved. Therefore, the labor employed by the producer must be highly skilled and trained. The mix of services the producer can provide to its customers is diverse. These range from routine services for maintenance to the use of specialized knowledge about the equipment to fix an unexpected breakdown. Due to the need for specialized knowledge and infrastructure, the customer is likely to have limited choices for purchase of a Functional Guarantee. The producer benefits from economies of scale and scope, since then technological investment can return value and risks are diversified.

Identification and analysis of services has always been a challenge, and different alternatives are found in the literature to facilitate the identification, classification, and evaluation of services (Fitzsimmons (1997)). In rest of this section, we will position Functional Guarantees in various taxonomies of services.

By strategic classification scheme (Lovelock (1999)), Functional Guarantees fall in the category where services are enabled by physical objects given to the customer. By the service process matrix (Schmenner (1996)), Functional Guarantees are 'service operations,' requiring high capital and customer involvement. Service Package (Fitzsimmons (1997)) views services as a bundle of goods and services: supporting facilities, facilitating goods, explicit services, and implicit services. Analyzing Functional Guarantees by service package features indicate their similarity with product warranty services (Blischke (1996, 2000)). However, there are very significant differences between the two. Supporting facilities for the Functional Guarantee include both the manufacturing plant and the site where the service is delivered after installation of the physical component. Facilitating goods include the replacement parts and all the sensors, diagnostics, and prognostics equipment that facilitate maintenance. Explicit services are defined in terms of units of functionality output received from the physical component per unit time and the expectation of near-zero downtime due to failures. Finally, implicit services include all the additional things the producer does to keep the physical component functional at acceptable (agreed upon) level.

The core of the Functional Guarantee framework, we described earlier, is an integrated approach to risk management. We next describe each component of the integrated risk management core in detail, along with elucidating how these components interrelate with each other and with the other components of the framework in Figure II.

Section V. Detailed Description of Risk Management Core of the Framework.

Our viewpoint is that all risks that are—and can be—anticipated will fall under one of the three categories. It is necessary to consider all risks in a comprehensive setting in order to develop an integrated risk management framework for the service. The integrated risk management approach will provide both insights into the interrelation of different categories of risk and a decision-making framework for managing them. The cost of the risks can be shared with the customer (via the price of the service), or transferred (perhaps partially) to a third party, such as a re-insurance agency. Risks such as legal or intellectual property are treated as extreme-event risks. In many cases, the service provided by the Functional Guarantee is regulated by a governmental body. These will need to be incorporated in the risk management considerations.

Strategic risk pertains to long-term decisions and outcomes related to the design and delivery of the service. A strategic analysis of uncertainties and the development of contingency plans for them are integral to providing a firm footing to the business. The strategic view lends a perspective that cuts across different services provided by the producer (and its corresponding potentially different physical components) and time-horizons.

Operational risk pertains to risks arising from the day-to-day operations, one customer and one service at a time. Tactical or operational risk management is decision making based on the view that each Functional Guarantee delivery to each customer operates semi-autonomously to an extent. Therefore, while strategic risk analysis gives a top-down view of the functioning of the business, operational risk analysis gives a bottom-up view; and both views can benefit immensely from the other.

Extreme-events risks pertain to risks that are exogenous, rare events that can have a catastrophic impact on the system and its service-delivery capabilities.

The existing research on operational risk management and extreme-events risk management can be applied to Functional Guarantees. Therefore, in order to provide integrated risk management, strategic risk management needs to be defined and a research agenda proposed. We will begin with a detailed description of strategic risk management, followed by a discussion of operational and extreme-events risk management.

Section V.1 Strategic Risk Management

Strategic risk management in the context of Functional Guarantees pertains to long-term decisions and outcomes related to the design and delivery of multiple services for multiple markets. Strategic analysis of uncertainties and development of contingency plans are critical for a successful business operation. A strategic view lends a perspective that cuts across different services provided by the producer (and their corresponding potentially different physical components) and time-horizons (Murthy (2000)). Strategic risk management is a well-studied area in Finance. Strategic risks are managed by making decisions to control the risk profile of a portfolio of assets by portfolio structuring and hedging strategies. We provide a brief overview of this literature.

Section V.1.1 Risk Management in Finance

Portfolio Structuring: Various publications focus on the optimal structuring of portfolios (Chen (1991), Consiglio (1999), Cooper (1998), Lee (2000), and Tucker (1994)). Three main objectives for portfolio structuring found in the literature are: (i) maximize the portfolio value, (ii) balance portfolio diversity, and (iii) align the portfolio with the producer's overall strategy (Cooper (1998)). Various approaches exist for **maximizing** the portfolio value (Crouhy (2001), Haley (1995), Mulvey (1992), Souder (1972)). These range from scoring models to methods that maximize the von Neumann-Morgenstern utility function. Other optimization techniques for portfolio structuring can be found in references (Chen (1991), Chen (1991b), Fields (1991), Tsai (1991), Wood (2000)).

Balancing portfolio diversity is a matter of determining the optimal mix of assets in a portfolio (Cooper (1998)). That is, how many long-term versus short-term, or high risk versus low risk, or mature versus new technology assets must comprise the portfolio? **Aligning** the portfolio with the overall business strategy is to ensure that, despite all other considerations, the constituent components of the portfolio truly reflect the producer's strategy (Mulvey (1994)). Others have also done work on optimal portfolio structuring (Chen (1991), Chen (1991b), Fields (1991), Tsai (1991), Wood (2000)) and portfolio risk management (Black (1973), Lintner (1965), Merton (1973), Sharpe (1964)).

Hedging Strategies: Many approaches to developing strategies for hedging against portfolio risk can be found in the literature (Dales (2001), Rossi (2002)). The traditional approach is to take a combination of mean and variance of the asset-returns and maximize the mean while minimizing the variance (Beenhakker (1997), Culp (2001), Crouhy (2001), Li (2000)). Here, the mean measures the reward and variance measures risk. Thus, a tradeoff between return on investment and risk levels (Tucker (1994)) is created, leading to a mean-variance efficient frontier (Hartley (2000), Markowitz (1952), Sharpe (1995)). In recent years, another measure for risk, **Value-at-Risk** (VaR), has gained importance. VaR can be defined as the worst loss that might be expected from 'owning' a portfolio over a given period of time, given a specified confidence level, $(1-\alpha)\%$ (Campbell (2001), Crouhy (2001), Hull (2000)). VaR asks the simple question, 'How bad can things get?' Therefore, while variance measures the spread around the average value of the random process, VaR gives a sense of the level of loss to expect at a certain confidence level. Extensions of VaR are also used (Topaloglou (2002)).

Section V.1.2 Strategic Optimization Levels for Functional Guarantees

The primary objective of the approach is to strategically mitigate the impact of risk, while maintaining sustained expected levels of profitability. As is shown in Figure III, optimization takes place at three levels of granularity; **(i)** the top-most level of optimization structures the company's portfolio profile. Such a portfolio may consist of identical physical components, different models of similar physical components, or dissimilar physical components. It is called

optimization of the portfolio, and creates a general set of guidelines, requirements, and objectives to be complied with during the design and execution of single Functional Guarantees. **(ii)** We term the second level optimization as the **optimization of a Functional Guarantee**. It reflects the optimization for Functional Guarantees based on similar physical components. It receives guidelines and requirements from the highest-level optimization, while defining how individual Functional Guarantee contracts should be written, and prescribes and defines requirements for the lowest level optimization. **(iii)** The third and lowest level optimization takes place at an instance level, and is termed **optimization of an instance**. An "*instance*" is a specific instance of a Functional Guarantee service, i.e., a specific producer installs a specific physical component at a specific customer site for providing a specific functionality. The level of detail is the highest at an instance level; therefore, the third level of optimization defines guidelines for strategic service practices. It additionally receives guidelines from the second level optimization. We note that under steady-state operations, the tree in Figure III needs to be first constructed from bottom to top. To understand the portfolio we first need to understand its constituents. Once this building up process is accomplished, the tree is traversed downwards to obtain a strategy that is consistent at all levels. In traversing down the tree, the portfolio optimization first takes place, which provides guidelines for Functional Guarantee contracts design. Similarly, through each Functional Guarantee optimization, a set of guidelines for instance level optimizations are derived. Thus, the three levels of optimization combine to provide a foundation for Functional

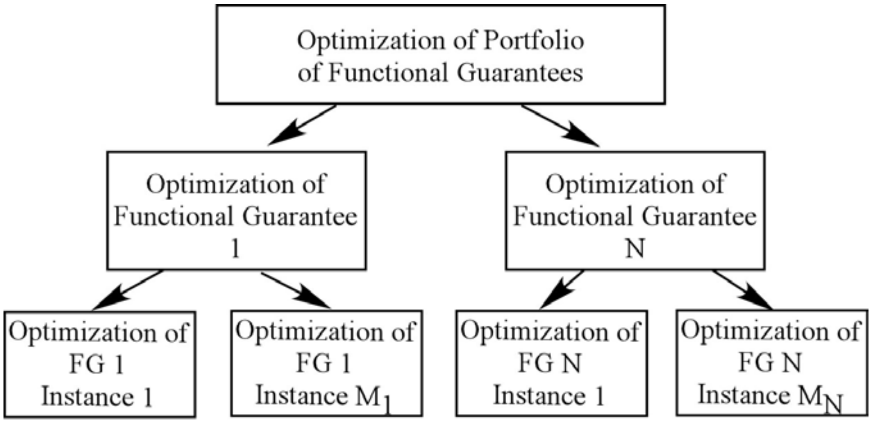


Figure III. Optimization Levels

Guarantee delivery.

Learning: Before reaching a steady state, *learning* plays a critical role in the theoretical foundation. As producers of Functional Guarantees gain more insight into the Functional Guarantees they are providing, it is essential that newly acquired information be retained and utilized in the subsequent decision making process -- as an opportunity to reduce uncertainty. This learning component will have a substantial impact on the risk management process. Specifically, as the service history for a particular physical component becomes defined, it will be possible to decrease uncertainty in problem formulation of the instance level optimization (see Figure III). This reduced uncertainty will improve decision-making for instances, as well as provide improved information in the formulation at the Functional Guarantee level optimization. Similarly, as the history of a given type of physical component becomes defined, the acquired information will play a critical role in reducing uncertainty in the formulation of the portfolio level optimization.

Section V.1.3 Strategic Risk Analysis of an Instance

The 'functionality' of a system is its inherent characteristic to perform a specified function according to specified requirements under specified operating conditions. The performance of the system in terms of producing its functionality can be measured using a single performance measure or a composite of several measures. Depending on the performance measures levels, the system (or any component within it) can be in one of three states: functioning, malfunctioning, or failed. By 'malfunctioning,' we mean that the system continues to deliver its functionality, but somewhat inefficiently.

Depending on how they are constructed, a certain range of levels of performance measures will indicate proper functioning of the system, while other levels will indicate malfunctioning or failure. In the Functional Guarantee contract, the producer and the consumer agree upon the terms to specify the degree of sensitivity of performance measures with respect to functional and malfunctional states. Additionally, the contract needs to specify the constraints, time-wise and others, that the producer will need to follow to bring the system back from malfunctional to functional state. The contract may also provide a guideline for acceptable frequency at which malfunctions may occur. All these aspects of the contract are design issues for an instance of Functional Guarantee. Appropriate decision variables and constraints will need to be identified to set up optimization problems for designing contractual agreements with the customers.

In the Functional Guarantee paradigm, the customer's tolerance for failures is extremely low. Additionally, the equipments will often need to function under governmental regulations. In order to allow no failures, although from the customer's perspective, performance measures indicate one of three states, from the producer's perspective they will need to be more versatile.

Strategic risk management also needs to seamlessly relate with the sensors-enabled condition-based maintenance approach of operational risk management. Therefore, from the producer's perspective, each performance measure is modeled to identify states of the system at a finer granularity. Each measure (and its values) will provide guidelines for the type of activities the producer needs to perform to deliver the Functional Guarantee and suggest desirable actions to prevent failures or frequent malfunctions.

Using reliability analysis techniques, such as, FMEA, FTA, simple parts-level models for failure distributions may be combined to develop models for performance or failure of subsystems of the physical component (see Section V.2). These performance measure models for physical component's subsystems will be employed for a detailed strategic risk management and Functional Guarantee contract design. The placement and operational usage of the sensors will also be guided by the performance measures used for strategic analysis of Functional Guarantee.

Let $\mathbf{P}(t) = [\mathbf{P}_1(t), \mathbf{P}_2(t), \ldots, \mathbf{P}_r(t)]$ denote the r-performance measures used to measure the functionality of a physical component. $\mathbf{P}(t)$ is an r-dimensional stochastic process defined on a probability space $(\Omega, \Im, P)$, with a natural filtration, $\Im_t$. Without loss of generality, each $\mathbf{P}_j(t)$

may be assumed to take values in interval [0,1], with '1' representing the best scenario. For each performance measure the producer can identify a critical value q_j (<1), such that if $\mathbf{P}_j(t)$ goes below q_j, the producer should consider a response-action to keep the physical component from malfunctioning. A single or a group of these performance measures going below their corresponding critical values will characterize a malfunctioning. There is nothing sacrosanct about a single critical value, and in fact, in some cases it may make more sense to have multiple critical values q_j^k, for each performance measure, each indicating a level of change in the condition of the subsystem of a physical component.

If the physical component may be assumed to begin functioning in the perfect functional state, i.e., $\mathbf{P}_j(0) = 1$ for $j = 1, \ldots, r$, then the **first passage time** is the first time any one of the $\mathbf{P}_j(t)$s goes below its critical level, q_j. Therefore, mathematically the first passage time is defined as:

$$\tau_p = \inf \{t > 0: \text{for some } j, \mathbf{P}_j(t) = q_j, \mathbf{P}_i(s) > q_i, \text{ for all } i, \text{ and } s < t, \text{ and } \mathbf{P}_i(t) > q_i, \text{ for all } i \neq j\}.$$

Depending on the performance measure $\mathbf{P}_j(t)$ that causes the first passage time, the producer will have certain choice of actions, each implemented with certain material, parts and labor costs. During the time spent in implementing the response action, the system will often not be available for usage; hence, the producer also incurs an opportunity cost. The set of possible actions the producer can take in response to occurrence of a passage time can be ordered by the cost of implementing them. Each action will result in varied degree of **post-remedy effects** on the distributions of the performance measures, thus affecting probability of post-remedy first passage time to different degrees. For instance, a minimal level of action will have a minimal effect, while almost replacing the entire physical component will make the physical component as good as new. Such a remedy-reward pair may be developed for each performance measure $\mathbf{P}_j(t)$ hitting the critical value q_j.

The challenge for the producer is to find the optimal policy for the response actions along the life of a Functional Guarantee such that the probability of failure is kept under control while the costs incurred due to the response actions are minimized. This is the cost side of the picture. The producer will also have to structure a desirable revenue stream, in negotiation with the customer, so that the costs and revenue streams are well balanced. A prototype optimization problem may look as follows:

$$
\begin{aligned}
&\max_{N,t_i,a_{\tau_j}} E[V(\sum_{i=1}^{N} \delta^{t_i} R_{t_i} - \sum_{j} \delta^{\tau_j} C(\tau_j, a_{\tau_j}))] \\
\text{subject to:}\quad & P(t_i \le \tau_j \le t_{i+1} \le \tau_{j+1}) \ge r,\ \forall i, j \quad \text{(revenue balance)} \\
& P(\tau_{j+1} - \tau_j \ge v) \ge s \quad \forall j \quad \text{(malfunction frequency)} \\
& P(\sum_{j_i} \mathrm{P}_{j_i}(t) \ge q) \ge u,\ \forall t,\ \text{set}\{j_i\} \quad \text{(failure minimization)}
\end{aligned} \tag{1}
$$

The above problem is a stochastic control problem where a control is imposed only when the system passes through its first passage time. R_t denotes the revenue stream and a_τ, the response-actions; r, s and u are numbers less than, but close to 1. Although not explicitly stated in the above formulation, after every control, the system partially renews itself and evolves according to modified probability distributions, depending on the nature of control employed.

There are two other issues to consider in the modeling: first, allowing the customer to intervene in the design processes of the Functional Guarantee and second, integrating the design phase of the physical component of a Functional Guarantee with all the subsequent activities of a Functional Guarantee. Customer participation may be incorporated in the design of the post-installation activities of a Functional Guarantee by introducing appropriate bounds and constraints. For example, the consumer may prefer a certain kind of response to a certain performance measure hitting its critical boundary, or the consumer may have a preference for a certain payment structure for the Functional Guarantee.

Integration with the design (of the physical component) can be accomplished if the dependence of the transition probabilities of the performance measures can be made to depend explicitly on the physical component's design attributes. This will directly integrate the design of the post-installation activities with the decisions made about design attributes of the physical component.

The transition probabilities may also be made dependent on a specific customer's usage characteristics or the environment the physical component will function in after installation. The optimization problem formulated above will be a large-scale multiobjective optimization problem.

Section V.1.4 Strategic Risk Management for a Portfolio of Instances

A single Functional Guarantee or single instances form basic units in terms of which the producer can evaluate and manage its Functional Guarantee business. The portfolio optimization aggregates over several instances of the same Functional Guarantee (level 2 in Figure III) and across different Functional Guarantees (based on different physical components) offered by the producer (level 1 in Figure III). For example, if a producer sells Functional Guarantees for different models of physical components for medical imaging and power generation, it views all the instances together as part of a portfolio of Functional Guarantees.

We further break the portfolio risk into strategic business risk and strategic financial risk. Strategic business risk relates to strategic business decisions and strategic financial risk relates to cash flow risks. Thus, developing risk analysis and management frameworks for the entire portfolio’s business and cash flow risks will provide an opportunity to truly reap the benefits of economies of scale and scope.

This aggregation across instances and Functional Guarantees poses a new set of challenges, since each contract is at a different stage of maturity. Therefore, the producer has a different degree of information from each, and interdependence of different Functional Guarantees needs to be understood to take advantage of the differential information and timing. The modeling approach described in the context of an instance needs to be extended to enable formulation of meaningful decision-making frameworks to manage the risks at the portfolio levels.

Decisions for the design of a Functional Guarantee instance are taken to maximize the **lifetime value** of the net cash flow of the instance, under the constraint that the system does not fail due to anticipated causes during its lifetime. Lifetime value ($LTV^i(t)$) of an instance, i, may be calculated in terms of the lifetime costs incurred due to response actions for each passage time, and the revenue structure negotiated with the customer.

One benefit of considering the problem at the portfolio level is to streamline decisions for each instance in accordance with the remaining Functional Guarantees in the portfolio, this is especially important when there are considerable interdependencies in the performance measures, $\mathbf{P}_j^i(t)$, $j = 1, \ldots, r^i$, of the Functional Guarantees. The response action to different passage times for an instance may change when viewed from the perspective of the portfolio. For example, consider two similar Functional Guarantees that are collocated. It may be more cost-effective to perform similar activities on the two Functional Guarantees simultaneously (Gupta (2003)).

The second control the producer would want to impose is to choose the time of initialization, T_s^i, of each instance in the portfolio. The producer cannot be expected to enjoy complete freedom in enforcing its preference in this regard, but to the extent possible, optimal staggering will be desirable to keep the value of the portfolio high. The danger of not being able to do so is clear, for instance, if the producer sells a large number of similar Functional Guarantees at the same time, which begin incurring large expenses around the same time of their lifetimes, this may render the producer's cash flows unsustainable. Bearing in mind that the nature of the equipment in this framework is high-capital products with expenses of maintenance comparable with the manufacturing costs itself; unsustainability of cash flows is a plausible danger.

The lifetime value of the portfolio of instances is a stochastic process dependent on the lifetime value of its constituent instances, their respective performance measure distributions, and response actions taken to deliver the Functional Guarantees, as well as the revenue each generates. The producer wants to maximize the lifetime value of the portfolio throughout the planning period, minimize the risk of large losses, or combine the two objectives as desirable.

Among the different ways risk may be characterized, the optimization process will select the most appropriate one. Value-at-Risk (VaR) is an attractive choice to control the downside risks (Crouhy (2001), Hull (2000)).

In a finite horizon of T years the producer sells M Functional Guarantees, with different starting points, T_s^i, and durations (termination dates, T_e^i). In order to manage the timing of each Functional Guarantee instance in the portfolio to control the potential losses, the decisions variables for the problem will be T_s^i, T_e^i, $i \in \{1, \ldots, M\}$. Additionally, to capture the effect of interdependencies between the performance measures, $\{\mathbf{P}_j^i(t), j = 1, \ldots, r_i\}$, of the Functional Guarantees, decision variables may also be incorporated for the key response actions for interdependent Functional Guarantees. This will require developing the structure for these interdependencies across identical, similar, or dissimilar but collocated Functional Guarantees. Therefore, an objective function of the portfolio optimization problem may have the following form:

$$\inf_{a_{\tau_j}^i, T_s^i, T_e^i} \{\sup_{0 \le t \le T} VaR(\sum_{i=1}^{M} LTV^i(t))\} \tag{2}$$

In order to simplify the expression, lifetime value of each instance ($LTV^i(t)$) is not explicitly written above; $a_{\tau_j}^i$ are the response-actions picked to be decided at the portfolio level. Constraints may also be introduced to depict the freedom the producer enjoys to enforce its preference on the timing of the Functional Guarantees and other constraints on interdependencies-related decisions.

Hedging Strategies for Strategic Risk Management: The producer does not have complete control over the initialization and duration of Functional Guarantee instances in the portfolio. When demand for a Functional Guarantee arises, the producer will need to respond to it or else lose the demand to a competitor. Therefore, even though the producer may attempt to time the Functional Guarantees in its portfolio optimally, some risks related to timing cannot be eliminated. However, other means of mitigating the risks are available; one approach is to develop specific hedging strategies. Hedging strategies are developed to manage risks associated with various cash flows. A decision-making approach to explicitly take positions in over-the-counter derivatives (e,g., forwards contracts, swaps) or traditionally traded derivatives (e.g., futures contracts, options) to hedge cash flow risks may be developed (Beenhakker (1997)). Therefore, the first step in this analysis is to identify, based on the strategic risk management for a portfolio of instances, the nature of risks that cannot be eliminated from the portfolio by timing of the constituent instances. The profile of this risk is the central driving factor for determining the appropriate hedging strategies. A hedging strategy allows for a temporal redistribution of cash flows to reduce the risk of unsustainable losses. The producer will need to identify specific derivative securities, either from traditionally traded or over-the-counter ones, which may be used to develop a hedging strategy for managing the residual risks.

Let us assume there are S such securities with values $\{Z_t^j, j = 1,\ldots, S\}$ that mature at T_z^j along with a pay-off of $Z_j(T_z^j)$ to the owner of the security. The producer will need to decide the positions $\{x_z^j(t), j = 1, \ldots, S\}$ to maintain throughout the planning period in order to minimize the Value-at-Risk of the portfolio of Functional Guarantee instances and the derivatives securities employed for hedging purposes. Thus, the portfolio problem is decomposed into two stages. In the first stage, the business decisions for the portfolio of Functional Guarantees are obtained, and in the second stage, after identifying the risk profile from the first stage, the optimal hedges are computed.

Section V.2 Operational Risk Management

Operational risks are those risks arising from the day-to-day operations necessary to provide the service to a customer. The goal of operational risk management is to minimize the breakdowns and downtimes of the physical components needed to provide satisfactory delivery of the Functional Guarantee. In order to accomplish this goal, design, engineering reliability analysis, and manufacturing of the physical components should be an integrated process, where potentially complex interactions may be required between these activities for the best outcome. Since the physical components are long-lived and have high capital requirements, service producers and customers have a common interest in design for reliability.

Managing these risks under the Functional Guarantee paradigm requires that technology be available to permit “sensing” the operations and their environment. Operations managers must be able to monitor and collect data in time to respond and provide corrective action. This monitoring must provide data on both status and location —especially important in the case of mobile physical components, such as, aircraft engines and trucks.

The next step in operational risk management is to provide an effective response to changes in operations that could degrade the provision of service to an unacceptable level. Responses may be automated in the form of preprogrammed routines or developed by operations managers, possibly with on-line, real-time assistance from field engineers. This “reasoning” amounts to analyzing data, drawing upon corporate knowledge, and making decisions, often in a time-constrained environment. An example is the service provided by GE Medical Systems to its customers (Gupta (2001), GE (1997)). Note that data may be unreliable and incomplete, but decisions must be made to keep the operations functioning—to provide the guaranteed service.

Operational risk management should be considered not an alternative to strategic risk management, but a complement. Consequently, an analytic approach proposed for operational risk management must be in accordance with strategic considerations, and vice versa (Wallace (1994), Wallace (1998)).

Section V.2.1. Design

Design of a physical equipment is a widely studied, researched, and actively developing area. In recent years, concepts such as design for reliability, assembly (Boothroyd (1983, 1994)), serviceability (Gershenson (1993)), quality of ownership, upgradeability, and safety have gained importance (Buckroyd (1994), Jeang (1996)). However, these concepts have not addressed the situation where the producer is responsible for ensuring that the physical components maintain their usability long after the customer purchases them. With this added responsibility on the producer, the concepts of design for reliability, serviceability, and safety take on even greater importance. These are essential concepts, since decisions made during the early stages of design determine more than 80% of the life-cycle costs of the equipment (Ishii (1995)).

The producer and customer often co-produce the process for a service (Fitzsimmons (2000)). Taking advantage of the services literature (Easton (2001), Pullman (1999), Verma (2001), Pullman (2001)), the design process should allow a wide range of customer involvement in customizing the design of the physical component. The two ends of the spectrum for level of customer involvement in the design process are – a standardized design and a unique design. Interactions between the producer and the customer during the design phase are important for a high capital, long-lasting physical component. A standardized design is when known processes with slight modifications solely determined by the producer are used. Hence, the producer can estimate future performance of the physical component accurately. Therefore, a standardized design involves significantly less risk than a unique design. Unique design is when the customer is completely integrated in the service realization process. In this case, since the future may not be as accurately predictable, the producer may want to share the risks involved in the service delivery with the customer.

The overriding goal of a Functional Guarantee service realization process is to design a service and the related physical component that is consistent with the firm's strategy, meets customers' needs in a responsible manner, and establishes a strong relationship with the customer. This has to be accomplished in a manner that the business is financially sustainable, which means that the design of service and the underlying physical component must be a suitable combination of quality and cost.

Section V.2.2. Reliability

Along with the design of the physical component, the producer needs to design the service delivery process. This includes the maintenance schedule, repair specifications, operating conditions, and guidelines during failures and breakdowns. The producer must also plan for logistics, labor, and inventory to support the service. This largely depends on the reliability of the physical component. Results of Failure Modes and Effects Analysis (FMEA) (Di Marco (1995), Eubanks (1996)) performed at the design phase are a good starting point for this detailed reliability analysis. FMEA is a bottom-up approach. It starts with failure events at the parts level and then proceeds to the system level to evaluate the consequences of such failures on the system performance. Failure Tree Analysis (FTA) (Blischke (2000)) is a top-down approach. It starts at the system level and then proceeds downward to the parts level, linking system performance with failures at the parts level. Combining FTA and FMEA leads to a cause-consequence logical relationship between all identified causes and their single or multiple consequences. Following this analysis, the overall outcome of reliability analysis is to build stochastic models (Dasgupta (1991)), using techniques such as failure interaction models (Murthy (1984), Murthy (1985), Blischke (2000)), to denote the future performance, breakdowns, and failures of the physical component. Appropriate failure distributions from Bernoulli, Binomial to Exponential, Weibull and mixed Weibull are used based on the characteristics of the failure process for parts of a physical component (Blischke (2000)). Models are also developed for material, parts, and labor costs of maintenance and repair. These combined with the reliability models indicate the right parts inventory levels to maintain to support the service delivery activities, while not incurring too high opportunity costs.

Section V.2.3. Service Infrastructure

Once a physical component is installed at a customer site, the producer needs to monitor its performance and perform diagnostics and prognostics. To observe the condition and relay the data to the producer’s command center, appropriate sensors and Information Technology infrastructure is put in place. A monitoring system integrates sensors within the structure of a physical component to observe the condition of areas of the physical component that are critical for its functionality. The specific areas are identified during damage tolerance and durability analysis, and therefore will depend on the specific physical component in consideration.

Adopting a condition-based maintenance (CBM) (Solvang (2001), Stephen (2001)) approach requires spending resources only on items with identified or possible defects. For a successful implementation of CBM, issues such as storage and accessibility of monitoring system data, frequency for data collection and analysis, and selection and development of data analysis techniques to ascertain the current state of equipment health (diagnostics) and predict its future performance (prognostics) must be addressed. When the physical component malfunctions, the producer also needs to identify the part(s) of the physical component that may be contributing to the problem and the level of action to be taken to fix the problem. The recursive binary partitioning and classification in the form of regression trees (CART) is used to develop an understanding of factors that split the better performing parts from the poorly performing ones. Decision Tree analysis is used to find the level of action needed for each malfunctioning component in the system to control the total maintenance cost (Pool (2001), Wallace (1993)).

Section V.3 Extreme Event Risk Management

Extreme events are those unanticipated, rare events which have a devastating effect on the performance of the physical component of a Functional Guarantee. We can classify the extreme events in a Functional Guarantee into three categories: extreme events caused by environmental conditions, engineering extreme events, and those caused by operational oversights. An extreme event caused by environmental factors cannot be predicted or controlled, yet it would result in large damages and losses. Similarly, operational oversights on the part of the customer cannot be predicted or controlled. An engineering extreme event is caused by a rare, inherent engineering attribute or mechanism of the physical component. Such unanticipated malfunctions or failures form an important post-installation risk component. Thus, estimating the distributions of the extreme events and optimally structuring a risk-management strategy for large losses brought about by these extreme events is essential (Kunreuther (1997)).

The Threshold method (Castillo (1988)) is used to identify the extreme events, where the method emphasizes the irregular data (outliers) that exceed a given (high) threshold (x_u) (Figure IV). Therefore,

x_1, x_3, and x_6 are identified as extreme values. To apply this to our problem, reliability models are exploited to identify possible engineering extreme events. Sensors cannot usually monitor environmental extreme events. Among the three families of extreme value distributions—Gumbel, Weibull, and Frechet—the Gumbel model has an exponentially decaying tail in the direction of largest values and has been widely used in modeling unanticipated events due to external conditions (Kellezi (2000)). Thus, it is a suitable candidate for modeling environmental extreme events in a Functional Guarantee. The acquisition of data for estimation of extremal parameters has significant time and cost requirements. Therefore, modeling of extreme events is a continual process, where the producer improves the estimation throughout the life of its Functional Guarantee business.

Based on an understanding of the distribution of extreme events and their interactions, the producer of a Functional Guarantee may structure an appropriate choice of insurance to purchase to transfer the risk to a third party (an insurance provider). Following the partitioned-multiobjective-risk method (Haimes (1998)), the losses are partitioned into different severity levels based on their exceedance probability, i.e., probability that loss is greater than a threshold value, L_i. The L_i values are chosen according to the extreme-value characteristics of the Functional Guarantees and the specifications of insurance policies available to the producer for purchase. The producer then faces two choices for each severity level: bear the loss due to extreme events in that range, if they happen, or purchase an insurance policy for that severity level, pay the premiums, and transfer the loss due to extreme events to the insurer. The outcome of this analysis is a structured plan for managing losses due to extreme events.

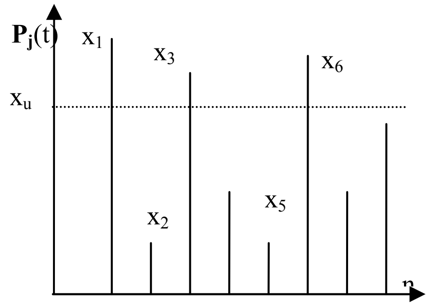
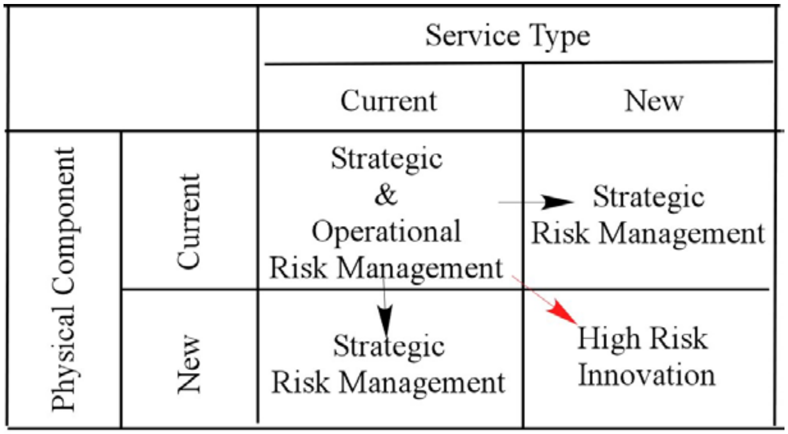


Figure IV. Threshold Method

Section V.4 Learning and Integration

All the uncertainty models developed so far heavily depend on prior information about the properties of the physical component of a Functional Guarantee, the environment it will be used in, and the usage characteristics of the customer or the consumer. For instance, a Functional Guarantee service must schedule condition-based maintenance according to reliability analysis, which in turn will require data from the design and operations stage. Additional data collected and knowledge gained along the way of conducting business should be incorporated in the models, and hence in the decision-making process. This is the learning component of the framework. In absence of constant learning, the producer is in the danger of losing its competitive edge.

Interaction between the three levels of strategic risk management lend very well to implementing learning strategies. Downward and upward iterations of the optimization tree in Figure III help in incorporating newly acquired information at one level into other levels. Interaction between operational risk management, extreme-events risk management and strategic risk management models is the other suitable venue for introducing learning strategies. Knowledge gained by the decision-making approaches in each risk management framework is utilized in the other two, thus integrating them together into a seamlessly comprehensive learning mechanism. The information methodically acquired, insights gained and constant methodological and model enhancement in each component of risk management and their interactions will bring continually greater efficiencies.



		Service Type	
		Current	New
Physical Component	Current	Strategic & Operational Risk Management	Strategic Risk Management
	New	Strategic Risk Management	High Risk Innovation

Table I. Innovation Effort Levels

The Learning-by-doing method is one approach for capturing new information as it is obtained (Larpre (2001)). Experience will help define the parameters of the *learning curve* equation for pertinent aspects of the Functional Guarantee operation. Recent research has applied the concept of Learning-by-doing to the implementation of Total Productive Maintenance in plants in Japan (Wang (2001)).

Learning is essential not only in efficiently executing the existing business, but also for the ability to innovate. Scope of learning is broken down as in Table I. Learning achieved at the level of an instance or a portfolio of existing Functional Guarantees based on strategic or operational decisions falls in the top left box. A simple innovation is introducing a new service for an existing physical component or offering an existing service for a new physical component. These simple innovations will directly benefit from the learning from the existing pool of business. Movement together in both dimensions however, is a high-risk move. Learning strategies will need to be developed to allow successful innovative moves in any of the above directions.

Section VI. Discussion

In this article, we presented a new service paradigm of Functional Guarantees, where the producer sells the long-term functionality of an equipment to its customers. An integrated risk-management based framework was developed to support a viable delivery of the service from the producer’s perspective. In this framework, design and delivery of the service are seamlessly tied together to create the right balance between long-term costs and rewards of the business. The framework will allow the producer to maintain profitability while meeting its customers’ needs. It will also help the producer to innovate based on its existing business.

Customer’s involvement in the design and delivery of a Functional Guarantee is essential. By a close involvement, the customer makes sure that its interests are met in the service delivery process as promised. Structuring the Functional Guarantee contract with right specifications is one way by which the customer can effect the involvement. If either party, producer or customer, holds back information regarding the service from the other, the danger of ill-effects of partial, imperfect information loom large. This is termed ‘**moral hazard**,’ a concept well studied in the insurance industry (Prescott (1999), Brewer (1997), Ely (1999)). In the context of an insurance provider, moral hazard is the possibility of loss to the provider arising from the character or circumstances of the insured. In Functional Guarantees, the producer could also keep information from the customer, which will adversely affect the overall quality of service. On the other hand, in order not to steal away the customer's benefits of Functional Guarantees, the customer should not be overloaded with the operational information. More research is required for complete formalization of the customer's role in the Functional Guarantee paradigm and elimination of moral hazard. Moreover, if a customer purchases many Functional Guarantees from one or more producers, they need to perceive all the Functional Guarantees purchased as a portfolio of contracts, and manage them together.

Existence of moral hazard in the Functional Guarantee service system also affects the consumers. Typically, the producers do not directly interact with the consumers; for example, GE Power Systems does not directly interact with the enterprises that purchase electricity from Niagara Mohawk utility company. However, the producer will need to function within the regulations and standards relevant for the physical components of the Functional Guarantees. Therefore, it is the responsibility of the government to establish regulations that protect the consumers. Governmental organizations may utilize the framework developed here as a guideline for creating the standards and regulations; however, more research is needed in this direction.

Section VII. Conclusion

Functional Guarantees are being provided today under different names without a strong theoretical backing of a rigorous framework. Long-term success of these service guarantees for critical equipment maintenance depends on sound management strategies. In this article, we presented a rigorous framework for the design and delivery of Functional Guarantees from the producer's perspective. An integrated risk management approach is the core of the framework. Research is required for components of the framework to enable the implementation of the framework proposed, specifically in areas of strategic risk management, learning and integration. As discussed in the previous section, research is also needed to formalize the customer's role and the governmental intervention to protect the consumers of the paradigm.

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Author Vitae:

Dr. Aparna Gupta is an Assistant Professor in the Decision Sciences and Engineering Systems department at Rensselaer Polytechnic Institute. Her research interests are in mathematical modeling of stochastic systems and optimization, with applications in decision-making and risk management in the service industry.

Dr. Norman K. Sondheimer is a Professor in the School of Management at University of Massachusetts. He is the director of the School of Management's Strategic Information Technology Center and co-Director of the University's Electronic Enterprise Institute. His research interests are in the commercial applications of IT, digital government, and IT support for aftermarket equipment service.

Dr. William A. Wallace is a Professor in the Decision Sciences and Engineering Systems department at Rensselaer Polytechnic Institute. Dr. Wallace teaches courses in the areas of Information Systems and Decision Sciences. Professor Wallace has over 20 years experience in developing, implementing, and evaluating decision support systems. Some of the on-going research includes decision support for group improvisation, visualization and the process of modeling, trust and knowledge management.