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Application of a Framework for Evaluating Risk in Innovative Product Development

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Abstract

This paper applies a novel framework developed by the authors for evaluating risk in innovative product design and development. The risk framework identifies three dimensions of risk in product development: *Envisioning Risk*, *Design Risk*, and *Execution Risk*. Applying the risk framework, the authors review several case histories of innovative product development, including development of the following: the consumer videocassette recorder, the personal computer, a gallium arsenide-based supercomputer, and an automated baggage handling system. The risk framework is used to evaluate the effect of product development risk on these development programs, to identify the risk-related failure modes for the unsuccessful innovative development programs, and to recognize several effective risk-mitigating development approaches used by the successful product developers. The prevalence of risk-induced failure modes in the high-stakes development programs analyzed emphasizes the need for further development and application of methodologies that will help product developers manage risk in innovative product development. The risk framework also points out the criticality of the interdependencies between all facets of the product development organization, and the resulting need for increased levels of concurrent engineering activity in innovative product development.

Keywords: Innovative Product Development, Risk Assessment, Risk Management, Case Studies

1. Introduction

Whether or not a company chooses to pursue innovative product development--development of new-to-the-world products or products offering quantum improvements in product value--and, if so, whether or not they are successful can have enormous implications on both the short-term and long-term success of the company. Consider some of the well-known successes (and failures) in innovative product development: Sony Corporation and the VCR (Ampex Corporation), IBM’s Personal Computer (Xerox Corporation), Cray Research Corporation’s supercomputers (Cray Computer Corporation). Although some of those markets have shifted and other leading companies have emerged since the advent of each innovation, Sony, IBM, and Cray Research Corporation were leaders of multi billion dollar industries based upon their ability to successfully develop innovative new products, or in the case of Cray Research Corp., to judiciously choose not to attempt development of an innovative product.

While those successful companies created new industries through their product innovation, Ampex, Xerox, and Cray Computer each experienced celebrated innovative product development failures--to the significant detriment of their organization. Ampex failed to recognize the technological potential of emerging VCR subsystem technologies, and Xerox failed to recognize the enormous market potential of their pioneering advances in several personal computer technologies. Cray Computer pursued with great vigor and at great expense the development of a gallium arsenide-based supercomputer, yet never produced a salable system.

Through our review of numerous case histories of innovative product development, eight of which are discussed later in this paper, two issues became excruciatingly clear: 1) both *ambiguity* and *uncertainty* had an enormous influence on the outcomes of the innovative product development cases, and 2) ambiguity and uncertainty are highly related to, and influenced by, the entire product development activity, including marketing, design, engineering, test, manufacture and sales. The presence of ambiguity and uncertainty leads to product development *risk* [1], which in turn gives rise to product development mishaps, misfires, and failures.

A lack of extant methods for dealing with risk in innovative product development has led the authors to develop the risk framework described briefly and applied in this paper. The purpose of the risk framework is to provide a method for identifying and classifying risk in innovative product development, so that individual risk elements may be more readily identified and acted upon by product developers.

2. Background: Three Dimensions of Risk

The authors define “risk” in innovative product development as the exposure to the chance of an unsuccessful development outcome due to the effects of ambiguity and/or uncertainty.

This section very briefly introduces a proposed framework for the evaluation of product development risk developed by the authors in another paper [2]. Due to space limitations, the authors refer readers to [2] for a detailed discussion of development of the risk framework discussed here, including placement of the framework in the context of existing methodologies.

Partitioning of the product development process into three stages--*Product Envisioning*, *Product Design*, and *Product Execution*--allows dimensions of risk to be directly defined in terms of the successful completion of each stage and the robustness of its output.

The decomposition and inspection of these product development stages has led to the proposed framework for evaluation of product development risk. The framework--represented graphically in Figure 1--decomposes the evaluation of product development risk into three distinct dimensions: *Envisioning Risk*, *Design Risk*, and *Execution Risk*.

INSERT FIGURE 1 HERE

Figure 1: Graphical representation of the framework for product development risk evaluation: the three dimensions of product development risk

The three-dimension risk framework focuses the evaluation of ambiguity- and uncertainty-generated risk on the *Product Vision*, the *Product Design*, and the *Delivered Product*, which are the defined deliverables of their respective stages of the product development process. Once the dimensions of risk have been defined, inspection of product development programs along each of the resulting dimensions of risk allows us to gain insight into the individual factors that drive risk in product development. Focusing the risk evaluation on the outputs of the individual design stages affords us the opportunity to evaluate the effectiveness, efficiency, and robustness of the individual product development deliverables themselves, as well as the organization and processes used to obtain them.

Considering each dimension of product development risk, the essence of each dimension of risk can be captured in a specific question:

Envisioning Risk: Will a product with the targeted product attributes of the Product Vision create Value for the customer and the company?

Design Risk: Does the Product Design embody the targeted product attributes of the Product Vision?

Execution Risk: Can the development team execute the conversion of the Product Design into a Delivered Product?

Consideration of the three-stage model and the risk framework reveals that the three dimensions of product development risk are highly interrelated and interdependent, since each product development stage output becomes the input to the next. The practical consequence of this fact is that actions taken to reduce risk in one dimension may lead to (possibly disproportionately) increased risk along another dimension.

This observation reinforces the critical role of concurrent engineering in reducing risk in innovative product development. Since different functional groups may have the lead role in each of the stages of innovative product development, input and understanding of the both the upstream and, particularly, the downstream functional groups and their needs will be critical to risk reduction and overall project success. For example, a Marketing group or person may take the lead in the Product Envisioning activity. But, if the product envisioner does not understand the capabilities of the technologies and/or the designers, they may create a Product Vision that is poorly matched to the technological or organizational capabilities, thereby injudiciously increasing Design and Execution Risk.

3. Application of the Risk Framework

Using publicly-available literature, the authors reviewed eight cases of innovative product development in three different industries: consumer electronics, computers, and automated equipment. Due to space limitations, the authors are only able to present the VCR and PC development histories in depth, with minimal treatment of the other two cases.

In the following sections, each case is evaluated via application of the risk framework to illuminate how product development risk led to development failure at the unsuccessful companies, or how the successful innovators were able to effectively manage each dimension of risk. Where appropriate, the authors indicate whether each risk element was uncertainty- or ambiguity-based.

3.1 Case 1: The Race for the First consumer VCR

In 1958, Ampex Corporation introduced the first commercially-available videotape recorder (VTR). The first VTRs were large and expensive, designed for use by television broadcasters. Since video tape recording provided a lower cost and simpler alternative to expensive and unreliable kinescope recordings used for delayed broadcasts to the West coast, the broadcasters were happy to purchase the VTR systems, even at $50,000 per machine. While the first VTRs in no way resembled a consumer product, many electronics manufacturers around the world immediately recognized the enormous market potential for bringing the video recording and playback technology to the home consumer.

In retrospect, success (or lack thereof) in the VCR market would be determined by each company’s ability to define, design and manufacture systems that offered quantum improvements over the broadcast VTR systems in three key attributes: size, cost, and ease of use. Later, after several competitors had successfully established themselves in the market, videocassette recording time would also become a key differentiator.

The following sections describe the development attempts of four of the world’s top electronics manufacturers to become the home video recorder innovator and market leader. Following review of the case histories, the authors apply the risk framework to identify the risk-based pitfalls and failure modes of those development programs.

3.1.1 Development of the Electronic Video Recorder at CBS

In the mid 1960’s, while Ampex refined its successful broadcast video recording systems, CBS was developing a film-based playback-only video system for the consumer market, dubbed the Electronic Video Recorder (EVR). CBS envisioned the EVR as a video player that would attain great success by satisfying the needs of both the consumer and commercial markets.

CBS focused its video recorder development efforts exclusively on the film-based EVR system. Its developers had decided that, based on its inherently high information content, film was the only viable alternative for meeting the data density and rate requirements of video recording. CBS did not believe that the lack of an at-home video recording feature would be a problem, on the assumption that once the EVR system was available to consumers and businesses, the entertainment industry would produce an abundant variety of movies and television recordings for consumer viewing.

After five years and $33 million of development, CBS demonstrated prototypes of the EVR to the public and immediately received great acclaim. The EVR system performed very well, demonstrating a bright, crisp picture with excellent color quality. Overall, the EVR demonstrated significantly better performance than several developmental tape-based systems that had been demonstrated by CBS's competitors. Soon after showing the EVR to the public in 1971, weekly articles in popular magazines such as *Business Week* and *Life* extolled the virtues of the new EVR technology, projecting its near-term, widespread adoption by consumers. CBS itself publicly projected that, in the following year, the EVR would "become commonplace in the home."

Based on the positive public reaction, CBS proceeded to set up a partnership of world-class companies to execute the manufacturing and sale of the EVR systems. These companies included Motorola, which was to produce the players; Twentieth Century Fox, which signed on to produce a library of movies; and Equitable Life which had agreed to use the EVR for training its employees. In addition, several Japanese companies signed licensing agreements to produce EVRs for the Japanese market.

However, after all the demonstrations, articles, and supply chain building, CBS finally turned its attention to validating the business case for the EVR system. The first, long-delayed step was executing a basic manufacturing cost analysis for production of the EVR systems and their recordings. Historical accounts claim that EVR program managers had long avoided addressing the manufacturing cost problem that in the back of their minds they knew existed [3]. CBS's manufacturing experts quickly confirmed their fears, finding that the tricky EVR film recording process--which involved shooting the film with an ion beam in a vacuum chamber--would lead to each 20-minute EVR cartridge costing an unacceptable $50 to $100 to produce at volume. Moreover, the quality of the tapes was expected to be highly variable.

Following that late realization, CBS could not identify any near-term cost reduction breakthroughs to address the cost of the EVR film production process. Because of the unacceptably high manufacturing cost of the EVR recordings, CBS realized that the EVR system could not be sold at a price that would make the system attractive to consumers. Thus, CBS immediately dropped the development and marketing of the EVR system.

3.1.2 Ampex's Failure to Pursue Consumer Video Recording

Ampex engineers had been highly innovative in developing the consumer video-enabling broadcast videotape recorder (VTR) technology. However, the company was not equally proficient at understanding potential markets for their new products. Just prior to introducing its first broadcast VTR in 1958, Ampex had conducted an analysis of the potential market for the product. This analysis led Ampex to predict total VTR sales of only thirty units for the first five years of production. However, within four days of their initial public introduction of the VTR, Ampex received orders for 80 machines at $50,000 a piece.

While this underestimation of the broadcast market potential was a pleasant surprise to the company, more significantly it demonstrated Ampex's systematic lack of confidence in the market and technological potential of video recorder products. Ampex, pleased but surprised by the strong broadcast market demand for VTRs, also failed to recognize the potential market for a home video recorder.

Following development of its first VTR, Ampex decided to focus exclusively on developing large, expensive, high-end systems for use in the broadcast industry. It is unclear whether Ampex did not envision a consumer desire for home VTRs or whether it did not see the long-term improvement potential of VTR subsystem and manufacturing technologies. In either case, Ampex chose not to pursue VTR technology development and design directions that had the possibility of producing the quantum improvements in the attributes of the VTR that would enable them to offer a product of high value to the consumer market.

After a number of years, Ampex was faced with competition in the broadcast market. The competitive influences forced the company to pursue at least modest improvements in the size, cost, and reliability of their broadcast VTR systems. Through ongoing R&D, Ampex had developed a derivative of the transverse scanning head--the helical scanning head. While the helical head design promised significant VTR size and cost reductions, it necessitated the use of transistorized electronics. Since at that time Ampex did not have the internal capability to develop the necessary solid-state circuitry themselves, and faced high internal resistance to adopting transistor technology, it was forced to outsource the transistorized electronics for their helical scanning systems.

To obtain the transistorized electronics, Ampex entered into an agreement with Sony Corporation. Sony was an emerging consumer electronics manufacturer with core competency in transistorized electronics. Under the agreement, which was signed in 1960, Sony supplied Ampex with solid-state electronics for use in Ampex's broadcast systems. In exchange, Sony was given royalty-free rights to Ampex's recording head technology for use in non-broadcast applications [4]. This seemed perfectly acceptable to Ampex, since Ampex was not anticipating a viable consumer video recording market.

By the early 70's, Sony and other Japanese companies had developed, produced, and marketed video recorders for the commercial and consumer markets. By the time Ampex recognized the enormous consumer market for video recorders, the company had fallen too far behind technically to make a viable attempt at developing a successful consumer VTR. In one of the most celebrated failures of a U.S. company to capitalize on invention and innovation, Ampex had not only passed up, but given away for free, its opportunity to become the world leader in consumer video recorders.

3.1.3 Development of a Videotape Recorder at RCA

In 1951, RCA President David Sarnoff issued a challenge to his company's engineers: to develop ". . . a television picture recorder that would record the video signals of television on an inexpensive tape . . ." [4]. RCA immediately launched a major research and development effort aimed at developing a tape-based video recording system, with consumer home video as the envisioned market.

From the start, RCA engineers focused on developing a machine that could attain sufficiently high data recording rates. Although many different approaches to solving the data rate problem were being explored worldwide, RCA developers inexplicably focused exclusively on a fixed-head recording approach. In order to achieve the high data rates necessary with the fixed head system, the magnetic tape had to be fed through the machine at exceedingly high speeds, often in excess of 20 miles per hour. With such high feed rates, over a mile of tape was consumed for a three-minute recording, allowing only four minutes of recording on a seventeen-inch reel.

The high tape speed itself gave rise to other engineering problems. At such high tape feed rates, video quality was highly sensitive to relatively small variations in the tape speed, often due to minor variations in either the tape drive speed or tape properties. RCA development engineers were consumed with solving the multitude of design challenges in making the longitudinal system perform. After five years of intensive development, they had greatly improved the picture quality of the longitudinal system through development of sophisticated speed control electronics and precision drive systems. However, those systems had only began to approach picture quality levels that would be acceptable to consumers [3].

While picture quality was indeed important, improvements in picture quality meant little if the video recorder system was not attractive to consumers. Because of the tape speeds involved, the longitudinal machines were inherently very large, very expensive, and hard to use. Further, they could only record a few minutes of video on each 17-inch reel. In retrospect, although they were being targeted for the consumer market, the longitudinal systems looked to be as expensive as broadcast systems, including the inherently high tape costs due to the excessive consumption rate. Despite Sarnoff's vision of developing and producing a video recorder for the consumer market, RCA's development path of its longitudinal video recorder system was taking the company further and further away from a viable system.

The bubble finally burst at RCA when Ampex introduced the transverse-scanning video recorder in 1956. Suddenly aware of the extreme shortcomings of the longitudinal video recording approach, RCA abandoned development of those systems. Unfortunately for RCA, five years focused solely on developing longitudinal video recorders had left them too far behind other competitors in the video recorder development race to offer a successful home video recorder product.

Ironically, in 1950, just prior to Sarnoff's initial challenge, an RCA engineer had received a patent for a high-frequency tape recording device that utilized a transverse-scanning data recording approach [5]. Inexplicably, the patent and its underlying approach were ignored by the RCA video recorder developers, who proceeded to focus exclusively on the longitudinal recording approach.

3.1.4 Development of the VCR at Sony

From its inception, Sony's company vision has been the development consumer products utilizing advanced technology [6]. In its first two decades of existence, Sony Corporation was a pioneering developer and manufacturer of many new-to-the-world high-tech consumer products. Sony's innovations included the first low-cost audio tape recorders, the first stereophonic audio systems, and the first transistorized pocket radios. Sony Corporation was also the first Japanese company to manufacture both transistors and transistorized products. Therefore, it was not surprising that once broadcast videotape recording systems began to arrive in Japan from the United States, Sony immediately initiated development of their own video recorder systems, aimed at volume production and sale to the consumer market.

Beginning in 1957, Sony aggressively pursued development and production of video recording systems for the commercial and consumer markets. Even prior to obtaining a technology licensing agreement with Ampex in 1960, Sony had developed its own transverse-scanning machine for the consumer market, the SV-201, which it quickly released once the agreement with Ampex had been signed. Following that first market entry, Sony quickly executed the development and production of a series of improved VTRs, including the PV-100, and the EV-series.

Despite Sony's technical and manufacturing strength, and excellent reputation with consumers, achieving successful sales of video recorders was an unexpectedly difficult challenge. While the aforementioned VTR systems were all directly aimed at the consumer market, each one was rejected by consumers as being too big, too difficult to operate, too expensive, and allowing too little recording time.

In 1965, Sony released the CV-2000 (CV for "Consumer Video"), which allowed a half hour of taping on a single seven-inch reel. Sony was confident that its innovation of "skip field" recording, which traded off a slight decrease in picture quality for twice the recording time, would lead to high consumer acceptance. Sony was incorrect again--consumers did not find the system attractive--but was fortunate that commercial and educational institutions became a solid market for the CV-2000 systems.

Recognizing that the machines were still too large and difficult to operate, Sony made the decision to move to a cassette-based system, modeled after the audiocassette, which had been introduced by Philips in 1962 [3]. In order to achieve acceptable size and packaging of a cassette-based systems, Sony's engineers drove technology improvements on several fronts, including videotape substrate film and magnetic powder improvements leading to higher data-density tapes, and manufacturing advancements allowing production of smaller, more precise recording heads. Those developments led up to the creation of the Sony "U-matic", which became the world's first videocassette recorder (VCR) when it was released to the public in 1971.

To Sony's surprise, the U-matic was shunned by consumers as once again being too big and expensive. A product cost overrun for the U-matic was partly to blame. Although Sony had originally targeted the U-matic for sale at a price of $500, manufacturing cost overruns forced Sony to price the recorder at a lofty $1000. Fortunately for Sony, the commercial and educational markets again came to the rescue. With Sony's addition of the American-invented digital time-base corrector to the U-matic, the picture quality of the U-matic was high enough to allow TV stations to adopt the system for remote news collection, which at last began to widen the application and adoption of video recording systems.

Following the release of the U-matic, Sony went to work on making the recorder even smaller and less expensive. The product development staff was explicitly challenged with the development of a player that would sit atop a standard television set, and was to use a paperback-sized cassette. To accomplish this clear goal, Sony developers worked for three years, making advancements in recording track spacing, tape production, integrated circuits, servo mechanisms, and head and drum construction. In concert, those advances enabled a 75 percent decrease in tape consumption rate, resulting in a substantially smaller, less expensive VCR system.

By 1974, Sony had developed a prototype of the product which was later named “Betamax.” When the Betamax went on sale in 1975, consumer electronics stores could not keep the product on the shelf. Sony had, at last, successfully ushered in the age of consumer video leading to the creation of a $7 billion industry worldwide [7].

3.1.5 Discussion: Evaluation of VCR Development

In this section, the authors evaluate the cases of VCR development from the perspective of the risk framework, considering risk elements in each of the three dimensions: *Envisioning Risk, Design Risk,* and *Execution Risk*. We use the framework to help us identify risk drivers and failure modes in each of the cases, as well as to identify development approaches used by the product developers to successfully mitigate risk.

3.1.5.1 Evaluation of Envisioning Risk

In each case, the video recorder developers inherently faced substantial Envisioning Risk, because no information was available on a consumer VCR market--since it did not yet exist. Without an existing product and customer base, the product developers had no way of ascertaining what features and functions would be attractive to consumers, what competitive products would be offered, or how those customer wants and needs might change during the product development lead time. Therefore, the viability of the Product Visions for their video recorder products was highly uncertain, leading to high levels of (ambiguity- and uncertainty-based) Envisioning Risk.

CBS had recognized that its system should provide high-quality playback to attract the home consumer, and strongly incorporated that requirement in the Product Vision. This requirement translated into high data retrieval rate requirements for the player, which led the company’s designers to select a film-based system.

Whereas the validity of the picture quality requirement was later confirmed by the excitement generated by the public demonstrations of prototype EVR systems, the product envisioners for CBS video system did not adequately emphasize the key attribute of *cost* to the consumer. The lack of emphasis on product cost in the Product Vision for the EVR system led to high levels of (ambiguity-based) Envisioning Risk. Even if the developers had met all the stated performance goals for the system (i.e., picture quality), whether the product would provide high value to the customer and the company was highly uncertain because of the complete lack of development focus on meeting a system cost requirement.

Beyond the issue of product cost, the product development team faced significant (uncertainty-based) Envisioning Risk due to uncertainty associated with market acceptance of the playback-only product. Even if the EVR performed technically as planned, consumer willingness to purchase the playback-only systems prior to availability of a substantial supply of EVR programming was highly uncertain. Likewise, the willingness of the entertainment and training industries to invest the money to create a substantial supply of EVR programming prior to the realization of a significant installed base of EVR systems existed was also highly uncertain.

Ampex's failure to pursue the consumer video recorder market, despite its technological leadership, was strictly due to Envisioning Risk. The lack of understanding of the possible improvements in video recording technology and manufacturing techniques led to Ampex's conclusion that the requisite improvements in picture quality, size, cost, and ease of use for creation of a successful consumer video recorder product were not feasible. It is unclear whether Ampex simply did not foresee the potential technological and design breakthroughs (ambiguity-based risk), or whether it saw the improvements as possible, but assessed that the small probability of success did not merit their pursuit (uncertainty-based risk). Either way, Ampex completely disregarded the potential of the consumer market for video recorders.

Unlike Ampex, RCA video recorder developers were not stymied by lack of vision. They were given clear direction by their president to develop a magnetic tape-based video recording device for the consumer market. Despite that far-sighted directive, RCA video recorder developers failed to translate Sarnoff's high-level vision into a comprehensive Product Vision that included *all* the product attributes required to produce a high value consumer product. The RCA developers headed into the design and development activity without a clear vision of the full range of required product attributes. Thus, RCA exposed itself to high levels of (ambiguity-based) Envisioning Risk through its failure to develop a comprehensive Product Vision.

Of the companies reviewed, only Sony developers operated with an explicit and comprehensive Product Vision. From the company ideology to the goals of the product development managers, Sony engineers had clear direction on their vision: commercialization of video recording technology in the consumer market. The product development managers frequently presented the development engineers with clear numerical targets for specific product attributes such as size and weight (mitigation of ambiguity-based risk), allowing pursuit of only the design approaches consistent with meeting those targets.

Despite strong communciation of the Product Vision and aggressive development goals, Sony suffered the effects of (uncertainty-based) Envisioning Risk in four consecutive product introductions between 1965 and 1971. Of those products, some had met all of their envisioned characteristics of the Product Vision, while others had fallen somewhat short of some of their development targets. Regardless, each was in turn rejected by the consumers for being too large, too expensive, or too hard to use. Yet, Sony persisted, and on its fifth attempt (mitigation of uncertainty-based risk) the company was finally successful in providing a high value product to the home consumer and achieved their sales and profitability targets.

Interestingly, although Sony was the market leader in consumer VCRs with its high-value Betamax, Envisioning Risk would once again prove to be its nemesis. In late 1976, JVC introduced the VHS format VCR, which provided two hours of recording capability to Betamax's one hour. The two-hour recording VHS format was also adopted by several other fast-follower VCR manufacturers, leading to a subsequent shakeout of video formats and the obsolescence of the Betamax.

Because Sony had not recognized the risk it faced due to a potential customer requirement of two-hour recording capability, the company had invested only in the one-hour Betamax format. Once the competing VHS systems had been introduced, customer demands quickly changed, and Betamax systems no longer offered high value to consumers.

Sony's experience in VCR development clearly illustrates the effects of Envisioning Risk: the possibility of product failure in the market, even if all of the stipulations of the Product Vision are met.

3.1.5.2 Evaluation of Design Risk

CBS envisioned the EVR system would meet the needs of the home and commercial consumers by offering high-quality video. While the EVR's attribute of high-quality video playback did attract a great amount of consumer interest, CBS had failed to design a system that would be affordable for the consumers and could thus produce a profit for the company. The product developer's focus on the "primary" problem of achieving high quality video playback reinforced ambiguity about how the EVR system would produce value for the home customer and the company, exposing the company to high levels of (ambiguity-based) Design Risk.

While Ampex failed to recognize the consumer VCR market due primarily to Envisioning Risk, had the company pursued the market, they would not necessarily been successful since it would have faced significant (ambiguity- and uncertainty-based) Design Risk. Ampex had developed a core competency around large, expensive, low-volume, vacuum-tube-based systems. Success in the consumer market would require small, inexpensive, high-volume, solid-state based video recorder systems. Ampex's ability to create a viable design for a system requiring such foreign design and manufacturing approaches would have been highly suspect.

RCA focused its development strictly on the most immediate and obvious problem: the data rate issue. However, as with CBS's development of the EVR, this single-minded development approach reinforced ambiguity of how its system would produce value. Although RCA did not provide a strong and comprehensive Product Vision, the product developers cannot be exonerated from failing to consider how the product requirements would create value. It should have been clear to the RCA developers that their longitudinal approach to meeting the data rate requirements would preclude them from meeting other essential and obvious customer requirements for the product such as size and ease of use. A clear example of ambiguity-based Design Risk, the product developers lacked understanding of the relationship between their selected solution path (longitudinal recording) and their ability to satisfy customer requirements (size, cost, ease of use).

Sony, on the other hand, effectively reduced Design Risk by comprehending the full array of customer requirements and pursuing multiple solution paths (mitigation of both ambiguity- and uncertainty-based Design Risk). Sony developers realized that the final product attributes faced uncertainty due to the many new technologies and design concepts being tested and implemented. To minimize Design Risk when engineering key product features and functions, the Sony engineers often used hedging strategies, pursuing several--sometimes as many as ten [7]--different design approaches simultaneously. Such hedging strategies maximized the probability that they would be successful in developing a design approach that met all of the design requirements. Sony designers also worked closely with production engineering to assure that the products could meet manufacturing quality and cost requirements. Through those efforts, Sony was highly successful in managing Design Risk.

3.1.5.3 Evaluation of Execution Risk

Of the video recorder development efforts described here, Sony was the only company to successfully complete the Product Execution phase, converting its Product Design into a Delivered Product.

Through its long string of commercialized innovative products, Sony had developed core competency in executing innovative products. The company's product development organization operated in several ways that greatly reduced both ambiguity- and uncertainty-based Execution Risk. First, all product development programs at Sony utilized close interaction of design engineering, test and validation engineering, production engineering, and management. Such communication led to everyone involved in the program possessing a clear understanding of the Product Execution needs and required roles. Second, Sony's strong Product Vision and robust Product Designs minimized the propagation of product development risk to the Product Execution activity. Third, Sony management maintained a stable product strategy, and ensured solid resource support for the product development activities. These combined approaches led to successful management of Execution Risk at Sony.

CBS minimized Execution Risk by developing a supply chain, a strong distribution plan, and was enjoying excellent response from its early marketing efforts (mitigation of uncertainty-based risk). Those efforts seemed to lay the groundwork for what would have been a smooth Product Execution. Unfortunately, due to Envisioning and Design Risk, CBS's EVR system was found to be non-viable and dropped.

Ampex would have faced a similarly adverse situation in Product Execution as in Product Design, since the company had not developed core competency for execution of small, low-cost, solid state-based video recorders to be produced in high volume. In fact, Ampex's resistance to solid state technology was so high at that time that some engineers put up "stamp out transistors" signs in their offices [3]. Even if Ampex had developed a viable Product Vision and Product Design for a consumer VCR, whether the company could have successfully executed the product is highly uncertain. Had the company pursued the consumer VCR market, it would have faced high levels of Execution Risk.

RCA's development approach lacked a strong emphasis on Product Execution and thus incurred (primarily ambiguity-based) Execution Risk. Although RCA had many consumer products on the market at that time, it did not have a clear plan for execution and commercialization of the video recorder system. Further, the company's product developers did not interact with production and marketing, which increased both Design Risk and Execution Risk.

3.2 Case 2: Two Key Challengers in the Development of the PC

One of the most significant product innovations of modern history is the personal computer (PC). Shortly after their introduction in the late 1970s, personal computers redefined the world's approach to business, education, and entertainment and grew into a new multi-billion dollar industry [9].

As in the race to develop and produce a consumer VCR, the companies who competed to become leaders in the emerging PC industry followed many and varied paths. Also similar to the gestation of the VCR industry, emerging technologies and changing consumer demands threw ambiguity and uncertainty into the development of those products.

In the next two sections, the authors discuss the efforts of two world-leading companies, Xerox and IBM, to become leaders in the PC industry. While both companies had originally achieved world-class standing by capitalizing on innovative product development (Xerox-photocopiers, IBM-mainframe computers), each had great difficulty in achieving success in the emerging PC market.

3.2.1 PC Development at Xerox

In the early '70s, Xerox's Palo Alto Research Center (PARC) embarked on the development of the first "personal distributed computing" system. Recognizing that the combination of the strong trend toward smaller, localized computer systems and rapidly improving price-performance of integrated circuits offered new product opportunities, the PARC researchers boldly envisioned a computer product which was to offer "personal distributed computing" while being "both cheaper and better" than the contemporary minicomputer systems [10].

Xerox PARC eagerly accepted the challenge of designing the machine that would meet that vision. However, in order for the new product to indeed be both cheaper and better than current minicomputers, across-the-board innovation was required to simultaneously improve the computer's function, features, size, cost, and performance.

The PARC researchers felt that foremost, the computer had to be interactive. Based on the latest thinking in man-machine interfaces, they adopted the now ubiquitous window-based graphical user interface combined with a "mouse" pointing device. The PARC researchers felt that the only effective display for the graphical user interface system would be a bit-mapped screen, which was inherently memory-intensive, and thus normally quite expensive.

However, PARC researchers knew they had to rigorously manage the price-performance trade-offs and be creative to reduce their hardware cost below the initial projections of $50,000 per unit.

In order to reduce system cost, the PARC developers moved to a reduced but optimized number of screen pixels to greatly lower memory requirements. They also invented an innovative multitasking scheme that reduced the number of processors required to one. In concert, these innovations reduced Alto's hardware cost by approximately 80%--to under $10,000--sixty percent below the cost of contemporary minicomputer systems [10]. The concept of the personal computer began to look viable.

In addition to developing the array of basic features of the Alto itself, PARC concurrently developed other innovations that enhanced the functionality and usefulness of the Alto. Those innovations included development of the "Ethernet" computer-to-computer communications system, which allowed Altos to communicate and transfer data to other Altos and peripherals. PARC also integrated laser technology with its patented xerography process to create the world's first laser printer. The Alto developers then turned toward development of software that would maximize the Alto's capabilities and value, including the world's first "wysiwyg" (what-you-see-is-what-you-get) word-processing software.

By 1973, PARC researchers had designed and built the world's first personal computer, dubbed the Alto, and an impressive list of value-added peripherals. Looking back, one can see that Xerox had created that first Alto an astonishing *eleven* years before the now-famous Apple Macintosh received great acclaim for its use of many of those same features demonstrated by the Alto (and, notably, it was approximately 16 years before Microsoft introduced "Windows" for the PC).

The PARC developers field tested the Alto system in 1975, providing an integrated network of Altos and a laser printer to personnel at a Xerox subsidiary in the publishing field. Due to its strong array of features and capabilities, and intuitive user interface and software, even the most technology-averse employees were quickly able to proficiently use the Alto system for text entry and editing. Some of the test subjects went so far as to say they couldn't imagine having done work differently. Within two years, the test-bed company was using the Alto-based system for production of over half of its books.

Based on their technology and field test successes, PARC researchers truly believed that the Alto would become Xerox's next entry in the rising electronic word processor market. The production of the Alto would, they assumed, be executed by Xerox's Office Products Division, the manufacturer of Xerox's line of typewriter-style word processors. However, when approached about manufacturing Altos, the Office Products Division felt that the Alto was too technically advanced to include in its product plans. Even though Xerox's corporate-level product planning task force had recommended that the Alto become the next-generation word processing product, the Office Products Division unilaterally decided that the "850" word processor, a product that had been developed in-house, should be produced rather than the Alto.

Although that first Alto represented a monumental lead in development of a useful, customer-appealing personal computer, and despite the company's publicly-stated company vision of being the leader in the coming "digital architecture of information," Xerox made a decision in 1976 not to produce the Alto. By choosing not to market its PC (in favor of a word-processing typewriter derivative, that once on the market had lackluster sales performance at best), Xerox threw away their opportunity to dominate what was to become a spectacularly lucrative

PC market. Within a few years, several other companies had introduced less capable personal computers into an explosive market, resulting in cumulative industry sales of several billions of dollars by 1981. Because of Xerox's risk-averseness and inability to translate the Alto into a Delivered Product, the company failed completely to capitalize on its path-breaking technology development.

3.2.2 Development of the PC at IBM

Throughout the 1960's and 1970's, IBM Corporation dominated the computer markets, based on its strength in large, mainframe computer systems. IBM's leadership in computer systems was an evolution of its leadership position in the traditional (mechanical) data processing equipment market, where they had built up a nationwide installed base of machines, as well as an extensive sales and distribution network. However, the company's real success came in computers, as a result of its willingness to make the bold and risky move from production of mechanical data processing equipment to manufacturing mainframe computer-based data processors.

However, IBM's dominance in mainframe systems became a two-edged sword: along with dominance of data-processing computer markets came a single-minded reliance on mainframe technology, as well as increasing levels of bureaucracy to support it. That bureaucracy had led to an environment focused exclusively on revenue and profit that killed innovation and flexibility. In addition, IBM's explicit commitment to its customers to never strand them by introducing new products with incompatible systems or software forced them to develop and market only evolutionary products and technologies [11].

By the time the personal computer market had begun to take off in 1979, IBM had fallen far behind in personal computer technology. Having at last recognized the threat of missing the PC market, IBM, without a significant PC development program in the development pipeline, launched a crash internal program to develop, manufacture, and market a personal computer.

IBM management wisely recognized at that time that their traditional product development processes would not allow the development team to deliver a new product--an innovative product nonetheless--fast enough to keep them competitive in the PC market. Having made such a realization, IBM management broke away completely from their traditional corporate development approach and set up a small, entrepreneurial development group in Boca Raton, Florida. The group was given ample funding and complete autonomy to quickly develop a personal computer product.

That aggressive move proved to be highly successful. The Boca Raton organization was very effective and innovative, operating more like a start-up company than an IBM development group. The Boca Raton group's product design and execution strategies led to several fortuitous synergies which enhanced the success of the PC product. In order to move quickly, the Boca Raton developers had gone outside IBM for much of the hardware and software. Their use of commonly-available components rather than the traditional custom-designed IBM components led to major cost savings and lead time reductions. Additionally, due to the resulting "open architecture" of the IBM PCs, they were soon "cloned" by other manufacturers, leading to the IBM PC architecture becoming an industry standard.

Another factor that contributed to success was that the IBM PC organization moved to develop retail distribution channels rather than using the traditional IBM sales force. By using retail distribution channels the IBM PC was able to quickly gain wide market coverage without incurring the time penalty and expense (and potential resistance) of training the incumbent IBM mainframe systems sales force.

The innovations of the Boca Raton group served to increase the IBM PC capabilities, while substantially reducing cost and meeting aggressive lead time targets.

Upon its release to the public in 1981, IBM's PC product was an immediate success. Two years later, the IBM PC had already snatched 17% of the PC market while Apple slid to 13% from its 21% market position [12]. That 17% of the market represented enormous revenues, since although aggressive projections had estimated the personal computer market at $2 billion by 1985, by that time it had actually exceeded $19 billion.

Unfortunately, unwilling to leave a good thing alone, IBM reintegrated the hugely successful Boca operation back into the mainstream operations shortly after the market introduction of the PC. Return of PC development to the corporate fold quickly halted the innovation that had been taking place. Once the group was reintegrated, new products and improvements from IBM began to come out slower than its aggressive upstart competitors, who immediately began to set the pace for new hardware, applications, graphics, and communications innovation.

3.2.3 Discussion: Evaluation of PC Development

In this section, the authors evaluate the cases of PC development from the perspective of the risk framework, considering risk elements in each of the three dimensions: *Envisioning Risk, Design Risk,* and *Execution Risk*. We use the framework to help us identify risk drivers and failure modes in each of the cases, as well as to identify development approaches used by the product developers to successfully mitigate risk.

3.2.3.1 Evaluation of Envisioning Risk

Ironically, as a corporation, Xerox had foreseen the coming PC revolution years before most of the competition and founded PARC specifically to develop such technologies. PARC researchers recognized the uncertainty with the current state of computer technology and its trend toward smaller, distributed systems. Although the company's vision was indeed sound, the uncertainty associated with the direction of computer technology and competitive influences resulted in the PARC researchers facing significant (ambiguity- and uncertainty-based) Envisioning Risk.

However, the PARC product envisioners possessed a deep understanding of the computer market, in particular, current computer product usage and their primary limitations. These insights could be attributed to the fact that most of the PARC researchers were computer aficionados as well as product developers with an intimate knowledge of the market, consumers, and current technology. Based on their knowledge, PARC developers created a Product Vision for the personal computer that had a high probability of providing high worth to the customer. Additionally, they specified aggressive cost targets for the system that would allow their system to provide high value to the customer while allowing Xerox to make an appropriate return. Thus, they had greatly reduced the (ambiguity-based) Envisioning Risk by stipulating a Product Vision based on customer and company value.

While Xerox was ahead of its time in envisioning the PC market, bureaucracy and reliance on its mainframe business led IBM to ignore the PC market, exposing the company to high levels of (ambiguity-based) Envisioning Risk. By the time the surging PC market could no longer be ignored, IBM had fallen far behind the PC leaders.

Once awakened to the lucrative potential of the PC market, IBM fortuitously recognized that achieving a fast time-to-market was critical for them to remain competitive. IBM moved forcefully toward becoming a PC competitor, at last creating a Product Vision for an IBM PC product with a strong stipulation of time-to-market. That realization, and the actions taken to speed their time to market greatly reduced their level of (ambiguity-based) Envisioning Risk.

3.2.3.2 Evaluation of Design Risk

Because the PC development was actually being conducted almost 10 years apart, Xerox and IBM faced significantly different levels of Design Risk in their development programs. The PC developers at Xerox were creating a bona fide new-to-the-world product. No one had ever created a personal, distributed computing system before, and the computer design concepts and subsystem technologies were in their infancies. The newness of personal computer design and technology injected ambiguity and uncertainty into the development process, leading to Xerox developers facing significant (ambiguity- and uncertainty-based) Design Risk.

IBM PC developers, on the other hand, were playing catch-up. By the late 1970s, numerous other companies had already put PC products on the market. Thus, the design approaches and technologies used were widely known and understood. The primary driver of Design Risk for IBM, rather than the PC technology *per se*, was the ability of the IBM organization, with its long history of designing large, expensive, incremental mainframe systems to successfully design a small, inexpensive, innovative PC.

Much to its credit, when IBM finally recognized the need to become a competitor in the PC arena, the company wisely recognized that its current product development organization and structure would be highly detrimental to the successful design of an innovative PC product in an extremely compressed time frame. The realization that the current organization would lead to unacceptably high (ambiguity- and uncertainty-based) Design Risk led IBM management to make the bold move to charter a completely new approach toward the development of the PC system. The new approach involved spinning off an autonomous, “start-up” style development team which was given full authority to do whatever it took to develop a successful PC.

That autonomy allowed the development team to decrease Design Risk by operating much more efficiently and effectively than an internal IBM program could have. Such autonomy also allowed the team to greatly reduce

Design Risk by implementing several innovative design, sourcing, and manufacturing approaches that most likely would never have been conceived of, let alone adopted, by an in-house product development team.

3.2.3.3 Evaluation of Execution Risk

By 1973, Xerox had envisioned and designed a product that had a vast array of high-worth features that other computers would receive acclaim for several years later. The Alto had been tested and validated, had received great reviews in initial field trials, and its developers had shown that it was cost competitive with current products that possessed only a small fraction of the Alto's features and functionality. How could it miss?

Despite the fact that PARC developers were right on the money with their Product Vision for a PC system, and that PARC developers had created a Product Design that represented a high value product for the customer (and certainly, had they sold the systems, for the company), the Alto was not able to cross the chasm between PARC and the product divisions. The reasons for the failure included bits of technology averseness, company politics, "not invented here," and a general lack of communciation and leadership. Each of those factors compounded Execution Risk, which in the end led to the rejection of the Alto by the product division and Xerox's lost opportunity to be the world's PC leader.

The Execution Risk faced by the Alto development team included both ambiguity- and uncertainty-based risk. Ambiguity-based Execution Risk stemmed from the product developer's lack of recognition of the importance of putting together a clear, supported, executable plan for production and sale of the product. Uncertainty-based Execution Risk arose from uncertain elements that affected the company's decision whether to manufacture the product. These included Xerox's actual product mix at the time of the commercialization decision, the company's financial position at the time of the decision, as well as its recent experience with other new technologies influencing the companies level of technology risk aversion.

IBM's move to reduce Design Risk through the use of an autonomous "spin-off" development team for the PC served equally well to reduce both ambiguity- and uncertainty-based Execution Risk. The smaller, highly communicative development team had a strong understanding of the test and validation needs for the product. The team itself had control over the way that the PC product would be produced, marketed, distributed, and sold. This allowed the team to further reduce Execution Risk by breaking away from the slow and expensive traditional mainframe marketing and distribution methods toward fast, low-cost retail marketing and distribution channels.

3.3 Cases 3 & 4: Cray Computer and the DIA Baggage Handling System

We also reviewed two well-known innovative product development failures: development of the Cray 3 gallium-arsenide (GaAs) supercomputer at Cray Computer, and development of an automated baggage handling system for Denver International Airport (DIA).

Cray Computer, spun off of Cray Research Inc. in 1989, attempted to develop the world's first gallium arsenide-based supercomputer, designed to be the world's fastest. However, from the outset, the "Cray 3" faced enormous amounts of product development risk. First, the product faced substantial (ambiguity-based) Envisioning Risk, as Cray Computer did not adequately recognize that it was developing the high-end system in an era of rapidly declining budgets for defense, intelligence, and the national laboratories--the main base of potential customers for the Cray 3. At the same time, both old and new competitors were striving to introduce new supercomputer products designed to challenge the computational speed of the Cray 3 while selling at a substantially lower price.

Second, the choice of gallium-arsenide promised high theoretical speeds, but imposed many significant design uncertainties and ambiguities, leading to Design Risk. One critical factor was that working with the temperamental gallium arsenide chips slowed development cycles to a standstill, inflicting long product delays. Third, the speediness of the GaAs chip technology led to (ambiguity-based) Execution Risk, since no off-the-shelf equipment existed that was fast enough to monitor and test the exceedingly fast processors. Not surprisingly, the effects of the aggregated product development risk led to Cray Computer, over four years late to market and having spent $200 million developing the GaAs computers, filing for Chapter 11 bankruptcy in March 1995.

In 1992, the Denver International Airport commission contracted with BAE Automated Systems, Inc. to develop and install an automated baggage handing system for the new airport. The project faced (ambiguity-based) Envisioning Risk from the outset, due to the fact that it was unclear how the $232 million baggage system would add value above a conventional baggage handling system that could have been installed at a fraction of the cost. Because of the complexity of the system and the design approach chosen, the developers faced enormous (ambiguity- and uncertainty-based) Design Risk. The system was to use 3,500 individually driven and guided “telecars” to deliver 60,000 bags per hour, across a complex network of over 20 miles of tracks. Moreover, BAE Systems had never before attempted to design and install such an enormous and complex system, not to mention that the company had agreed to complete the project in one year rather than the four years it had originally projected the project would take. Additionally, high levels of Execution Risk were caused by the enormous size and complexity of the system, and by the frequent meddling of Denver airport officials.

Not surprisingly, the baggage system was unable to perform adequately by the scheduled airport opening date. Despite an enormous effort to get the system operating properly, problems with the system persisted, causing a 16-month delay in the opening of the airport, which was possible only after installation of a $51 million conventional baggage handling system to substitute for the faulty automated system. The cost penalty to the airport of the baggage system-induced delay has been estimated at $360 million.

4. Conclusions

The review of several historical cases of innovative product development has revealed the criticality of product development risk. In the cases reviewed, product development risk led to development failures costing up to hundreds of millions (or billions) of dollars in lost investment or lost sales. Of those cases, many of the failures could clearly have been avoided if the product developers were better able to identify and manage product development risk.

Table 1 presents a summary of the authors assessment of risk-based failure modes of the innovative product development cases discussed in this paper. In the table, the authors have identified the primary and secondary failure modes for each of the cases. The failure modes seen to be the fundamental causes of program failure are identified as primary failure modes. Program failure modes that contributed to the overall failure or were a significant detriment to development progress but were not the primary reason the program failed are identified as secondary failure modes. The authors also indicate to which dimension of product development risk the project failure mode was related, as well as whether the risk was ambiguity- or uncertainty-based.

The cases reviewed demonstrate failure modes induced by all three types of product development risk: Envisioning Risk, Design Risk, and Execution Risk. Moreover, in different cases, ambiguity and uncertainty each were found to be primary contributors to the risk-based failure modes. This emphasizes the diversity of types and sources of risks facing innovative product developers.

Before a product development team can manage product development risk, its members must be able to effectively identify risk drivers. By using the framework to examine the development programs along the three dimensions of risk, the underlying *risk drivers*--the actual product- or process-related uncertainties and ambiguities that generated product development risk--were also uncovered. In the historical analysis, examination of each risk dimension quickly led to identification of the underlying risk drivers. This leads to a conclusion that up-front application of the risk framework will be effective in evaluating risk drivers in ongoing innovative product development programs. Therefore, use of the risk framework should prove to be a powerful tool in product development risk management.

The risk-based failure modes observed in the cases also demonstrate the important role of concurrent engineering in management of risk in innovative product development. Many of the innovative product development failures observed in the cases could have been avoided had a higher level of concurrent engineering activity been pursued.

For example, if CBS had involved its film production personnel early, the company would quickly have realized that the cost of the recordings was prohibitively high and moved on to other design solutions, or possibly would have had time to develop a cost-effective film production method. Had RCA marketing been involved in VTR development, they would surely have pointed out that the big, expensive systems using the high-speed, high-tape-consumption longitudinal design would be unsalable. That insight could have prevented RCA from wasting several years developing an inherently non-viable design. Also, had Xerox involved its product division as an integral team member throughout the development process, the company would certainly have avoided a great deal of the risk-averseness and “not invented here” that led to the rejection of the Alto.

INSERT TABLE 1 HERE

Table 1: Summary of the risk-based Primary and Secondary Failure modes observed in innovative product development cases

Also, the framework and cases show that product development risk must be managed in its entirety rather than individually along each dimension. This means that product developers must have a clear understanding of how actions taken to address risk along one dimension will affect the level of risk along other dimensions. Minimization of total product development risk can only be accomplished through simultaneous minimization of risk along each dimension. In most circumstances, doing so will require a very high level of concurrent engineering activity. The risk framework and these historical examples reveal that aggressive implementation of concurrent engineering is particularly critical in innovative product development. This approach of aggressive implementation of concurrent engineering in innovative product development the authors term ***concurrent innovation***.

The insights gained through application of the risk framework in this paper has demonstrated its value as a tool for examination of product development risk. Review of historical cases has also verified that both ambiguity and uncertainty play key roles in generating product development risk.

The authors ongoing work is aimed at further investigating ambiguity- and uncertainty-based risk drivers, and developing and enhancing methodologies for their evaluation and management.

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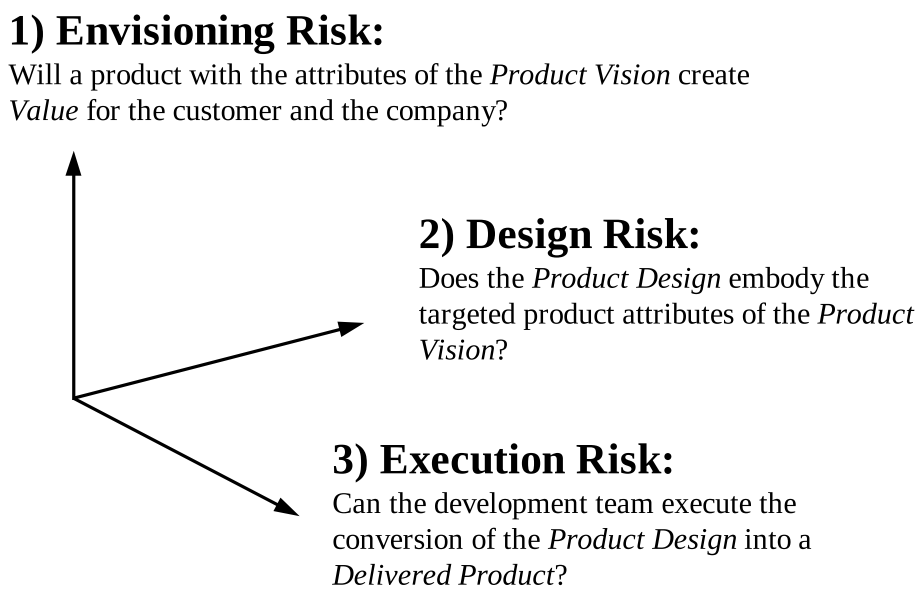

Figure 1: Graphical representation of the framework for product development risk evaluation showing the three dimensions of product development risk

Case	Success or Failure?	*Envisioning Risk*		*Design Risk*		*Execution Risk*	
		Ambiguity	**Uncertainty**	**Ambiguity**	**Uncertainty**	**Ambiguity**	**Uncertainty**
CBS EVR	*F*	PFM		SFM			*
Ampex VCR	*F*	SFM	PFM				
RCA VCR	*F*	SFM		PFM			
Sony VCR	*S*	*	*	*	*	*	*
Xerox PC	*F*	*	*	*	*	PFM	SFM
IBM PC	*S*	*		*	*	*	*
Cray Computer	*F*	SFM			PFM		
DIA Baggage Sys.	*F*	SFM	SFM	PFM	PFM	PFM	PFM

Key:
F - Product development effort Failed, **S** - Product development effort was a Success; **PFM** - Primary Failure Mode of development program, **SFM** - Secondary Failure Mode of development program; ***** - Product developer demonstrated effective product development risk management

Table 1: Summary of the risk-based Primary and Secondary Failure modes observed in innovative product development

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