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DISRUPTIVE VS. SUSTAINING TECHNOLOGY AND THE DESIGN PROCESS

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ABSTRACT

The preliminary stages of design often focus on how to configure the artifact in such a way as to beat the existing competition in a performance attribute widely available in the marketplace. But this approach ignores an aspect of the business systems environment in which the product will exist. Business considerations, including competitive positioning and marketing, are most often addressed only after the product is fully developed. It is thus possible that the wrong performance attributes were improved, at the cost of ignoring others that could better enhance long term marketplace competitiveness. This can lead to products that are either not competitive, and/or that are not marketed in an appropriate manner. This paper presents a framework for including marketplace systems considerations into the early stages of product development. During this early stage, design decisions are being made that determine which performance attributes should be developed, and the extent to which efforts should be made to improve those features. An example of development of a novel air pollution control system is presented that illustrates the benefits of employing the framework.

Keywords: Sustaining, innovation, disruptive, marketing, attributes, commercialization

1 INTRODUCTION

Thirty years ago, product designers began to realize that the design process should include consideration of many factors beyond the physical artifact, most notably manufacturing cost and quality. Some recent examples illustrate the benefits of considering changeover losses [1], social context [2], environmental impacts [3] and incremental innovation [4] during, not after, the design process.

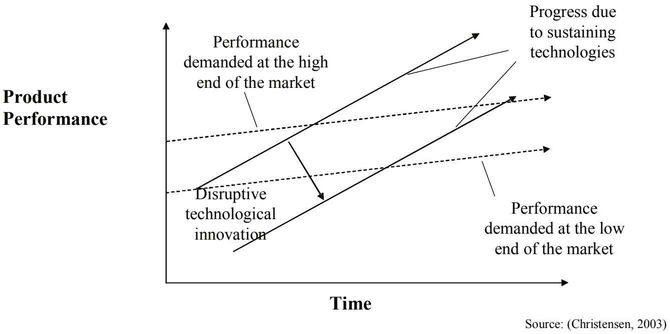
Marketing strategies should also be incorporated into the early product design process, rather than after the fact. For commercial success, design innovation needs to anticipate commercialization strategies. The most successful marketing strategy varies, and depends on the type of technological innovation. The two major categories are "sustaining" and "disruptive". New technologies either sustain the current trends along accepted technological dimensions, or disrupt the current technological capabilities of existing markets [5]. The diffusion of disruptive technologies depends, to a great extent, on their ability to create new functionalities, and thus attract new customers or change the behavior of existing customers [6]. The traditional view of commercialization does not distinguish between disruptive technologies (DT) and sustaining technologies (ST) [7].

However, there is a growing literature which suggests that due to distinct distinguishing features of DT and ST, there is a need to devise different strategies for product design and development, and also the introduction of these products into the marketplace. The idea of an ambidextrous organization which is structured to continue with incremental improvements to existing products and production systems, while at the same time harnessing capabilities to develop new breakthrough products is presented by Tushman et al. [8]. Creation and successful financial implementation of DTs have been studied for established as well as new firms [9]. Due to the uncertainty in the market success of DTs, it is often difficult to justify financial investment in them. To address this reluctance towards realizing the potential of DTs, Kaplan [10] suggested strategies which can be used for commercialization of DTs. These strategies include competitively replacing competitors' products, cannibalizing one's own products with new value-added products, creating new demand in the market, and creating altogether new markets. An overview of disruptive technologies with regard to the distinction between new and established firms is provided by Walsh, et al. [11]. The results for 72 micro-electrical-mechanicalsystems (MEMS) firms show that newer firms use both market-pull and technology-push strategies in commercializing disruptive technologies, and also have advantages in shorter times to market.

The objective of this paper is to present how these marketing issues can be considered during design, with an illustrative example of an air pollution control device, based on the conceptual framework proposed by Christensen [12]. The next section explains distinguishing features of disruptive and sustaining technologies. Section 3 describes the example technological innovation; a novel product that both captures organic vapors, which many are hazardous air pollutants, and also recovers the originating raw material for reuse in the manufacturing process, as well as the competing technologies in that market. Section 4 analyzes the business landscape and determines the disruptive vs. sustaining nature of the new technology. Section 5 completes the assessment and presents recommendations for commercialization.

2 FRAMEWORK FOR SUSTAINING AND DISRUPTIVE TECHNOLOGIES

The distinction between sustaining and disruptive technologies is described in this section. The motivation for determining whether a new technology is disruptive or sustaining is to identify which product attributes the design effort should focus on, and how to market it. Virtually every successful new product category is first commercialized in small niche markets, rather than larger mainstream markets. The DT framework helps us project growth potential into larger mainstream markets, but the product must first break into the niche market. Design efforts should focus on the *new* attributes that appeal to the niche market (rather than the traditional attributes that appeal to the mainstream), and marketing efforts should focus on bringing these new attributes to the attention of the niche market. This strategy allows DT products to explore their small niche markets initially to perfect their new product offering(s) and at the same time provide them freedom to fail. Some of the important distinguishing characteristics are depicted in Figure 1 and summarized below:



Source: (Christensen, 2003)

Figure 1. The Impact of Sustaining and Disruptive Technological Change [12]

- Sustaining technologies (STs) improve product performance along the traditional dimensions that are currently valued in the existing markets by mainstream customers. On the other hand, disruptive technologies (DTs) offer a new value proposition and/or new features which were not present previously.
- Typically, DT products initially offer diminished performance along one or more of the traditional dimensions of the existing markets. One example would be the low resolution of the first digital cameras. However, DTs exhibit certain advantages such as simplicity, small size, ease of operation and cost-effectiveness. DTs may use new component configurations to create new architectures.
- DTs initial diminished performance along one or more dimensions is tolerated by only a small number of customers (rather than the mainstream), who respond favorably to the new value

proposition offered by the DT. In many cases, such a niche market needs to be identified and established for the DT firms to gain experience and start attacking the mainstream markets from below. This is possible because DT products are able to improve their performance in the traditional attributes while simultaneously offering the new ones.

- New markets for DT products are built on improving performance in the traditional attributes, making the product more attractive to mainstream customers. It is worthwhile to note that the same technology may have a sustaining influence in one form and a disruptive influence in another form due to different architectures or applications.

Other strategies for disruptive design include setting up a firm small enough to be rewarded by success in the small markets which do respond to the new value proposition. Many DTs have potential to improve performance in traditional attributes, satisfying mainstream markets and displacing the existing product offerings which are based on STs. Larger, well-established firms are better at exploiting the ST innovations and poor at DT innovations as smaller markets do not solve their growth needs.

3. EXAMPLE TECHNOLOGY AND POTENTIAL MARKET FOR AIR POLLUTION CAPTURE AND RECOVERY DEVICE

3.1 Electrothermal Swing Adsorption

The example discussed here is a novel air pollution control technology that not only captures hazardous air pollutants, but also recovers them for reuse. Its design and development is described in further detail in [13] and [14]. Figure 2 shows a schematic of the electrothermal swing adsorption (ESA) design that uses activated carbon fiber cloth (ACFC) as the adsorbent.

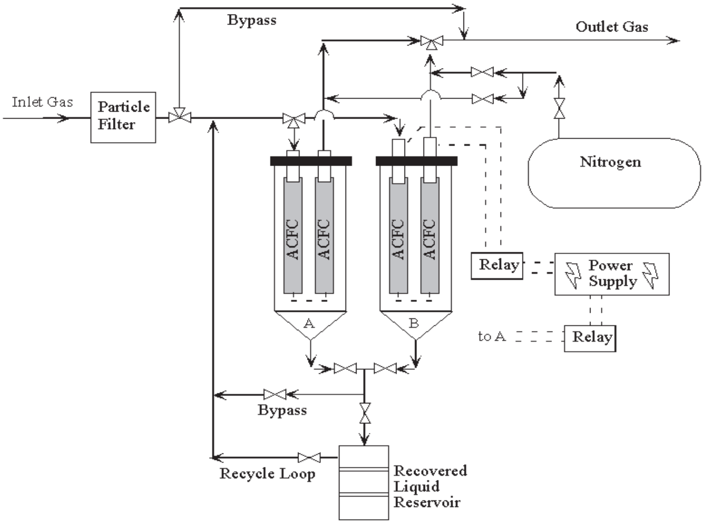


Figure 2. Electrothermal Swing Adsorption Design

The application market identified for ESA technology is air pollution control systems for volatile organic vapors. In the United States, the Clean Air Act, promulgated in 1963 and amended in 1970, 1977 and 1990, is the governing regulation for the control of air pollution. Releases of hazardous air pollutants (HAPs) and organic vapors are widely known as risks to human health and the environment. An estimated 1.63×10^{10} kg of volatile organic compounds (VOCs) were emitted to atmosphere during 2001 with solvent utilization accounting for 28% of these emissions [15]. During the same year, 1.31 x 10^9 kg of HAPs were released to the environment along with other air pollutants, accounting for 45% of total releases [16].

3.2 Air Pollution Control Markets in the United States

This application of ESA falls broadly under the air pollution control (APC) market, which includes control, mitigation and reduction of emissions from stationary and mobile sources. Table 1 shows that equipment used for air pollution control is the largest component of the APC market. Table 2 shows trends in the APC market revenues in the United States [17]. The growth rates in both these tables can be characterized as moderate.

Table 1. Air Quality Markets in the United States (Billions of Dollars)

	1994	1997	2000
Stationary sources market			
Equipment	3.7	3.5	3.7
Consulting & Engineering	1.6	1.3	1.4
Instrumentation	0.6	0.5	0.6
Analytic services	0.1	0.1	0.1
Indoor air pollution	0.5	0.5	0.6
Total	6.5	5.9	6.4
Mobile sources market			
Equipment	10.8	12.3	13.5
Consulting & Engineering	0.2	0.2	0.2
Instrumentation	0.2	0.3	0.4
Analytic services	0.4	0.6	0.9
Total	11.6	13.4	15
Total air pollution control	**18.1**	**19.3**	**21.4**

Table 2. U.S. Environmental Industry Revenues, Trends, and Forecasts (Billions of Dollars)

Industry Segment	1996	1997	1998	1999	2000	2001	2002
Air pollution control equipment	15.3	15.7	16.2	16.6	17.1	17.5	18.0

3.3 Competing Technologies

The advantages and disadvantages of existing competing technologies are summarized in Table 3 and discussed here. Based on whether the organic vapors are converted to other less hazardous chemicals or recovered after capture, the existing technologies can be broadly categorized as destructive and non-destructive [18], [19]. The most commonly used destructive technology is thermal oxidation which converts the pollutants by combusting them at high temperatures to other compounds like CO_2, water, CO, NO_x and SO_2. The efficiencies of thermal oxidizers are very high (95-99%). However, they also generate secondary pollutants such as HCl while oxidizing halogenated pollutants. For low concentration streams, thermal oxidation becomes very costly when high removal efficiencies are needed due to significant energy requirements. Products of combustion such as CO_2 which is a greenhouse gas may contribute to the global warming [20] and NO_x contributes towards formation of tropospheric ozone. Biofiltration can also be used for low concentration pollutant streams. The biofilters consist of microorganisms, which aerobically degrade the pollutants when the air stream is passed through them. Advantages of biofiltration are low energy requirements and complete destruction of pollutants without any transfer to other media. A careful control of operating conditions such as temperature, pH and moisture is necessary for effective operation of biofilters. Disadvantages include the inability to handle variable inlet concentration and halogenated compounds, a large footprint and the possibility of channeling [21].

Among the non-destructive methods, absorption requires a contacting liquid in which the pollutant is soluble. It is used mainly for removal of SO_2 using lime and H_2S from natural gas using amines. Absorption is not commonly used for organic vapor removal because suitable contacting fluids are not available. Absorption is energy intensive since it requires contact fluid pumping. It also requires the separation of absorbed pollutant by distillation or extraction, which is also energy intensive. Direct condensation is suitable for very high concentration streams (>1% by volume) and for pollutants with low saturation vapor pressure. Condensation occurs by over-saturation of pollutant either by lowering temperature or overpressurization. Membrane separation is another method, which is not yet fully commercialized for capture and recovery of air pollutants. Physical adsorption is attractive from the point of view of recovery of pollutants and is considered the most energy-efficient method for capturing low concentration organic vapors [22]. Activated carbon is the most commonly used adsorbent for removal of organic vapors from gas streams because of their higher surface areas, relative non-polarity, availability at low costs and high adsorption capacities [23], [24].

Table 3. Summary of Existing Organic Vapor Control Technologies

Technology	Advantages	Disadvantages
Thermal or Catalytic Oxidation	Highly flexible (can oxidize many VOCs over wide concentration ranges), high removal efficiencies	Needs pre-concentration and/or supplemental fuel, produces greenhouse gases and other HAPs
Carbon Adsorption	Low energy requirements, selectively removes dilute components	VOC recovery is costly, disposal of saturated granular activated carbon (GAC)
Biofiltration	No disposal of saturated carbon, does not generate NO_x or CO, lower operating costs	Careful control of moisture, large footprint, not suitable for variable concentration streams and halogenated compounds
Absorption		Generates liquid waste, needs suitable contact fluid and has high energy requirements
Condensation	Allows recovery of organic vapors	Suitable for VOCs with high concentrations (> 1%)
Membrane Separation		Material compatibility, high capital costs and pressure drops

The specific application targeted by ESA is the control of organic vapors. Table 4 shows the revenues from different existing technologies for 1999 and 2004 with annual average growth rates.

Table 4. US Air Pollution Control Market for Volatile Organic Compound Recovery and Abatement (Millions of Dollars)

Technology Group	1999	2004	AAGR (%)
Filtration systems	1,020.1	1,297.1	4.9
Oxidizers	866.4	1,241.1	7.5
Scrubbers/ strippers	876.7	1,021.3	3.1
Adsorbent systems	306.0	408.1	5.9
Energy recovery	122.0	166.4	6.4
Membranes/ Separations	92.7	134.8	7.8
Novel technologies	25.3	37.7	8.3
Total	3,309.2	4,306.5	5.4

Among these technologies, thermal oxidizers and GAC adsorbers are considered as two substitution targets for ESA technology. Thermal oxidizers are selected as a substitution target because they command one of the largest market shares (28.8% in 2004) and have a high growth rate, in terms of both percentage and the amount of revenue. Additionally, ESA uses adsorption for removal of organic vapors and can also replace existing GAC adsorbers.

4 ASSESSMENT OF BUSINESS LANDSCAPE AND NATURE OF ESA TECHNOLOGY

4.1 Business Landscape

A business landscape for APC market is developed here starting with the providers of two existing technologies: oxidizers and carbon adsorbers. The motivation for developing the business landscape is the need to understand where and how a firm will compete in that landscape. The five forces framework developed by Porter [25] seeks to explain relative profitability of participating firms in a market on the basis of five components: degree of rivalry, threat of entry, threat of substitutes, buyer power and supplier power. Among the generalizations and extensions to the five forces framework, value net proposed by Brandenburger and Nalebuff [26] has been most successful, primarily because it highlights the role of complementors. The complementors are those participants in the market who sell complementary products or services to customers or who buy complementary resources from suppliers. Thus they increase the buyer's willingness to pay for new products or services. Examples of complementors include doctors in the pharmaceuticals market and hardware and associated software manufacturers in high-tech markets.

The value net for the organic vapor control market for two substitution targets is shown in Table 5. In each group, representative participants are indicated. For this market, USEPA and air quality consultants can be thought of as the complementors. Market information such as this can be obtained from a variety of sources including Thomas Register, Hoover's Online, Environmental Expert, Air Quality Web, Air Pollution Equipment, and individual company literature.

Table 5. Value Net Elements for Organic Vapor Control Market

Customers	**Complementors**	**Competitors**		**Suppliers**	
		Oxidizers	Revenue in $million	***Activated Carbon***	Revenue in $million
Automakers	United States Environmental Protection Agency	Calgon Carbon	258.1	Calgon Carbon	258.1
Pharme-ceuticals		John Zink	228.3	Norit Americas	45.5
U.S. Army	Air quality consultants	MEGTEC	150-200	John Zink	228.3
Paint booths		Selas Fluid	31.7	Waterlink	64.1
Printing		Colt Tech.	20	Carbochem	6.7
		Carbon Adsorbers		***Catalyst or Thermal Packing***	
		Calgon Carbon	258.1	Johnson Matthey	250
		John Zink	228.3	Engelhard	300
		Norit Americas	45.5	Koch Knight	10
		Waterlink	64.1	Catalytic Products	10
		Envitrol	15	Emerachem	7.5-10

Another way of understanding the business landscape is to plot the revenue distribution of competitors in the market, which is shown in Figure 3. This plot makes the fragmented nature of the market clear, where a small number of large companies dominate over a large number of small companies.

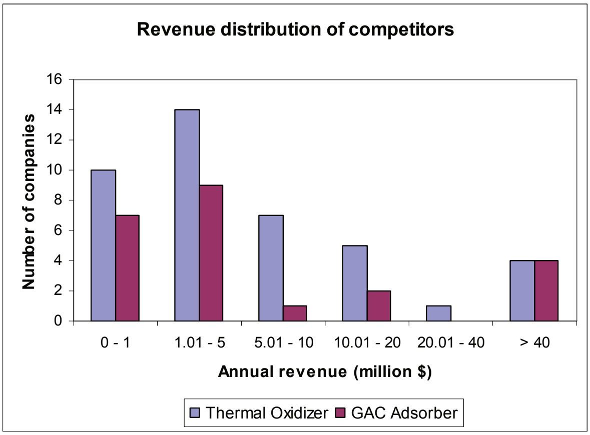


Figure 3. Revenue Distribution of Competitors

4.2 Search for New Value Proposition

A survey of product datasheets of oxidizers and adsorbers indicates that the following product attributes are mentioned as important selling points by the manufacturers of these technologies, suggesting that they are deemed important by mainstream customers.

- Gas flow rates treated by the product (cubic feet per minute)
- Removal efficiency (% inlet concentration removed)
- Flexibility (range of inlet concentrations treated and type of organic vapors treated)
- Ease of maintenance
- Small footprint (square feet)
- Lower costs ($)

The first step in determining whether ESA technology could be a successful disruptive technology is to estimate the expected improvement in each of these product attributes over time. The next step is to determine whether these improvements provide a compelling reason or new value proposition to disrupt the existing market.

Many of the performance features of ESA follow along the dimensions valued by customers of existing technologies. These include ease of scalability (range of flow rates treated), better adsorption capacity (removal efficiency), less maintenance and simpler operation (ease of maintenance), less expensive operation (lower costs), adaptability to a range of organic vapors and concentrations (flexibility) and compactness (small footprint). In addition, ESA has a lower probability of bed fires, since the adsorbent does not contain ash, a common impurity in GAC. Ash can catalyze oxidative reactions leading to decomposition of the adsorbate and to fires which prevent the use of GAC for many HAP/VOC control applications that contain ketones [27], [28].

4.3 Determination of Sustaining or Disruptive Nature of ESA Technology

The following questions are used to determine the sustaining or disruptive nature of ESA technology:

1. Whether ESA technology can create new markets and serve customers who did not exist historically.
2. Whether there are customers at the low-end of the existing market who can buy ESA if it is available at lower price and provides satisfactory performance.
3. Whether ESA technology is disruptive to all the important competitors in the target market.

If the above analysis provides affirmative answers to all the questions, then ESA can be considered a disruptive technology for the organic vapor control market. It is also noted that ESA offers a new feature, which is the *recovery* of organic vapors from the capturing medium for the purpose of their reuse in the originating or another manufacturing process. ESA allows for energy-efficient electrothermal desorption (ED) of adsorbed organic vapors because it utilizes resistive heating of the carbon fiber cloth, where electrical energy is applied directly to the fibers and controlled independently of the carrier gas flow rate. ED is considered superior to other desorption methods using steam because it eliminates the need for an adsorbent drying step and recovers organic vapors as pure liquids. It also eliminates ancillary processes required to separate, dispose of recovered solvent/water mixtures that are required with conventional steam regeneration technology and it requires less energy. It is expected that this feature will be an important pollution prevention tool for customers as it also offers cost efficiency for non-use of new organic vapor solvents.

However, a closer examination of this value proposition suggests that recovery is important primarily because it offers the advantage of cost savings, which is one of the dimensions valued by customers in current technologies. Nonetheless, it can be argued that beyond the cost savings offered by recovery using ED in ESA system, it is also beneficial for the environment as it eliminates the need to manufacture new organic solvents, as well as disposal of the steam-organic vapor mixture which is necessary for GAC adsorbers.

Table 6 shows the competing technologies and their performance in the attributes capital cost (X_1), operating cost (X_2) and environmental impact(X_3). Also shown are the resulting single attribute utilities $U_i(X_i)$ and multiattribute utility U(X). Results in Table 6 shows that for a flow rate of 4,000 ft^3/min, ESA has the lowest operating costs, and in fact generates revenue, due to the recovery and reuse of the organic vapors. The environmental impact column includes impacts arising from use of the technology, including energy consumption and hazardous waste disposal. ESA results in lower environmental impact since it does not use steam for desorption, even though other electricity requirements (desorption, process blower and nitrogen generation compressor) are higher than those of the GAC adsorber.

Table 6. Utilities and Rankings of Competing Technologies

Competing Technologies	**Capital Cost**		**Operating Cost**		**Environmental Impact**		**Multi-attrib. Utility**	**Rank**
	$K	**$U_1(X_1)$**	**$K**	**$U_2(X_2)$**	**Pt**	**$U_3(X_3)$**	**U(X)**	
I. Electrothermal Swing Adsorption	280.7	0.74	-32.3	0.98	6,808	0.99	0.97	2
II. Granular Activated Carbon	245.9	1.00	-27.4	0.90	9,801	0.96	0.99	1
III. Thermal Incinerator (70% heat recovery)	317.3	0.50	121.0	0.00	75,783	0.00	0.42	5
IV. Thermal Incinerator (50% heat recovery)	254.4	0.95	160.4	0.00	128,739	0.00	0.81	4
V. Thermal Incinerator (35% heat recovery)	214.7	1.00	191.3	0.00	169,223	0.00	0.85	3

Figure 4 illustrates the tradeoffs among the single attributes on the y-axis, scaled where 0 is defined as the worst that the decision maker would be willing to consider in the set of design alternatives, and 1 is defined as the best available in the set of design alternatives. Multiattribute utility is determined by methods described in Kaldate et al.[14]. The tradeoff is that ESA has higher capital costs as compared to GAC. However, the overall evaluation of the two technologies conducted using a multiattribute utility function reveals that both of them are valued approximately equally. Even if the results indicate that ESA is cost-effective as compared to GAC as measured by total equivalent cost, this again is not a fundamentally new value proposition.

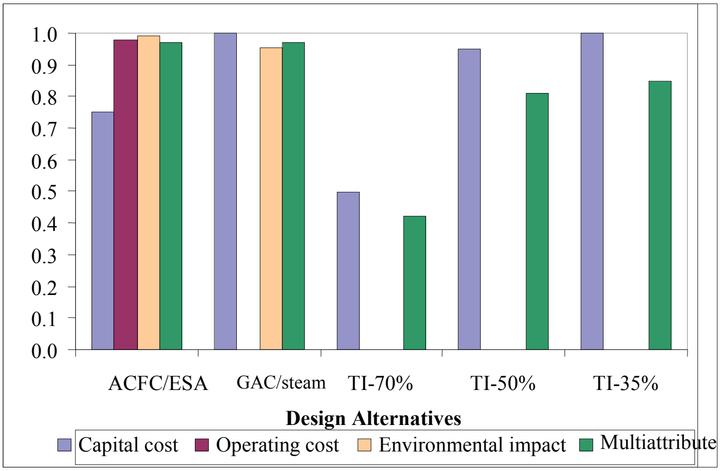


Figure 4. Single and Multiattribute Utilities of Competing Technologies

For the customers at the low end of the current market, switching to ESA is attractive for reasons of economic benefits. However, even for these customers, the capital cost of installing the ESA technology is higher than GAC. The case for replacement of oxidizers/ incinerators by ESA is quite feasible. Since ESA is not disruptive to all the competitors in the target market, it is concluded that ESA is a sustaining technology which provides improved performance on the dimensions currently valued by mainstream customers.

Being a sustaining technology for the organic vapor control market, it is recommended that ESA be commercialized through one of the major established companies in the market. The improved performance of ESA along the existing dimensions of both capital cost and operating cost can be effectively utilized by the well-established market leaders.

5 SUMMARY

It is important for designers to focus their efforts where the potential payoff in the marketplace is greatest. The traditional design strategy of improving mainstream features that are currently valued by the broad market is highly effective for “sustaining” design innovations that will compete directly against existing technologies. However, for “disruptive” innovations that seek to define a new type of product, the best design strategy is to focus instead on improving *new* product features that might be valued by only a niche market. This niche market seeks out new product features, and is willing to sacrifice some performance in mainstream features in order obtain them. In this small niche market, designers have the luxury of testing new concepts with minimal investment. Once the designers determine which combination of new and mainstream features are most valued, design and development efforts can be focused on improving performance in mainstream features in order to supplant existing competing products.

This paper has presented an example of an air pollution control technology that at first appeared to have the potential to be disruptive in that the air pollutants were not just captured, but also recovered for reuse as a raw material in the manufacturing process. Despite this innovation, the analysis revealed that this was a sustaining, rather than a disruptive, technology. Hence, design efforts should be focused in areas that enhance its competitiveness in the broader, mainstream market with existing technologies, rather than a niche market. The design efforts should focus on decreasing capital costs, and the marketing efforts should focus on the economic value of the recovered air pollutants.

This approach ties marketing and design efforts much closer together. Thus, marketing issues can help steer the design effort in the direction of greatest potential.

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