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# Exploring the duality of disruptive innovation: a technology-utility model analysis of market encroachment

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## Abstract

This study explores and explains how duality enables disruptive innovation to encroach on the market and redefine its boundaries under constraints of consumer preferences, purchasing power, technological performance, and complementary technologies. The findings indicate (1) disruptive innovation introduces a new value dimension into the market and enhances the heterogeneity of consumers' demand, which creates prerequisites for its market encroachment while avoiding competing directly with incumbent enterprises; (2) when considering purchasing power constraints, the disadvantage of disruptive innovation in the preexisting value dimension becomes a price advantage of encroaching on the low-end market; (3) under the constraint of complementary technologies, disruptive innovation can open up new markets that incumbent enterprises have not yet touched by virtue of its advantages in the new value dimension; (4) disruptive innovation does not rely on technological performance to encroach on the market, indicating technological performance is not a necessity for identifying disruptive innovations.

**Keywords** Disruptive innovation, Duality, Market encroachment, Consumer utility and preference

## 1 Introduction

The innovation theory has developed rapidly since the economist Schumpeter insightfully unveiled the economic meaning behind the concept of innovation. Many relevant new concepts emerged, and innovation types have been further subdivided. Among different types of innovation, disruptive innovation attracts considerable attention (Currah 2007; Das et al. 2018; Petzold et al. 2019; Wang et al. 2021). Especially with the technological

development, academia, industry, and technology policymakers are increasingly interested in disruptive innovation. The concept of disruptive innovation was first coined by Professor Christensen to describe the phenomenon that emerging enterprises successfully encroach on the market with late-developing and inferior products, technologies, or services (Christensen and Raynor 2013; Christensen and Bower 1996), which has been identified widely in industries including steel, excavator, motorcycle, retail, software, and pharmaceuticals.

The successful market encroachment of disruptive innovation requires joint action of various factors, including prices, technology performance, incentive measures, consumer preferences, relative advantages, and complementary technologies, etc. (Assink 2006; Habtay 2012; Pinar-Pérez et al. 2022; Vinodh et al. 2014). Researchers put considerable effort into the assessment and identification of the drivers of disruptive innovations using diverse approaches. Rafii and Kampas (2002) designed a scorecard that includes product quality, cost

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and usability, to assess the disruptive threat to incumbent enterprises. Momeni and Rost (2016) proposed a method based on patent-development paths, k-core analysis, and topic modeling of past and current trends of technological development to identify technologies that have the potential to become disruptive technologies. Ganguly et al. (2010) constructed a systematic framework to evaluate the success factors of disruptive innovation, including market positioning, technology performance, expected utility, etc. Antonio and Kanbach (2023) investigated influencing factors by systematically reviewing 62 articles and argued that market factors, actions and interactions of market actors affect the emergence and diffusion of disruptive innovation. Si and Chen (2020) reviewed relevant literature published in SSCI journals and suggested that the key influence factors of disruptive innovation at the network level mainly include suppliers, customers, complementors, and policymakers in the network. In addition, some studies on disruptive innovation mainly focus on a set of factors, such as market diffusion (Wang et al. 2006), industry cost structure (Droege and Johnson 2010), environmental regulation (Zhu et al. 2021), or differences in income (Corsi and Di Minin 2014).

Drawing from rich empirical data, Schmidt and Druehl (2008) summarized the market encroachment patterns of disruptive innovation into three categories, i.e., “fringe-market”, “detached-market”, and “immediate” encroachment. Briefly, “fringe-market encroachment” sees disruptive products gradually infiltrate both traditional markets and uncharted territories, demonstrating their capability to challenge established products and tap into untouched markets as evidenced in the U.S. hard drive industry; “detached-market encroachment” starts with innovations establishing themselves in entirely new markets before gradually infiltrating and compacting mainstream markets, reminiscent of cell phones displacing landlines; “immediate encroachment” features innovations debuting at the mainstream market’s lower end and rapidly advancing, in line with the way discount stores impact hypermarkets.

Although a multitude of empirical evidences have been accumulated and favored many exploratory studies since the commencement of disruptive innovation theory, a crucial issue still hovers around its theoretical foundation (Danneels 2004; Guo et al. 2020; Hopp et al. 2018a, b; Tellis 2006; Weeks 2015). As Danneels (2004) and Barney (1997) argued, a disruptive innovation might be easy to identify after its occurrence. The empirical evidence can hardly provide insights beyond hindsight. Disruptive innovations seem to be able to ensure success because they have to succeed to become identifiable, which brings survivorship bias into the empirical evidences. It

is a dilemma for researchers and practitioners to cope with disruptive innovation proactively based on post hoc perspectives. A feasible move to address such dilemma might be to shift from the methodology from induction to deduction. Technically, such methodological shift suggests transforming the conceptual framework into a formal mathematical or computational model that capture the stylized facts regarding disruptive innovation while providing a broader view. Mathematical models can also serve as an inference tool to handle counter-factual scenarios where disruptive innovations fail.

Despite the abundant empirical information and practical use, formulating disruptive innovation into a formal model is a fairly rare attempt due to the intricate interplays among various entities involved in disruptive innovation. This research does not ambitiously intend to develop an all-encompassing model but to build a parsimonious mathematical model mitigating the survivorship bias issue. A major target of the model is to explain the formation of disruptive innovation’s market encroachment patterns. As put by Brady (2008) and Machamer et al. (2000), understanding the formation of a phenomenon entails the understanding of the low-level entities involved. During the market encroachment of disruptive innovation, incumbent enterprises, disruptive enterprises and consumers are all low-level entities. Incumbent enterprises and disruptive enterprises provide different technologies or products, while consumers make innovation adoption decisions within alternatives according to the principle of utility optimization. By integrating the consumer side with enterprise side, a technology-utility model is constructed.

A core concept and imperative component of the technology-utility model is “duality”, which serves as a bridge linking the intrinsic nature of disruptive innovation and the market encroachment patterns. One might notice that disruptive innovations affect two types of markets. On the one hand, disruptive innovation originates in the niche market on which it depends. This niche market may be the low-end market ignored by incumbent enterprises or a new market; On the other hand, disruptive innovation will eventually encroach on the mainstream market occupied by incumbent enterprises and squeeze the market share of incumbent enterprises. Therefore, the market encroachment process of disruptive innovation can be divided into the development of new markets and the competition of existing mainstream markets, that is, the encroachment pattern reflects the characteristics of “duality”.

According to Merriam-Webster dictionary, duality refers to “the quality or state of having two different or opposite parts or elements”. Disruptive innovation has typical duality. Christensen and Raynor (2013) and

Utterback and Acee (2005) pointed out that the attribute set of new products or technologies can be regarded as the combination of core attributes and additional (new) attributes. Taking the hard drive market as an example, small hard drives can be regarded as the disruptive innovation to large hard drives, since small hard drives not only have the function of storage data, but also add the portability compared with the existing large products. A product may have multiple attributes. When analyzing the innovation of a product, these attributes can be simply summarized into two dimensions, one of which represents the basic attribute and the other represents the new attribute. If the former is excluded, disruptive innovation will lose its basis for existence. For example, if small hard drives lose the attribute of data storage, there is no premise for further discussion in both theoretical and practical sense; If the latter (portability) is removed, small hard drives degenerate into ordinary ones and lose the symbolic characteristics of disruptive innovation.

In addition, Adner (2002) decomposed the attributes of disruptive innovation into two dimensions to build a computational model, and believed that the competition between disruptive innovation and existing technologies is the competition in two different dimensions. If the track of disruptive innovation is closer to the existing technologies, the encroachment on the existing markets will be more obvious than that of opening up new markets, leading to greater impacts on the incumbent enterprises. If disruptive enterprises focus more on improving technologies or products in new dimensions, they have less influence on the incumbent enterprises while more influence on opening up new markets. The advantage of disruptive innovation is that it changes the competitive basis of enterprises through two different dimensions and changes the evaluation matrix of consumers for technologies or products.

Apparently, the existing literature has recognized the benefit to decompose disruptive innovation into two dimensions but only regards such treatment as an effective analytical method, instead of explicitly pointing out that “duality” is the key attribute that distinguishes disruptive innovation from other types of innovation. The lack of explicit emphasis on the key attributes of disruptive innovation is not conducive to the formation of theoretical consensus or the focus of academic discussion, but hinders the construction of a parsimonious and coordinated systematic theory. Therefore, on the basis of the existing literature, this study defines the “duality” of disruptive innovation as “dual attributes with both traditional and new value dimensions”.

This research contributes to the existing literature from four aspects: (1) first proposing “duality” as the core

attribute of disruptive innovation, which contributes to the development of disruptive theory and framework; (2) a novel technology-utility model is built to explore and explain how duality enables disruptive innovation to encroach on markets from a perspective of multiple market entities’ optimal decisions. The research takes incumbent enterprises, disruptive enterprises, and consumers as the starting point to explore the mechanism of how these entities make supply or adoption decisions based on benefit maximization and drive disruptive innovation to encroach on the market under constraints of consumer preferences, purchasing power, technological performance, and complementary technologies; (3) explaining typical patterns of market encroachment of disruptive innovation from a mathematical view and presenting a consistent analytical framework for integrating multiple market entities and theoretical elements; (4) providing the theoretical basis that helps authorities effectively identify disruptive innovation and formulate policies.

The rest of this paper is organized as follows. Section 2 describes the methodology and details of the model-building process. In Sect. 3, the results of market encroachment of disruptive innovation are analyzed based on various constraints. Section 4 discusses the mechanism of market encroachment of disruptive innovation. Section 5 presents the conclusion and limitations.

## 2 Methodology

In light of resource constraints, businesses endeavor to efficiently allocate resources within the current technological paradigm, aiming to optimize the multifaceted value propositions of technologies or products. These optimal products, representing varying value dimensions, delineate the Pareto frontier of corporate technological R&D. While this frontier bears similarities to the production possibility frontier, a critical distinction exists: the latter signifies a company’s production capabilities under resource limitations, as opposed to its R&D capacity. Thus, the Pareto frontier can aptly be termed the technological possibility frontier for businesses. On the market’s demand side, a diverse array of consumers exists, each with unique preferences, indicating their heterogeneity. For the purpose of this analysis, it is assumed that initially, a single dominant enterprise holds the entire market share. However, over time, emerging disruptive businesses challenge this monopoly. Disruptive innovations, introducing novel value dimensions compared to pre-existing products, inherently possess a dualistic nature. Consumer valuation arises from a holistic evaluation of these two distinct value dimensions. Consequently, both product attributes and consumer

preferences can be represented as two-dimensional vectors. The objective of this section is to construct a model elucidating the inherent correlation between the dual value structure of disruptive innovation and the ensuing market encroachment patterns, all within an optimization framework.

For simplicity, the model assumes that the continuously differentiable technology possibility frontier is  $G(x, y) = C$ , where  $C \in \mathbb{R}^+$ ,  $x > 0$ ,  $y > 0$ . Then according to the implicit function theorem, there is a mapping  $f: x \rightarrow y$ , i.e.,  $f(x) = y$ . For consumer  $i$  with preference  $\vec{\lambda} = (\lambda_{ix}, \lambda_{iy})$ , it will look for products that can bring the maximum utility  $U_i(x, y)$  on the technology possibility frontier. In terms of utility functions, combined with the Cobb-Douglas utility function, Adner (2006) took into account consumer preferences, technologies in different value dimensions, complementary technologies, and prices to obtain the objective function in Eq. (1). Adner concentrates on the demand side analysis without considering the technology possibility frontier. The constraints in Eq. (1) reflect the technology possibility frontier. Therefore, it is more in line with the reality to consider the behavior of both supply and demand sides in pursuing the benefit maximization.

$$\begin{aligned} \max U_i(x, y) &= [(x - x_{i0})^{\lambda_{ix}} \cdot (y - y_{i0})^{\lambda_{iy}}]^{\gamma_{iv}} \cdot \left(\frac{1}{g(x, y)}\right)^{\gamma_{ip}} \\ \text{s.t. } \begin{cases} y = f(x) \\ x > x_{i0} \\ y > y_{i0} \end{cases} \end{aligned} \tag{1}$$

$x_{i0}$  and  $y_{i0}$  respectively represent the lowest thresholds of consumers in the new and preexisting value dimen-

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$$\frac{d(\ln(V_i))}{dx} = \frac{-(x_i^* - x_{i0})f'(x_i^*)/(x - x_{i0}) + f'(x)(f(x_i^*) - y_{i0})/(f(x) - y_{i0})}{f(x_i^*) - y_{i0} - (x_i^* - x_{i0})f'(x_i^*)} \tag{5}$$


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sions. In the context of disruptive innovation, the lowest threshold can be interpreted as the requirements of complementary technologies, and technologies or products that fail to meet this lowest threshold cannot be adopted by consumers.  $g(x, y)$  is the price function of products.  $\gamma_{iv}$  and  $\gamma_{ip}$  respectively represent consumer preferences for the net value of products and the price, and meet the requirement of  $\gamma_{iv} + \gamma_{ip} = 1$ . Directly using

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$$\frac{dh(x)}{dx} = \frac{(x_{i0} - x)(y_{i0} - f(x))f''(x) + (x_{i0} - x)(f'(x))^2 + (f(x) - y_{i0})f'(x)}{(f(x) - y_{i0})^2} \tag{7}$$


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the objective function in Eq. (1) to expand the analysis will get a lengthy formula, which is difficult to interpret the practical significance. Adner did not use this utility function for the mathematical analysis, but used it for the subsequent numerical simulation. In order to avoid the dilemma that the model can be analyzed but cannot be interpreted due to the lengthy derivation, let  $\gamma_{ip} = 0$ , set  $U_i(x, y) = (x - x_{i0})^{\lambda_{ix}} \cdot (y - y_{i0})^{\lambda_{iy}} = V_i(x, y)$ , and Eq. (2) can be obtained combined with constraint conditions. This formula means that consumers only need to weigh between the two technological value dimensions and choose the products that maximize the utility regardless of price factors.

$$\begin{aligned} \max V_i(x, y) &= (x - x_{i0})^{\lambda_{ix}} \cdot (y - y_{i0})^{\lambda_{iy}} \\ \text{s.t. } \begin{cases} y = f(x) \\ x > x_{i0} \\ y > y_{i0} \end{cases} \end{aligned} \tag{2}$$

If consumer  $i$  can find products with the maximum utility on the technology possibility frontier, then:

$$\lambda_{ix} = \frac{-(x_i^* - x_{i0})f'(x_i^*)}{f(x_i^*) - y_{i0} - (x_i^* - x_{i0})f'(x_i^*)} \tag{3}$$

$x^*$  represents the value of  $x$  when  $V_i$  takes the extreme value. Taking the logarithm of both sides of the objective function in Eq. (2) and substituting Eq. (3) into it to obtain:

$$\ln(V_i) = \frac{-(x_i^* - x_{i0})f'(x_i^*)\ln(x - x_{i0}) + (f(x_i^*) - y_{i0})\ln(f(x) - y_{i0})}{f(x_i^*) - y_{i0} - (x_i^* - x_{i0})f'(x_i^*)} \tag{4}$$

The derivative of  $x$  in Eq. (4) can be obtained:

The common factor  $(f(x_i^*) - y_{i0})/(x - x_{i0})$  is extracted from the numerators in Eq. (5) to obtain:

$$\frac{d(\ln(V_i))}{dx} = \frac{\frac{f(x_i^*) - y_{i0}}{x - x_{i0}} \left( \frac{-(x_i^* - x_{i0})f'(x_i^*)}{f(x_i^*) - y_{i0}} + \frac{(x - x_{i0})f'(x)}{f(x) - y_{i0}} \right)}{f(x_i^*) - y_{i0} - (x_i^* - x_{i0})f'(x_i^*)} \tag{6}$$

The derivative of  $h(x) = (x - x_{i0})f'(x)/(f(x) - y_{i0})$  can be obtained:

Due to resource constraints,  $x$  and  $y$  have a substitutional relation on the technology possibility frontier, so  $f'(x) < 0$ ; On account of the marginal decreasing effect of R&D revenue, the revenue of increasing  $x$  by sacrificing  $y$  becomes increasingly small. Thus,  $f''(x) < 0$ , that is, the technology possibility frontier is a monotonically decreasing concave function. It can be seen that  $h(x)$  is a monotonically decreasing function in the range of  $x > x_{i0}$ . Therefore, when  $x > x_i^*$ , the sign of  $d(\ln(V_i))/dx$  is negative; Otherwise, it is positive. This also means that in the range of  $x > x_{i0}$  and  $y > y_{i0}$ , if there is an optimal solution for  $V_i$ , then the optimal solution only corresponds to one consumer preference. In this way, the consumer preference can be expressed as a function of  $x$ . In other words, all the analysis can be transformed into the analysis of technological value dimensions in this framework.

In the market, due to the large number of consumers and the limited types of products provided by enterprises, it is difficult to find products that are completely consistent with consumer preferences. In the context of disruptive innovation, if the incumbent enterprise enters the market first, and the product is denoted as  $A(x_A, y_A)$ , then the utility it provides for the consumer  $i$  is:

$$V_{Ai}(x, y) = (x_A - x_{i0})^{\lambda_{ix}} \cdot (y_A - y_{i0})^{1-\lambda_{ix}} \tag{8}$$

If  $x > x_{i0}$  and  $y > y_{i0}$ , then the product A will be the only choice without considering the price function. The following is a discussion of the effect of disruptive innovation on the market boundaries in different situations.

### 3 Scenario-based analysis of technology-utility model

#### 3.1 Baseline scenario analysis

In the baseline scenario, consumers are under no constraints and able to freely choose whatever they prefer within the achievable domain. Since it is one of the scenarios involving the least variables, it can be used as the basic scenario analysis. After the product A enters the market, the product  $B(x_B, y_B)$  begins to enter the market. If the consumer  $i$  who chooses to change from purchasing A to purchasing B satisfies  $x_B > x_{i0}$ ,  $y_B > y_{i0}$  and  $V_{Ai} < V_{Bi}$ , it can be further deduced:

$$\ln\left(\frac{(x_A - x_{i0})(y_B - y_{i0})}{(x_B - x_{i0})(y_A - y_{i0})}\right) > \ln\left(\frac{y_B - y_{i0}}{y_A - y_{i0}}\right) \tag{9}$$

The specific value range of  $\lambda_{ix}$  is related to the minimum requirements of the consumer  $i$  for the technological

dimension and the relative value between A and B. But it is certain that:

$$\lambda_{ix} = \ln\left(\frac{y_B - y_{i0}}{y_A - y_{i0}}\right) / \ln\left(\frac{(x_A - x_{i0})(y_B - y_{i0})}{(x_B - x_{i0})(y_A - y_{i0})}\right) \tag{10}$$

$\lambda_{ix}$  defines a market boundary. According to Eq. (3), a value of  $x$  can be determined, so that consumers on the one side of  $x$  prefer A, while consumers on the other side prefer B. In order to make the analysis more geometrically intuitive to observe how disruptive innovation uses the new value dimensions to segment the market, the utility function can be further simplified. The minimum required threshold of consumers for technological value dimensions is not considered temporarily, and the linear additive utility function is used. This assumption is consistent with the linear additive reservation price of the Schmidt model (Schmidt and Druehl 2008; Schmidt and Van Mieghem 2005):

$$U_i(x, y) = [x, y] \cdot [\lambda_{ix}, \lambda_{iy}]^T \tag{11}$$

By substituting  $\lambda_x + \lambda_y = 1$ , it is not difficult to obtain that when  $U(x, y)$  takes the extreme value and satisfies  $f'(x) = \lambda_x / (\lambda_x - 1)$ , that is, the tangent of the technology possibility frontier  $G(x, y) = C$  passing through  $(x, y)$  is parallel with the vector  $(1, \lambda_x / (\lambda_x - 1))$ , which is exactly the normal vector of the preference  $(\lambda_x, \lambda_y)$ . This also means that for any consumer preference, the corresponding product on the technology possibility frontier enables the utility of this consumer to reach the extreme value in the reachable domain. Therefore, preference  $\vec{\lambda}_i = (\lambda_{ix}, \lambda_{iy})$  can be expressed as:

$$\vec{\lambda}_i = (\lambda_{ix}, \lambda_{iy}) = \left(\frac{-f'(x_i)}{1-f'(x_i)}, \frac{1}{1-f'(x_i)}\right) \tag{12}$$

$x_i$  is the value of the product in the  $x$  dimension when the consumer utility reaches the extreme value. According to the setting that incumbent enterprises of disruptive innovation enter the market first, there is only one product in the market initially, namely the mainstream product A provided by incumbent enterprises. The preference of consumers that takes A as the optimal choice is the normal vector passing through the technology possibility frontier of the point A, which can be expressed by  $A(x_A, y_A)$ . It is assumed that the technology possibility frontier is a continuously differentiable function, thus the utility that the product A can bring to consumers who choose it as the best choice is:

$$U_A(x_A) = [x_A, y_A] \cdot [\lambda_{x_A}, \lambda_{y_A}]^T = [x_A, f(x_A)] \cdot \left[ \frac{-f'(x_A)}{1-f'(x_A)}, \frac{1}{1-f'(x_A)} \right]^T \tag{13}$$

$$= \frac{-x_A f'(x_A) + f(x_A)}{1-f'(x_A)}$$

Since there is only product A in the market, consumers with different preferences can only choose product A. For any consumer with the preference  $\vec{\lambda}_M = (\lambda_{x_M}, \lambda_{y_M})$ , the most preferred product is  $M(x_M, y_M)$ . Limited to the fact that the consumer can only select the product A, the utility that A can bring is:

$$U_M(x_A) = [x_A, y_A] \cdot [\lambda_{x_M}, \lambda_{y_M}]^T = \frac{-x_A f'(x_M) + f(x_A)}{1-f'(x_M)} \tag{14}$$

For any point on the technology possibility frontier, the utility that can be provided for the consumer M (i.e., the consumer who most prefers the product M, which is expressed in accordance with the same rules below when referring to products or consumers) is:

$$U_M(x) = [x, y] \cdot [\lambda_{x_M}, \lambda_{y_M}]^T = \frac{-x f'(x_M) + f(x)}{1-f'(x_M)} \tag{15}$$

For Eq. (15), the derivative with respect to  $x$  is:

$$U_M'(x) = \frac{f'(x) - f'(x_M)}{1-f'(x_M)} \tag{16}$$

Since  $f'(x) < 0$  and  $f''(x) < 0$ , the sign of  $U_M'(x)$  is determined by  $x - x_M$ . When  $x - x_M > 0$ , then  $U_M'(x) < 0$ ,  $U_M$  is monotonically decreasing; When  $x - x_M < 0$ , then  $U_M'(x) > 0$ ,  $U_M$  is monotonically increasing; When  $x - x_M = 0$ , then  $U_M'(x) = 0$ ,  $U_M(x)$  takes the maximum value. This property demonstrates that  $U_M(x)$  is a concave function in the domain. The lower half of Fig. 4 presents this property of  $U_M(x)$ . When the latecomer enterprise introduces the new product  $B(x_B, y_B)$ , and  $x_B > x_A$ ,  $y_B < y_A$  (as shown in Fig. 1), the utility it brings to the consumer M is:

$$U_M(x_B) = \frac{-x_B f'(x_M) + f(x_B)}{1-f'(x_M)} \tag{17}$$

Now considering a special case where A and B can bring the same utility  $U_M(x_A) = U_M(x_B)$  to the consumer M, it can be obtained in combination with Eq. (15):

$$f'(x_M) = \frac{f(x_A) - f(x_B)}{x_A - x_B} \tag{18}$$

Equation (18) shows that the tangent of the technology possibility frontier passing through point M is parallel to its secant AB. It is not difficult to prove that for any consumer with the preference  $\vec{\lambda}_{E_1} = (\lambda_{e11}, \lambda_{e12})$ , the most preferred product of this consumer is denoted as  $E_1(x_{e1}, y_{e1})$ . If  $x_{e1} < x_M$ , this consumer prefers the product A. Using Eq. (15), it can be obtained that the utility difference brought by the two products A and B to the consumer E is:

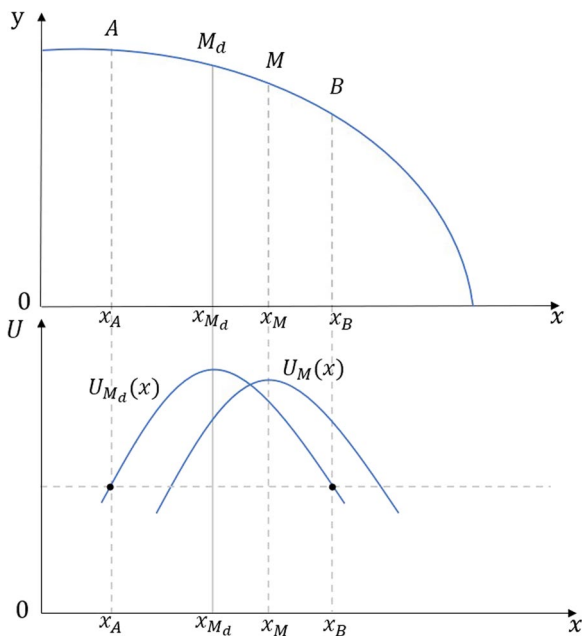


Fig. 1 The products and utility under non-consumption constraints

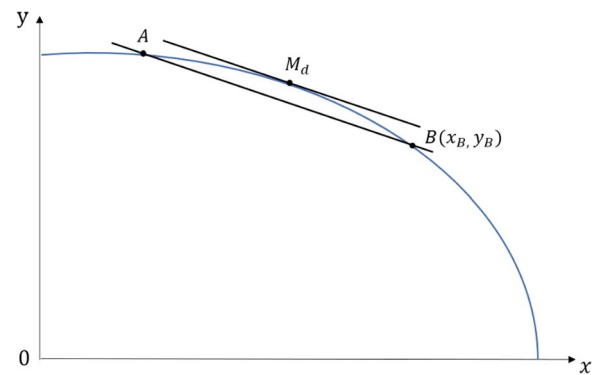


Fig. 2 The market segmentation point of disruptive innovation

$$U_{E_1}(x_A) - U_{E_1}(x_B) = \frac{(x_B - x_A)f'(x_{e1}) + f(x_A) - f(x_B)}{1 - f'(x_{e1})} \tag{19}$$

$$= \frac{f'(x_{e1}) - \frac{f(x_B) - f(x_A)}{x_B - x_A}}{(1 - f'(x_{e1}))(x_B - x_A)} \tag{20}$$

$$> \frac{f'(x_M) - \frac{f(x_B) - f(x_A)}{x_B - x_A}}{(1 - f'(x_{e1}))(x_B - x_A)} \tag{21}$$

Since  $f'(x) < 0$ ,  $f''(x) < 0$  and  $x_B > x_A$ , combined with Eq. (18), it can be concluded that the difference is positive. Similarly, if  $x_{e1} > x_M$ , the difference is negative. Therefore, it can be said that the point M has become the split point of the two products A and B in the market. For the convenience of expression, the split point of the market is denoted as  $M_d(x_{M_d}, y_{M_d})$ . Equation (18) actually provides a geometric method to find  $M_d$ , that is, make a secant of the technology possibility frontier through A and B, and then translate it to be tangent to the technology possibility frontier. The point of tangency is the market segmentation point  $M_d$  (as shown in Fig. 2).

Based on the above analysis, the model has the ability to explain the disruptive innovation encroachment on the existing market. As the only product that incumbent enterprises supply in the market at the initial stage, product A possesses the whole market share. After the product B enters the market, the original market is divided into two. Consumers on the left side of the market segmentation point will continue to favor product A, while consumers on the right side of the market segmentation point will give up product A and turn to product B. The analysis shows that incumbent enterprises have not completely lost the market, that is, the emergence of disruptive technologies does not mean the complete replacement of incumbent enterprises. In

most cases, incumbent enterprises still maintain a certain market share (Christensen and Raynor 2013; Lepore 2014; Weeks 2015). The process of redefining the market boundary due to the entry of product B is shown in Fig. 3. This process corresponds to the fringe-market encroachment proposed by Schmidt and Druehl (2008). Taking advantage of the duality of value dimensions, disruptive innovation changes the competition basis of the existing markets and the consumer evaluation matrix, which is just one of the ways it affects the market. Due to the existence of new dimensions, disruptive innovation still has the ability to open up new markets. The case of the hard drive industry shows that disruptive innovation will attract price-sensitive customers ignored by incumbent enterprises. When the product price is lower than the purchasing power of consumers, their purchase behavior will occur. In other words, in the evolution of disruptive innovation, the price constraint on consumers is an important factor affecting market encroachment.

### 3.2 The scenario analysis under purchasing power constraints

In the case of the hard drive industry, hard drive capacity is the main factor determining the selling price. When the hard drive density remains unchanged, the hard drive volume is positively correlated with the hard drive capacity. In other words, under the constraints of the same resources, the hard drive capacity developed by enterprises has a trade-off relationship with portability. On the technology possibility frontier, larger capacity means lower portability and smaller capacity means higher portability. Therefore, the restrictions on the price can be transformed into the restrictions on the hard drive capacity. For product  $P(x_p, y_p)$ , which sells for  $p$ , the more expensive price means that the product has the larger  $y_p$ . In the following analysis, the price  $p$  corresponding

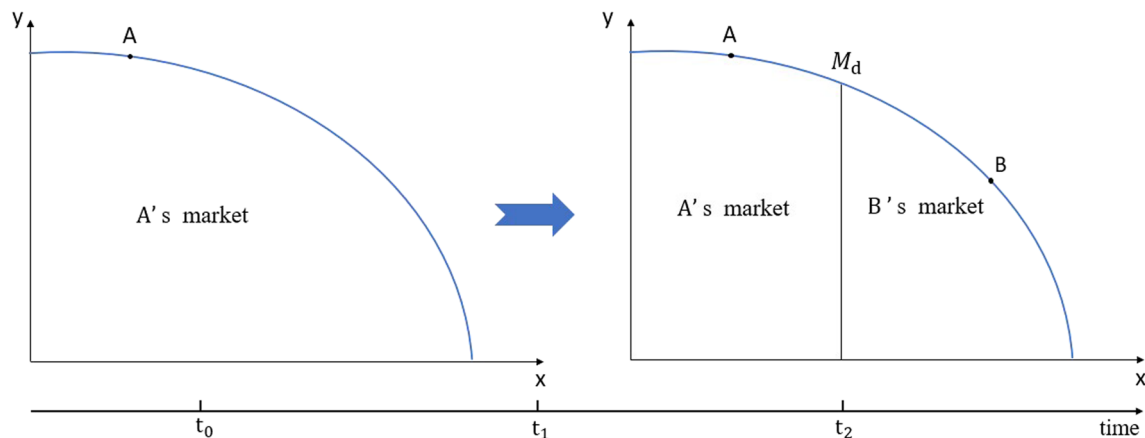


Fig. 3 The encroachment process of disruptive innovation under non-consumption constraints

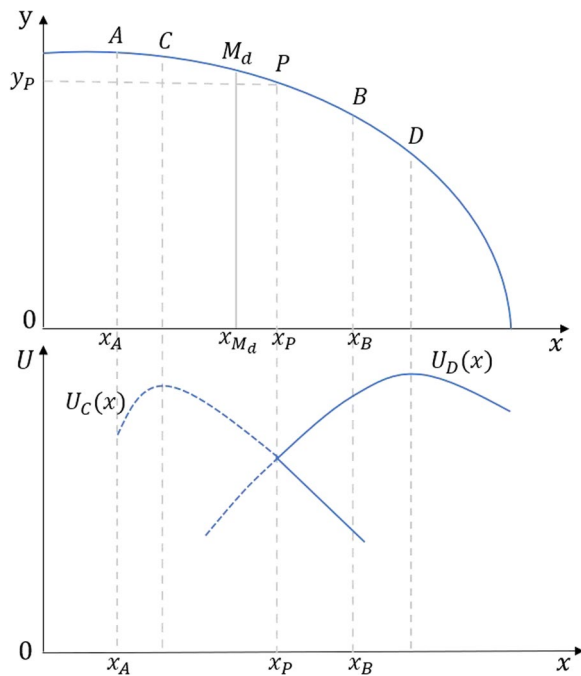


Fig. 4 The products and utility under purchasing power constraints

to product  $P(x_p, y_p)$  will serve as the boundary for dividing the purchasing power of consumers. The two types of consumers discussed below will only be able to purchase products at prices not higher than  $p$ . Enterprises that set the product price above  $p$  will not acquire the whole market, even if only the products of incumbent enterprises exist. Only when products at a lower price appear, the potential market will be activated. Figure 4 presents how the two types of potential customers convert into real customers under price constraints. The consumer

$C(x_C, y_C)$  represents the first type of customers and satisfies the inequality:

$$x_C < x_{M_d} \tag{22}$$

$$P_B < P_C = p < P_A \tag{23}$$

$x_{M_d}$  represents the market segmentation point of the two products A and B without constraints;  $P_C$  represents the highest price that the consumer C can afford;  $P_B$  represents the price of the product B;  $P_A$  represents the price of the product A. The inequality  $x_C < x_{M_d}$  indicates that consumers prefer the product A to the product B because it is at the left side of the market segmentation point. The inequality  $P_B < P_C < P_A$  means that consumers can afford to purchase B but cannot afford A. B is the only option. In the lower half of Fig. 4, the dotted portion of  $U_C(x)$  represents the product range that the consumer A cannot afford, while the solid portion represents the product range that the consumer A can afford. Obviously, without the purchasing power constraints, due to  $U_C(x_A) > U_C(x_B)$ , the consumer C will necessarily purchase A instead of B.

$$x_D > x_{M_d} \tag{24}$$

$$P_B < P_D = p < P_A \tag{25}$$

Another type of consumers is denoted as  $D(x_D, y_D)$ .  $P_D$  represents the highest price that the consumer D can afford. This set of inequalities indicates that consumer D prefers product B and can afford the sufficient price.  $U_D(x)$  in Fig. 4 represents the utility curve of the consumer D. The dotted portion of  $U_D(x)$  indicates the product range it cannot buy, and the solid portion indicates the range it can afford. Consumer D prefers product B to

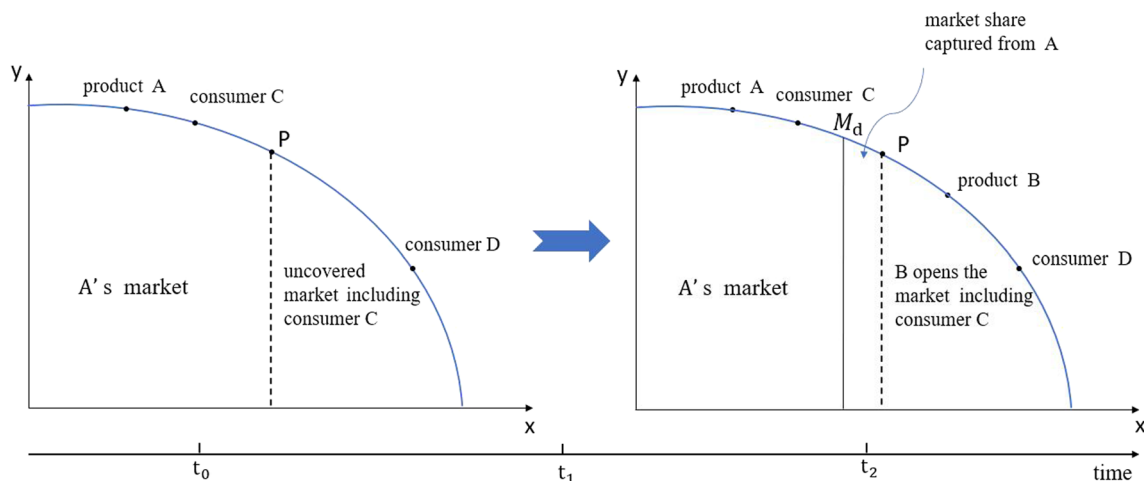


Fig. 5 The encroachment process of disruptive innovation under purchasing power constraints



product A, and also lacks the purchasing power of product A, thus product B is the ideal choice. The emergence of the product B activates the potential price-sensitive market. The existence of consumers C and D explains the blue ocean effect caused by product B, which opens up a market untouched by incumbent enterprises. At the same time, consumers who have strong purchasing power but prefer product B will also make choices according to their preferences. The behavioral outcomes of such consumers can be explained by the scenario under non-consumption constraints. Therefore, product B as the disruptive

innovation has triggered both the red ocean and the blue ocean effects, and the process is shown in Fig. 5. This process corresponds to the immediate low-end encroachment pattern proposed by Schmidt and Druehl (2008).

### 3.3 The scenario analysis under complementary technology constraints

More portable hard drives benefited from the development of complementary technologies (Christensen and Raynor 2013). Incumbent enterprises initially focused on the mainframe computer users who needed greater hard drive capacity, while ignoring the emerging micro-computer market. With the development of integrated circuit technology, a large number of microelectronic products were developed, facilitating the growth of the market demand for small-size hard drives. Complementary technologies are more crucial explanatory factors than consumer preferences in this section. Only when the size of hard drives is smaller than a certain threshold, hard drives can match the complementary technologies.  $x_T$  represents the minimum value required by complementary technologies for the second value dimension of disruptive innovation. If product A ( $x_A, y_A$ ) is the first product to appear in the market, since it fails to meet the requirements of complementary technologies for  $x_T$ , it must fall on the left side of  $x_T$ , as shown in Fig. 6. If product B ( $x_B, y_B$ ) appears on the right side of  $x_T$ , it can meet the demand of markets uncovered by the product A. The consumers who favor this product are denoted as E ( $x_E, y_E$ ). If their demand  $x_E$  for the new value dimension of disruptive innovation satisfies the following inequality, they will choose to purchase B.

$$x_T < x_E < x_B \tag{26}$$

The lower half of Fig. 6 shows the utility curve  $U_E(x)$  of consumer E. It can be seen that when  $x < x_T$ , the utility

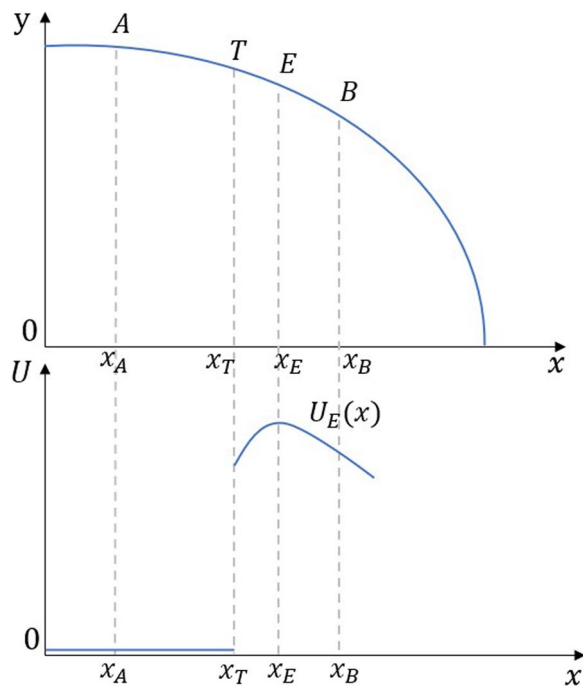


Fig. 6 The products and utility under complementary technology constraints

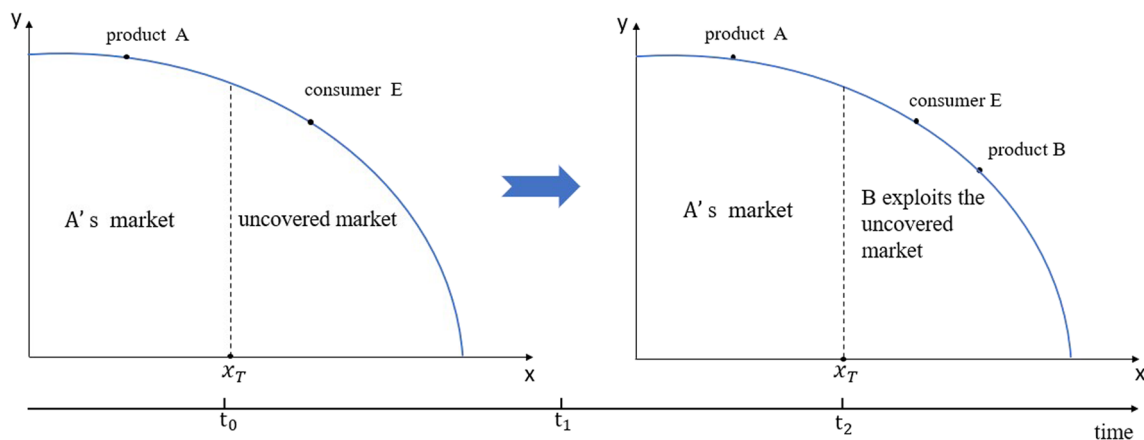


Fig. 7 The encroachment process of disruptive innovation under complementary technology constraints

of  $U_E(x)$  to the consumer E is 0 (in the figure, for the sake of illustration, this part of the line is moved up a small distance relative to the horizontal axis). The demand for new value dimensions of disruptive innovation by complementary technologies acts as a barrier to incumbent enterprises. Under the constraints of complementary technologies, disruptive innovation merely opens up the blue ocean market, exerting no influence on the original mainstream market.

This process is shown in Fig. 7. In this scenario, if disruptive innovation continues to make progress in the preexisting value dimension after its emergence, it may impact the mainstream market. In the case of hard drives, hard drive capacity is a key performance indicator, so disruptive enterprises have the motivation to continuously improve hard drive capacity to meet the needs of different niche markets, eventually approaching or even encroaching on the mainstream market. This process corresponds to detached-market encroachment proposed by Schmitt and Druehl (2008).

### 3.4 The scenario analysis under technological performance constraints

The previous analysis assumes that disruptive enterprises and incumbent enterprises have the same technological capability, that is, products are on the same technology possibility frontier. In fact, many cases show that the R&D capacity of disruptive enterprises is inferior to that of incumbent enterprises. Therefore, it is necessary to explore the mechanism of how disruptors with inferior technological capability successfully encroach on the market. It is assumed that there is still only one product  $A(x_A, y_A)$  in the market at first, and the product  $B(x_B, y_B)$  is a type of disruptive innovation relative to A, which requires the same degree of technical capacity. At this point, what needs to be explored is not the impact of B on A, but rather the focus on  $B'(x_{B'}, y_{B'})$ , whose technological performance is weaker than B, that is,  $B' < B$ .  $B'$  deviates from  $\Delta x$  and  $\Delta y$  ( $\Delta x \in (0, x_B)$ ,  $\Delta y \in (0, y_B)$ ) along the  $x$  and  $y$  axes respectively relative to B, then  $B'$  can be expressed as  $(x_B - \Delta x, y_B - \Delta y)$ . In order to make the coordinates of  $B'$  meaningful, there must be  $x_B - \Delta x > 0$  and  $y_B - \Delta y > 0$ . For any consumer  $M(x_M, y_M)$  with the preference  $(\lambda_{xM}, \lambda_{yM})$ , the utility  $B'$  can provide is:

$$U_M(B') = (x_B - \Delta x, y_B - \Delta y) \cdot (\lambda_{xM}, \lambda_{yM}) \quad (27)$$

$$= \frac{-(x_B - \Delta x)f'(x_M) + f(x_B) - \Delta y}{1 - f'(x_M)} \quad (28)$$

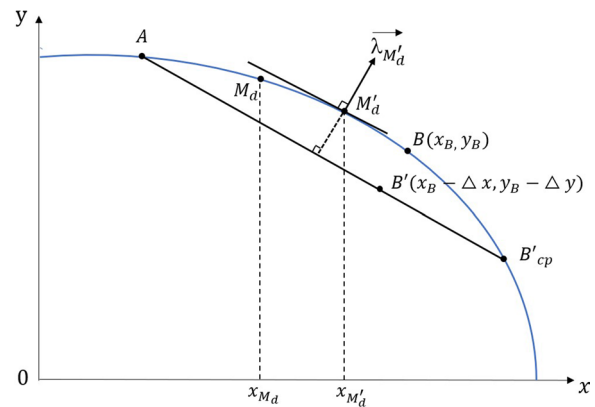


Fig. 8 The adjustment of segmentation point when disruptive technology is inferior

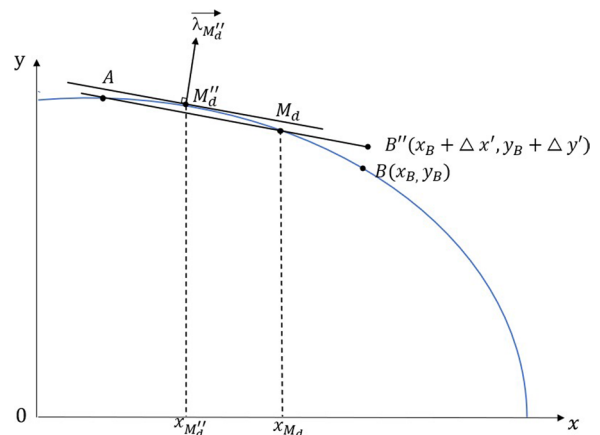
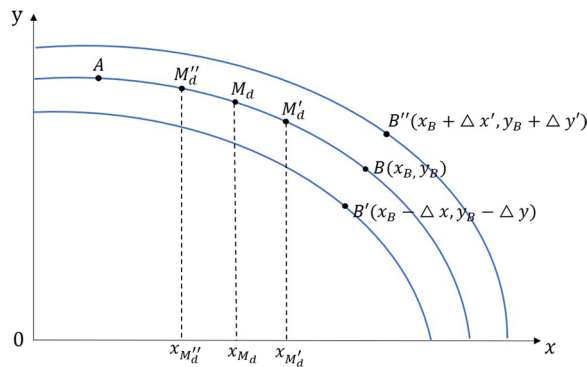


Fig. 9 The adjustment of segmentation point when disruptive technology is superior

To find the market segmentation point of A and  $B'$ , let  $U_M(B') = U_M(A)$ , the following can be obtained:

$$f'(x_M) = \frac{f(x_A) - (f(x_B) - \Delta y)}{x_A - (x_B - \Delta x)} \quad (29)$$

The market segmentation point satisfying Eq. (29) is denoted as  $M_{d'}(x_{M_{d'}}, y_{M_{d}'})$ . This equation means that the market segmentation point of products A and  $B'$  is the tangent of the technology possibility frontier passing through  $M_{d'}$  and parallel to  $AB'$ , as shown in Fig. 8. Although  $B'$  is not on the same technology possibility curve as A and B, a point can still be found on the curve to make it equivalent to the impact of  $B'$  on the market.  $AB'$  is extended and intersected with the technology possibility curve at  $B'_{cp}$ , that is, the equivalent point is obtained. This means that even on the different technology possibility frontiers, the analysis of  $B'$  can still be



**Fig. 10** Disruptive innovation with various technological performance and corresponding market segmentation points

transformed to the same technology possibility frontier. However, this method can only be used in a limited range, otherwise a tangent of the technology possibility frontier parallel to  $AB'$  may not be found. The model can also be used to analyze the scenario that the technical strength is stronger than that of the incumbent enterprises. Supposing that  $B''(x_{B''}, y_{B''}) = (x_B + \Delta x', y_B + \Delta y')$  appears, and  $\Delta x', \Delta y' \in (0, \infty)$ , then  $B'' > B$ . To calculate the market segmentation point of A and  $B''$ , make  $U_M(B'') = U_M(A)$  to obtain:

$$f'(x_M) = \frac{f(x_A) - (f(x_B) + \Delta y')}{x_A - (x_B + \Delta x')} \tag{30}$$

The point satisfying Eq. (30) is denoted as  $M_d''$ . This equation means that the market segmentation point for determining A and  $B''$  can still be obtained by translating the secant to be tangent to the technology possibility frontier, as shown in Fig. 9. Figure 10 can be obtained by listing the relative positions of  $M_d, M_d', M_d'', B, B'$  and  $B''$  in the same coordinate system. Figure 10 shows three different technology possibility frontiers, representing different technical capabilities. The emergence of  $B, B'$  and  $B''$  will redefine the market boundary of A. In a word, disruptors with stronger technical capabilities will capture greater market share from incumbent enterprises, which is not contrary to intuition. However, it is worth noting that this also demonstrates that the technical strength of disruptive enterprises is not a determinant of whether they encroach on the market of incumbent enterprises, but only affects the degree of encroachment. In other words, technological capacity is not a necessary condition for identifying disruptive innovation.

### 3.5 Suggestions based on the scenario analysis

From the aforementioned scenario-based analysis, several actionable recommendations can be inferred for parties engaged in disruptive innovation. For incumbent enterprises, it is crucial to strengthen their competitive positioning by enhancing customer satisfaction and catering to diverse consumer needs, thereby mitigating threats from emerging enterprises. Furthermore, they need to be acutely aware of shifts in both internal and external environments. It is essential not just to respond to these changes but to proactively identify and adjust to related disruptive innovations, breaking free from path dependencies and actively influencing market demand (Feng et al. 2022). Additionally, these enterprises should identify and incorporate new complementary technologies relevant to their sectors, expanding potential markets and addressing the evolving preferences of consumers, especially in today’s digital age.

Disruptive enterprises, on the other hand, should prioritize innovation strategies that resonate with their inherent strengths and the demands of the market. A significant opportunity lies in targeting low-end markets, which established enterprises often neglect. By leveraging mature technologies, disruptive enterprises can drive cost-effective innovations and carve out a dominant position within these niche areas. As they broaden their market share, it is imperative to bolster their technological prowess. Contrary to common misconceptions, disruptive innovation does not equate to subpar technology. Therefore, ramping up R&D investments is vital to augment technological maturity and further expand their market influence.

Lastly, while the role of authorities may not be directly outlined in the analysis, its importance in the realm of disruptive innovation cannot be overlooked. These bodies must proffer preferential policies or fiscal incentives, providing robust support to nascent disruptive businesses’ R&D ventures. There is also a pressing need for them to champion innovations, particularly those tailored for the nuances of low-end and niche markets, rejuvenating market vitality and paving the way for the birth of new enterprises. Commitment to cultivating an environment conducive to innovation is necessary. This involves safeguarding technological breakthroughs, promoting the integration and dissemination of groundbreaking technologies, and curbing the monopolistic tendencies of dominant enterprises in both the market and technological domains. Such measures are pivotal to deter undue influence on the trajectory of disruptive innovation and its transformative reach.

#### 4 Discussions

The supply and demand are the most basic elements of the market. To explore the mechanisms of market encroachment of disruptive innovation, it entails the study of the decisions and interactions between the supply and demand sides. In this encroachment process, the supply side comprises incumbent and disruptive enterprises, offering sustaining and disruptive innovations, respectively. Each type of innovation possesses distinct technological attributes, catering to consumers of varied preferences. Thus, delving into the decisions and interactions between supply and demand during this process equates to examining the alignment between technological supply and consumer preferences. Providers of technology utilize their enterprise resources to remain competitive, whereas consumers opt for alternative products offering maximum utility. Even though a myriad of performance metrics is essential to assess a technology, disruptive innovation notably introduces novel value dimensions in contrast to pre-existing products. This shifts the consumer decision matrix and alters the foundation of market competition. Consequently, the value dimension of technology can be categorized into the pre-existing value dimension and the new value dimension, i.e., the first and second value dimensions, as cited by Danneels (2004) and Schmidt and Porteus (2000).

In light of this, this study introduces a technology-utility model to discern the market encroachment patterns of disruptive innovation across varied scenarios. This model amalgamates the technological possibility frontier with consumer utility functions and crucial constraints. It addresses the gaps left by earlier research that predominantly emphasized just one facet, rendering this model more aligned with real-world applications. Schmidt and Druehl (2008) undertook a comprehensive exploration of the market encroachment patterns linked to disruptive innovation, identifying three primary patterns. This research's discourse on disruptive innovation's market encroachment patterns largely aligns with Schmidt's findings. Such alignment underscores that the newly proposed model can aptly reflect pivotal facts about disruptive innovation. However, it is worth noting that the structuring and rationale of this research differ markedly from Schmidt's approach, with more comprehensive components considered. This provides a new perspective of understanding the market encroachment mechanics of disruptive innovation.

This research considers the market encroachment of disruptive innovation when consumers are under no constraints and able to freely choose whatever they

prefer within the achievable domain, which corresponds to the fringe-market encroachment induced by Schmidt and Druehl (2008). Even as a relatively basic scenario, this model still demonstrates how disruptive innovation encroaches on the markets occupied by incumbent enterprises through asymmetric advantages. This model considers the heterogeneity of consumer demands. After disruptive innovation enters the market, the evaluation of consumers on products changes from the previously single dimension to two dimensions, so that disruptive innovation can successfully encroach on the fringe market by making use of the advantages of the second value dimension, even though it has a disadvantage in the first value dimension. Therefore, the heterogeneity of consumer demands and the duality of disruptive innovation are the critical factors to explain the successful encroachment on the market.

The research subsequently discusses the market encroachment of disruptive innovation under the purchasing power constraint, which corresponds to the immediate low-end encroachment of disruptive innovation summarized by Schmidt and Druehl (2008). Since incumbent enterprises tend to focus on improving the first value dimension, and technology R&D will fall into the dilemma of diminishing marginal returns, they can only aim at the market with higher premium. This leads to some consumers unable to purchase existing products due to the purchasing power constraint. After the emergence of disruptive innovation, it is inferior to the existing products in the first value dimension, while this disadvantage turns into an advantage in the low-end market. In addition, disruptive innovation also introduces a new value dimension, namely the second value dimension, thus making up for the disadvantages in the first value dimension to some extent. Therefore, disruptive innovation not only attracts customers in the low-end market ignored by incumbent enterprises, but also attracts customers who are not restricted by purchasing power but prefer the second value dimension, thus encroaching on both the low-end markets and the markets occupied by some incumbent enterprises at the same time. Therefore, the duality of disruptive innovation makes the advantages and disadvantages relative. Relativity is another important factor for the successful market encroachment.

The complementary technology constraint is a strong objective constraint, which restricts the technological scope that consumers can choose. Due to the mandatory constraint of complementary technologies, the products of incumbent enterprises fail to cater to the potential market; thus, consumer demands cannot be met until the emergence of disruptive innovation. With the advantages

in the second value dimension, disruptive innovation breaks through the limitations of complementary technologies, and enters the potential market that incumbent enterprises have never set foot in. Since consumers' characteristics and requirements for products in this market are significantly different from the target customers of incumbent enterprises, disruptive innovation actually has first-mover advantages in this market. The market encroachment pattern of disruptive innovation under complementary technology constraints corresponds to the detached-market encroachment of Schmidt and Druehl (2008)'s research. The analysis shows that complementary technology constraints provide critical prerequisites for disruptive innovation to successfully open up new markets.

Quite a few researchers and practitioners believe that an important feature of disruptive innovation is that its technological disadvantages compared with sustaining innovations. However, the technological performance of disruptive innovation is not invariable. The disadvantages can continue to narrow and be accepted by mainstream consumers over time (Christensen and Raynor 2013). In other words, the role of disruptive innovation is unchanged when technological performances improve from "obvious disadvantage" to the "unobvious disadvantage". This means that the "identity" of disruptive innovation will not change with the improvement of technological performance. Christensen et al. (2018) contended that disruptive innovation is a process. Thus, it is necessary to emphasize the experience from weak to strong. As Barney (1997) argues, it is difficult to know exactly which technologies will survive and thrive. The technology paradigm theory of Dosi also contends that the survival of new technologies needs to undergo rigorous market selection, just like the natural selection for the biological survival (Dosi 1982). Therefore, regarding disruptive innovation as a process not only fails to avoid the problem of "post judgment", but also lacks the practical feasibility. The technology-utility model demonstrates that technological performance only regulates disruptive innovation's market encroachment effect but do not change the patterns or mechanisms of market encroachment in nature.

## 5 Conclusions and limitations

### 5.1 Conclusions

This study constructs a technology-utility model using the technological possibility frontier and consumer utility function, to discuss the mechanisms of market

encroachment of disruptive innovation under constraints of consumers' preferences, purchasing power, technological performance, and complementary technologies.

Since the products of disruptive enterprises have asymmetric advantages, they can better meet consumers' heterogeneous demand than existing products do, which impact the existing market and take the market share of incumbent enterprises. Under the purchasing power constraint, some consumers are unable to purchase existing products, which leaves a blank in the low-end market. Disruptive innovations are inferior to existing products in the first value dimension, so they enter the market at a lower price, which not only attract consumers who prefer disruptive innovation in the mainstream market but also attract some non-adopters subject to purchasing power. Under the complementary technology constraints, consumers have the minimum requirements for the second value dimension and cannot simply choose products according to their own preferences. Therefore, when only the products of incumbent enterprises exist, part of the market will be left blank, creating opportunities for disruptive innovation to open up new markets. This study uses different technology possibility frontiers to represent the differences in the technological capacity of enterprises, and analyzes the influence of technological performances on the market encroachment of disruptive innovation. The analysis demonstrates that different technological performances do not change the way that disruptive innovation affects the market, but only influences the effect of market encroachment. This also indicates that disruptive innovation is mainly characterized by duality, and the technological performance of an enterprise might not lead to a substantial change in the way it redefines the market boundary.

### 5.2 Limitations

This study explains the relationship between the duality of disruptive innovation and the possible market phenomenon under various scenarios using the technology-utility model and concentrates on the changes of market boundary before and after the disruptive innovation encroachment. This mathematical model has the advantage of simplicity, but fails to fully reflect the dynamic process of market encroachment and interactive behaviors among entities. Future research can conduct in-depth analysis on the decision-making and the interactive behaviors of low-level entities involved in the market encroachment process of disruptive innovation, and build dynamic models to further explore the mechanism of the market encroachment of disruptive innovation.

The preference of various consumers can be introduced, which may consider more heterogeneity on the demand side. As disruptive innovation is a process not an event (Christensen 2006; Christensen and Raynor 2003), it is also necessary to take the S-shaped curve of technology development into account, which gains more heterogeneity on the supply side. Agent-based modeling is a powerful tool that could be used in the future research to deal

with high level of heterogeneity, and could also inject dynamics into currently static model (Shi et al. 2023, 2020).

## Appendix

See Table 1.

**Table 1** Nomenclature

Parameter	Meaning
$G(x, y)$	Technology possibility frontier
$x$	Represents the new value dimension of a product or technology
$y$	Represents the preexisting value dimension of a product or technology
$\lambda$	Consumer preference vector
$\lambda_{ix}$	Preference of consumer $i$ for the $x$ value dimension
$\lambda_{iy}$	Preference of consumer $i$ for the $y$ value dimension
$U_i(x, y)$	Utility function for consumer $i$
$x_{i0}$	The lowest threshold of consumers in the new value dimension
$y_{i0}$	The lowest threshold of consumers in the preexisting value dimension
$g(x, y)$	Price function of products
$\gamma_{iv}$	Consumer preference for the net value of products
$\gamma_{ip}$	Consumer preference for the price
$V_i$	Alternative utility expression for consumer $i$
$h(x)$	A function derived from the technology possibility frontier and consumer preferences
$x_A, y_A$	Represents the value of $x$ and $y$ for the product denoted as A
$V_{Ai}(x, y)$	Utility of product A for consumer $i$ based on $x$ and $y$ value dimensions
$U_A(x_A)$	Utility function for product A
$U_M(x)$	Utility function for a consumer M based on product M's properties
$\lambda_{e11}, \lambda_{e12}$	Component preferences for consumer $E_1$ in dimensions $x$ and $y$
$E_1(x_{e1}, y_{e1})$	The product most preferred by consumer $E_1$ characterized by its properties $x_{e1}$ and $y_{e1}$
$U_{E_1}(x_A), U_{E_1}(x_B)$	Utilities of products A and B for consumer $E_1$
$M_d(x_{M_d}, y_{M_d})$	The market segmentation point (split point) between products A and B
$x_P, y_P$	Properties of product P in dimensions $x$ and $y$
$p$	Price of the product
$C(x_C, y_C)$	Consumer type C characterized by their preferences in dimensions $x_C$ and $y_C$
$x_{M_d}$	The market segmentation point between products A and B
$P_C$	The highest price consumer C can afford
$P_B$	Price of product B
$P_A$	Price of product A
$D(x_D, y_D)$	Consumer type D characterized by their preferences in dimensions $x_D$ and $y_D$
$P_D$	The highest price consumer D can afford
$U_C(x)$	Utility curve for consumer C
$U_D(x)$	Utility curve for consumer D
$x_C, y_C$	Preference of consumer C in dimensions $x$ and $y$
$U_C(x_A)$	Utility value of consumer C for product A
$U_C(x_B)$	Utility value of consumer C for product B
$x_D, y_D$	Preference of consumer D in dimensions $x$ and $y$
$x_T$	The minimum value required by complementary technologies for the second value dimension of disruptive innovation
$x_E, y_E$	The value dimensions representing the product preferred by consumer E

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### Authors' contributions

YZ: Writing, Conceptualization, Methodology. YS: Writing- Reviewing, Validation and Editing. ZW: Writing -original draft preparation, Writing-Reviewing and Editing. MZ: Visualization, Reviewing and Editing.

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#### Competing interests

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