Curbing Fashion Waste and Overproduction: A Supply Chain Perspective

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Abstract Overproduction is one of the most pressing issues in the fashion industry. It leads to not only a tremendous amount of unsold products that end up incinerated or landfilled, but also excessive pollution and depletion of resources along the supply chain. In this chapter, we posit that examining this issue warrants a holistic supply chain perspective that goes beyond downstream operations related to finished goods. Through an analysis of fashion brands' production and fabric acquisition practices, we show that tracing the impact of fashion into the upstream can generate fundamental insights into the causes and cures of fashion waste and overproduction. In particular, our results indicate that widely-adopted waste reduction approaches such as *quick response* and *upcycling* may worsen fabric overproduction and in turn exacerbate the overall environmental footprint of the fashion supply chain. Textile recycling, in contrast, may effectively alleviate fabric overproduction, but suffers from immature technologies and infrastructure which limit its waste reduction capabilities.

1 Introduction

The fashion industry is known for its creativity that fuels endless possibilities for product offerings on the supply side, and a volatile consumer market with ever-changing needs and tastes on the demand side. With this comes the challenge of matching supply with demand, and of dealing with inventories that do not sell—commonly referred to as *deadstock*. It is estimated that deadstock constitutes about 15% of the overall textile production across brands, retailers, factories and mills, adding up to an annual loss of around \$152 billion for the global fashion industry

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[81]. This includes both newly made apparel items that are never sold [45] and excess fabric in the upstream of the fashion supply chain [47].

The severity of the fashion deadstock problem has long been recognized in practice, though earlier discussions had largely focused on the monetary burden of deadstock on fashion brands rather than its environmental implications. The situation changed in 2018 when intense media scrutiny—triggered by the huge amount of unsold items burnt by some of the world's most prestigious brands—revealed that the majority of fashion deadstock was directly sent to incinerators or landfills [77, 44]. The news drew massive public attention and raised concerns about the environmental impact of fashion waste and overproduction. Setting aside brands' claims that their incineration processes recover energy and thus are responsible ways of disposal [15]—which are debatable by themselves (e.g., burning synthetic fabric leads to air pollution [12]), many recognize that the problem extends beyond pollution at the disposal stage. That is, fashion products, including those incinerated when brand new, are environmentally costly to begin with. In particular, upstream textile production consumes a large amount of natural resources and is a major source of pollution. It is estimated that textile production accounts for 20% of water pollution as well as 10% of carbon emission in the globe [38]. The production of a simple garment such as a cotton T-shirt can require 2,700 liters of water—enough to satisfy one person's drinking needs for two and a half years, emit 4.3 kg of CO_2—more than the emission of driving 10 miles in a standard passenger car, and cause significant water and land pollution through the use of pesticide in cotton farming and chemicals in the dyeing process [58, 31, 74]. Garments made of synthetic fabric such as polyester have an even larger carbon footprint [58], and even the production of ostensibly sustainable options such as plant-based fabric (e.g., viscose) can cause severe pollution [72]. These environmental issues have plagued countries that are major players in the global textile industry. In Central Asia, cotton farming is one of the main reasons behind the dried up Aral Sea [76]. Toxic wastewater from textile factories has left rivers and lakes in China, Cambodia, Bangladesh and Vietnam dangerously polluted [14, 71]. In all, fashion overproduction leads to not only tremendous waste in the downstream markets but also, more importantly, excessive pollution and depletion of valuable resources in the upstream supply chain. The varying impacts along the supply chain also give rise to an environmental justice issue as upstream textile production typically takes place in developing countries, which benefit far less than developed countries (if at all) from the consumption of fashion products.

The facts above illustrate that to understand the true environmental cost of fashion waste, we need to trace the life-cycle impact of fashion products across different supply chain stages, including upstream production of raw materials. This supply chain perspective, however, is largely missing in the extant waste management literature. One reason for the omission is that this literature has traditionally focused on industry/markets with relatively stable demand so that overproduction and deadstock are much less severe issues compared to those in the fashion industry, and waste predominately occurs after consumption. This traditional focus has motivated a large research area that studies *post-use* waste (as opposed to *pre-use* waste such as fashion deadstock); see [2, 73] for a review. In particular, there is extensive research on managing end-of-life solid waste such as electronic waste, focusing on three aspects: (i) waste reduction via business model innovations such as leasing, renting and servicizing (e.g., [4, 3, 66, 1]), (ii) product reuse options such as remanufacturing (e.g.,[28, 41, 42, 35]; see [9] for a review) and (iii) recycling (e.g., [70, 10, 34, 54, 36]). The innovation stream in (i) applies life cycle analyses to evaluate the overall impact of new business models with a focus on finished goods production, consumption and disposal stages, and typically embed the upstream impact into that of finished goods production. Such a simplification is reasonable in stable markets; however, for volatile industries such as fashion where overproduction occurs at various stages of the production process, a comprehensive supply chain evaluation warrants separate discussions of the upstream and downstream stages. The remanufacturing and recycling streams in (ii) and (iii) consider how components or raw materials from post-use products can be fed back into the production process, but do not explicitly evaluate the impact of these operations on upstream production.

Another type of post-use waste is lightly used consumer returns. These products have been returned almost new and hence, similar to pre-use waste such as deadstock, can be used to satisfy consumer demand after being repaired or refurbished. Papers that study consumer returns often adopt an inventory management focus and take into account demand uncertainty (e.g., [69, 22]). However, this literature primarily analyzes the economic value of downstream operational decisions such as marketing and retailing of repaired/refurbished consumer returns, and does not study the impact of such operations on the rest of the original equipment manufacturer's (OEM's) supply chain or their environmental implications.

In a related litearture, researchers have studied pre-use waste in the form of food waste, albeit rarely from a supply chain perspective [5]. Of the few exceptions, several papers analyze the leftover inventory that occurs at various stages of the food supply chain (e.g., warehouse, grocery store, and household level) without taking production into account (e.g. [16, 6]), whereas other papers specifically study waste management in food production without considering the downstream market (e.g., [60, 8]).

In this chapter, we present an application of the supply chain perspective to analyze fashion waste and overproduction. Our goal is to illustrate how that perspective may change the conventional wisdom and yields new insights for curbing waste and overproduction in fashion. To do so, we adopt a modeling framework that incorporates fashion firms' decision-making in both downstream stages such as finished goods production and disposal, and upstream stages such as fabric acquisition. This dual-decision setup allows us to evaluate not only deadstock generation at the end of fashion production but also fabric need as input for that process, which determines the production and environmental burden imposed onto the upstream supply chain. In the next three sections (§2-4), we use this framework to examine the respective effectiveness of the 3R strategies in circular economy models—i.e., reduce, reuse and recycle—in addressing the deadstock problem. We conclude with a discussion on the general insights and future research directions in §5. We refer the readers to [62] for the proofs and technical details of all results presented in this chapter.

2 Deadstock Reduction

2.1 Quick Response and On-demand Strategies

The root cause of overproduction in the fashion industry is the high uncertainty of demand for fashion products, which makes supply planning difficult. Such high uncertainty is due to not only consumer's fast-changing needs and tastes in the fashion market but also the long production lead time in traditional apparel supply chains, which could take five to eight months [57]. As a result, fashion brands are forced to place orders with manufacturers long before they understand the market trend and the demand for their products. Hence, a natural way to address overproduction and reduce deadstock is to reduce lead time and delay finished goods production until consumer needs are well understood—i.e., to make products in response to actual demand. This approach is referred to as *quick response*.

The fashion industry has embraced quick response since its advent, driven by the associated profit benefits from better matching of supply and demand. In particular, quick response forms one of the fundamental underpinnings of the fast fashion business model, which relies on short lead times to supply highly fashionable products to the market. Relatedly, fashion firms have also developed other on-demand production strategies, such as postponing product differentiation by delaying certain parts of the production process (e.g., dyeing), and mass customization that provides on-demand product designs with common components. In the operations literature, on-demand production strategies such as quick response have been extensively studied as an example of operational flexibility (e.g., see [43, 57, 61, 78, 23, 20]). These papers focus on the profit benefits of these strategies and analyze ways for firms to best leverage such benefits.

In recent years, fashion practitioners have started to pay attention to the environmental implications of quick response. In particular, amid the growing media coverage and public scrutiny over fashion deadstock, the fashion industry turned to quick response as an environmentally beneficial production approach that could reduce deadstock. Quick response has featured prominently in major brands' agenda. Examples include the speed-factories at Adidas [64] and preorder-based production at Jacquemus [19]. Other on-demand production strategies can also be observed. For example, Ralph Lauren offers customizable styles, and Uniqlo and Delta Apparel have adopted on-demand production technologies such as 3D knitting and digital printing [64, 29]. In general, the industry views quick response as a potential win-win strategy under which brands can reduce unnecessary production and cut deadstock while maintaining and even increasing profitability [50].

Motivated by these developments, operations scholars have also started to investigate the environmental impact of on-demand production strategies. Their findings so far are mixed. On the one hand, some studies confirm the waste reduction benefits of on-demand production. For example, [63] study quick response practices in the fast fashion industry and show that they can reduce excess finished goods production. [25] show that adopting 3D printing enables the firm to postpone production and hence could achieve "finished good inventory wastage reduction". On the other hand, researchers have also found that operational complexities in the fashion industry can undermine, eliminate or even negate the potential environmental benefits of on-demand production. In particular, [63] show that in the fast fashion industry, quick response could lead to lower product quality which reduces the products' reuse options (resulting in more products landfilled or incinerated). [7] study the environmental implications of mass-customization strategies, focusing on a hybrid system where a firm offers mass-produced and mass-customized products before and after demand is known, respectively. They show that although mass-customization alone can perfectly match supply and demand (and thus leads to zero leftover inventory), adopting such strategies could increase leftover inventory in the firm's mass production channel and lead to higher inventory wastage overall.

In the next subsection, we analyze the impact of quick response from a supply chain perspective. Our analysis extends the above literature by introducing the firm's raw material acquisition decision and the associated environmental implications in the upstream supply chain.

2.2 Production and Fabric Acquisition under Quick Response

We analyze and compare the production and waste outcomes with versus without quick response. Below we first introduce the model preliminaries (in §2.2.1) and then analyze how quick response affects the firm's decisions and the associated environmental outcome (in §2.2.2).

2.2.1 Model Preliminaries

Consider a fashion firm that sells its products to a market at price p_f. For simplicity we assume price to be exogenous in this chapter; see [62] for discussions and extensions that relax this assumption. The market size is modeled by a random variable Y that follows a known distribution $F(\cdot)$. In this market, a consumer is willing to buy the focal firm's product if and only if the consumer's valuation for the product (denoted by θ) exceeds the product price p_f, i.e., $\theta - p_f \geq 0$. We assume that θ is uniformly distributed from 0 to 1 among consumers in this market. This yields the focal firm's demand function $D_f(Y) \doteq (1 - p_f)Y$.

To meet market demand, the firm acquires fabric from upstream suppliers and produces finished products in order to maximize its expected profit. Depending on whether the firm has access to quick response, we consider two models as described below.

Benchmark model: For comparison purposes, we first construct a hypothetical benchmark model where the firm is assumed not to have quick response capabilities, i.e., there are no production opportunities after demand realizes. Specifically, before demand realizes (which we refer to as stage 1 of the decision making process), the firm decides first how much fabric to purchase (denoted by the variable x) at a unit cost of c_m, and then how many products to make (denoted by the variable q) at a unit production cost of c. We assume that each product requires a unit of fabric to make, which yields the constraint $q \leq x$. Furthermore, both decisions are made based on knowledge of the demand distribution $F(\cdot)$. This assumption simplifies practice where the firm could receive additional demand information between the times of fabric acquisition and finished goods production in stage 1. This simplification does not structurally affect our insights (see [62] for a discussion).

After demand realizes (which we refer to as stage 2), the firm sells to consumers using the product inventory q. We assume in this section that all deadstock, i.e., fabric unused or products unsold, will be disposed of at negligible cost (e.g., via incineration). In §3 and §4 we relax this assumption and consider deadstock reuse and recycling, respectively. For a meaningful analysis, we let $p_f > c + c_m$ so that the firm is profitable in the benchmark model.

The firm's expected profit in the benchmark model can be formulated as $\mathbb{E}\Pi^B(x,q) = p_f \mathbb{E}\min\{D_f(Y), q\} - c_m x - cq$. The next lemma characterizes the firm's optimal decisions that maximize $\mathbb{E}\Pi^B$.

Lemma 1 *In the benchmark model, the firm's optimal decisions* (x^B, q^B) *are given by* $F\left(\frac{q^B}{1-p_f}\right) = 1 - \frac{c_m+c}{p_f}$ *and* $x^B = q^B$.

Lemma 1 indicates that in the absence of quick response opportunities, it is optimal for the firm to purchase just enough material to satisfy its production needs because additional fabric acquired does not generate profit. Accordingly, the benchmark model becomes a classical Newsvendor problem, and the optimal production quantity can be obtained from the critical fractile formula as shown in Lemma 1.

Quick Response model: We then construct a quick response model where the firm can choose to produce finished products on-demand. Specifically, the firm can decide whether and how much to produce after demand realizes in stage 2, which we model by a production quantity decision q_δ. We assume that production via quick response incurs a higher unit cost $(c+\delta)$ than regular production (i.e., production in stage 1). Here $\delta > 0$ captures the expenses associated with quick response production, such as the cost of expedited shipping and overtime. In the case that the firm has invested in its own on-demand production capabilities, δ can also represent the increase in labor and operating expenses due to the physical proximity of the production facilities to the firm's main market, or the cost of deploying advanced technology to expedite production.

We assume that fabric acquisition still occurs in stage 1 and cannot be expedited due to the long lead times associated with fabric acquisition in the fashion industry ([46]). Accordingly, as in the benchmark model, the *total* production cannot exceed the amount of fabric acquired, i.e., $q_\delta + q \leq x$ must hold.

The firm's expected profit in the quick response model is

$$\mathbb{E}\Pi^Q(x,q,q_\delta) = p_f \mathbb{E}\min\{D_f(Y), q + q_\delta\} - c_m x - cq - (c+\delta)\mathbb{E}q_\delta. \quad (1)$$

Note that the quick response production quantity q_δ depends on the realized demand and thus is a random variable itself in stage 1. We summarize the key structural properties of the firm's optimal decisions that maximize $\mathbb{E}\Pi^Q$.

Lemma 2 *In the quick response model, there exists a threshold $\bar{\delta}^Q$ such that*

(i) if $\delta < \bar{\delta}^Q$, the firm's optimal decisions in stage 1, (x^Q, q^Q), satisfy $q^Q < x^Q$. The firm's optimal decision in stage 2 is $q^Q_\delta = \min\{(D_f(y) - q^Q)^+, x^Q - q^Q\}$.

(ii) if $\delta \geq \bar{\delta}^Q$, the firm's optimal decisions in stage 1 are the same as those in the benchmark model in Lemma 1. The firm's optimal decision in stage 2 is $q^Q_\delta = 0$.

Lemma 2 indicates that whether the firm engages in quick response depends on its cost. Specifically, when the cost of quick response is relatively low, the firm finds it worthwhile to hold some additional fabric inventory at the end of stage 1, which it uses in stage 2 for additional production if needed. This contrasts with the benchmark model where the firm uses all of its fabric for production in stage 1 (i.e., $q^B = x^B$), and only holds inventory of finished goods before demand realizes.

2.2.2 Environmental Impact of Quick Response

Downstream impact: We first evaluate the impact of quick response on activities in the the downstream supply chain, which involve the production, consumption and waste (i.e., leftover inventory) of finished goods.

Proposition 1 *Compared to the benchmark model,*

1. the firm produces fewer units in stage 1 in the quick response model, i.e., $q^Q \leq q^B$;

2. the firm fulfills more demand in expectation in the quick response model, i.e., $\mathbb{E}\min\{D_f, q^Q + q^Q_\delta\} \geq \mathbb{E}\min\{D_f, q^B\}$;

3. there is less deadstock finished goods in expectation in the quick response model, i.e., $\mathbb{E}[(q^Q - D_f(Y))^+] \leq \mathbb{E}[(q^B - D_f(Y))^+]$.

Proposition 1 shows that quick response indeed reduces overproduction and waste when we consider finished goods only. Specifically, Proposition 1(1) suggests that quick response incentivizes the firm to produce less finished goods inventory, which in turn reduces the amount of deadstock finished goods (according to Proposition 1(3)). Moreover, Proposition 1(2) shows that quick response helps fulfill more consumer demand even as deadstock is reduced. These results indicate the environmental benefit of quick response in the downstream.

Upstream impact: We now turn to the upstream supply chain and compare the firm's optimal fabric acquisition decision in the quick response model with that in the benchmark model.

Proposition 2 *Compared to the benchmark model,*

1. the firm acquires more fabric in the quick response model, i.e., $x^Q \geq x^B$.

2. there is more deadstock fabric in expectation in the quick response model, i.e., $\mathbb{E}[(x^Q - q^Q - q^Q_\delta)^+] \geq x^B - q^B$.

Proposition 2(1) indicates that the firm purchases more fabric in the quick response model than in the benchmark model (i.e., $x^Q \geq x^B$). This is because quick response increases the value of fabric for the firm—having fabric on hand now enables the firm to produce more after demand realizes. This is an example of the *option value* of resources, which was introduced by [82] and has been discussed in several flexible production contexts. For example, [78] show that when production postponement is possible, more timely information and higher demand variability enhance the value of postponement and thereby lead to higher capacity investment by the firm. [26] also show that higher postponement flexibility incentivizes the firm to invest in a higher capacity level. In a similar spirit, we show that the option of quick response induces the firm to increase its production "capacity" by acquiring more raw material.

The environmental implication of Proposition 2(1) is that quick response increases fabric production and therefore the associated environmental burden (e.g., resource consumption and pollution) in the upstream supply chain. Moreover, Proposition 2(2) indicates that at least some of that increase in fabric produced ends up being wasted, resulting in an increased amount of deadstock fabric.

From an environmental justice point of view, the above discussions suggest that quick response can reduce waste in the downstream supply chain at the expense of worsened overproduction in the upstream. Given that the downstream fashion markets and upstream textile industry are typically located in developed and developing countries, respectively, our analysis indicates that quick response may aggravate the environmental disparity between these regions.

Overall supply chain impact: Finally, we analyze the net effect of quick response on the overall fashion supply chain. We first analyze the total deadstock generation in the supply chain.

Proposition 3 *Compared to the benchmark model, there is more total deadstock in expectation in the quick response model, i.e.,* $\mathbb{E}[(x^Q - q^Q - q^Q_\delta)^+] + \mathbb{E}[(q^Q - D_f(Y))^+] \geq x^B - q^B + \mathbb{E}[(q^B - D_f(Y))^+]$

Proposition 3 indicates that when quick response opportunities are introduced, the increase in upstream fabric deadstock outweighs the decrease in downstream finished goods deadstock so that the total deadstock in the supply chain increases. Intuitively, this is because quick response—by increasing the option value of each unit of fabric inventory—incentivizes the firm to tolerate a higher risk of that unit of inventory not being sold. Note, however, that deadstock fabric could arguably have a lower environmental impact compared to finished goods deadstock due to more reuse options. We will explore the possibility of deadstock reuse in §3.

For a comprehensive environmental evaluation of the impact of quick response, one needs to consider not only deadstock at the disposal stage but also the environmental impact in production and consumption stages of the supply chain. [62] analyzed this, and their main insight can be illustrated by the following carbon emission example: A recent life cycle assessment conducted by the fashion brand Ganni ([52]) estimates that 85% of the carbon emissions from an average piece of Ganni clothing comes from fabric production, 9% comes from the production and distribution of finished goods (e.g., cutting, sewing, packaging, transportation and sales), and the remaining 6% comes from product use (e.g., washing); deadstock disposal is considered carbon neutral since waste-to-energy incineration is used. Based on these estimates, [62] calculated the carbon emissions from the products/fabric involved in each supply chain stage (from fabric and finished goods production to consumption and disposal), and showed that quick response increases the overall carbon emissions of the supply chain if the firm's gross margin without quick response is below around 80%, which applies to most fashion brands [79]. The general takeaway from this example is that for industries such as fashion where raw material production drives the lion's share of the supply chain's environmental impact (e.g., in terms of resource consumption or pollution), quick response is likely to worsen that overall environmental impact.

3 Deadstock Reuse

Quick response attempts to eliminate deadstock at the source and hence focuses on the "prevention" of deadstock. Meanwhile, a different approach that is gaining momentum in the industry focuses on the "treatment" of existing deadstock. This approach aims to reduce the environmental impact of deadstock by diverting it from incinerators/landfills and ensuring that it is reused or properly recycled. In this section, we discuss the impact of deadstock reuse strategies. In particular, we focus on *upcycling*, i.e., using deadstock to make new clothes, which is a major reuse option that is rapidly gaining ground in the fashion industry.

3.1 Upcycling Opportunities in Practice

Upcycling refers to the creative reuse of discarded items in a way that adds value to the items. In the fashion context, both deadstock fabric and deadstock finished goods can be upcycled. However, upcycling finished goods entails working with fabrics that have already been cut and sewed, and therefore is much more difficult and less common than upcycling fabric rolls [18]. Upcycling fabric could also be challenging, and often requires a different set of design and supply chain expertise than what traditional fashion firms possess. In fact, traditional fashion firms rarely use their leftover fabric from previous seasons to produce new collections, due to the limited availability of such fabric and the restrictions they would impose on the design/production process [80]. Instead, these firms value and prioritize raw material supply continuity in their business models. A game changer in recent years is the emergence of companies that specialize in sourcing and production using deadstock fabric in limited runs. Examples include Reformation, TALA, Christy Dawn, Raeburn, Bug Clothing and Bilum, among others. By purchasing deadstock fabric from traditional fashion brands, these specialized upcycling companies provide opportunities for the traditional brands to engage in upcycling. Some fashion brands already actively embrace such opportunities and incorporate large-scale deadstock resale channels into their business models. For example, LVMH, a fashion conglomerate, has launched a resale platform *Nona Source* in 2021 to make its deadstock fabric available for upcycling designers [51]. More recently, Gucci launched *Gucci Continuum* with the same purpose in 2023 [49]. In addition to selling to upcycling companies/designers, some fashion brands upcycle through fabric donation. For example, Burberry partners with the British Fashion Council to donate its leftover fabric to fashion schools and universities [48].

Although upcycling is often lauded as a silver bullet for fashion's deadstock problem, the environmental effectiveness of this approach remains debatable. Two issues stand out. First, whether upcycling opportunities presented by the upcycling companies translate into deadstock reduction depends on the willingness of traditional brands to share their deadstock, which is far from a guarantee. Despite the aforementioned moves by leading brands such as LVMH and Gucci, many other brands have stayed on the sidelines. A common concern from traditional fashion brands is that sharing fabric with upcycling companies would lead to substitute products and undermine the traditional brands' own demand. In particular, by using the same fabric/raw material, upcycled products can often offer a similar luxury feel to that of the original brand at lower price points, and thus can be appealing to the original brand's customers [68]. Prompted by such concerns, some fashion brands, especially luxury houses, may keep their excess fabrics hidden away in warehouses or destroy them rather than risk having them used by potential competitors [75, 32]. Some fashion brands have even filed recent lawsuits against upcyclers that repurpose their material to make new products [68].

Second, even when brands make their deadstock fabric available for upcycling, whether such activities indeed lead to environmental benefits such as waste reduction requires detailed investigation. In particular, some practitioners are concerned that the existence of an upcycling option for fabric may reduce incentives for firms to make prudent fabric acquisition/production decisions in the first place [30, 40]. These concerns call for a more comprehensive analysis of upcycling's environmental implications, to include not only fashion brands' downstream decisions but also how these decisions interact with their fabric acquisition practices. Such an analysis is particularly needed given the lack of transparency in fashion supply chains [30], where it could be difficult for upcycling companies to even distinguish true deadstock—fabric that becomes leftovers unintentionally—from fabric that is *purposefully* produced to be sold under the label of deadstock [84].

Existing research on upcycling has mainly taken a fashion design perspective. Specifically, this stream of research studies design innovations that help incorporate upcycling into mass production processes or, more generally, traditional fashion business models [24, 55]. What has not been analyzed is the impact of upcycling on fashion brands' incentives and supply chain operations. Concepts similar to upcycling have been explored in non-fashion contexts in the operations literature. For instance, a number of papers study business models that leverage by-product synergy and turn waste into value [59, 60]. There also exists extensive research on remanufacturing (see §1 for a brief review). However, upcycling in the fashion context presents unique challenges. For example, the by-product synergy literature typically considers in-house operations where the firm that generates the waste turns it into by-products itself. Moreover, the main product and the by-product are assumed to be sold in different markets, which precludes the substitution effects that accompany fashion upcycling. The remanufacturing literature considers competition between OEMs and third-party remanufacturers. However, there are typically no payments involved between the two competing parties whereas an upcycling company in fashion buys fabric from a traditional brand. Another key difference lies in the fact that upcycling in fashion utilizes raw material that is unused in production, whereas remanufacturing involves utilizing cores from existing products. In the rest of this section, we leverage the decision model in §2.2 to explore the impact of upcycling.

3.2 Production and Fabric Acquisition under Upcycling

3.2.1 Upcycling Model

We introduce a simple model to characterize the impact of upcycling through the lens of a traditional brand. Specifically, we consider the same fashion firm modeled in §2.2 and assume that it now can potentially sell its deadstock fabric to an upcycling firm at a unit price of w. For ease of reference, we shall call this fashion firm the *focal* firm in this section.

We make a few assumptions to maintain a focused study. First, we assume that the focal firm acquires fabric only to meet its own demand, and do not consider fabric intended to be sold as deadstock to upcycling companies. We ensure this focus by assuming that $0 < w < c_m$ so that there is no arbitrage, i.e., the focal firm cannot profit by purchasing and then selling fabric to the upcycling firm. Second, we assume the focal firm has access to quick response opportunities (without which our model leads to no deadstock as shown by the benchmark case analysis in §2.2.1, and thus upcycling is not applicable). Third, we assume that while the focal firm can decide how much deadstock to share with the upcycling firm (which we denote by S, with $S = 0$ indicating that the focal firm does not engage in upcycling), the upcycling firm buys all deadstock available. This reflects the current reality where fashion brands can freely decide how much deadstock fabric to share, and upcycling firms are often short of raw materials [17]. Last but not least, we note that modeling deadstock fabric transaction as a direct payment w between the focal and the upcycling firms is a simplification of the complex supply processes of deadstock fabric in practice, which can involve multiple intermediaries before the fabric reaches the upcycling firm.

The sequence of events in the upcycling model is the same as that in the quick response model introduced in §2.2.1 except that now the focal firm decides the amount of fabric S to sell to the upcycling firm in stage 2 (along with its production decision). After acquiring the deadstock fabric, the upcycling firm uses that fabric to produce its own products. Then, the focal firm fulfills its demand in the presence of the upcycling firm's products. We denote the focal firm's demand by $D_f^U(Y)$. As discussed in §3.1, the focal firm's upcycling incentives depend critically on the extent to which the focal and upcycling firms' products are substitutable (due to the same fabric used). To model this, we assume that in the focal firm's target market, a consumer's valuation for the upcycling firm's product is $\alpha\theta$, where $\alpha \in [0, 1)$ is the substitution factor and represents the disparity in consumer preferences for the focal versus the upcycling firms' products. Recall that we denote the focal firm's product price by p_f. Similarly, let p_s denote the price of the upcycling firm's products. Accordingly, a consumer prefers to purchase the focal firm's product if $\theta - p_f \geq \alpha\theta - p_s$ and $\theta - p_f \geq 0$, and prefers to purchase the upcycling firm's product if $\theta - p_f < \alpha\theta - p_s$ and $\alpha\theta - p_s \geq 0$. Analysis of these inequalities yields two situations:

(1) when α is sufficiently low (specifically, when $\alpha \leq \frac{p_s}{p_f}$), no consumer in the focal firm's target market would purchase from the upcycling firm. In that case, the focal firm's demand is not affected by upcycling and remains $D_f^U(Y) = D_f(Y)$ as defined in §2.2.1. This reflects situations where the upcycling firm makes different types of products or operates in different markets from that of the focal firm.

(2) when $\alpha > \frac{p_s}{p_f}$, a segment of the focal firm's target market prefers the upcycling firm's product, and would purchase that product if it is available. As a result, the focal firm's demand is reduced—an effect that we refer to as *demand encroachment*. The extent to which demand encroachment arises depends on the amount of fabric upcycled (S) which constrains the upcycling firm's production. As such, the focal firm's demand reduces to a fraction of its original size, with the fraction dependent on both the substitution factor α and the focal firm's upcycling decision S. That is, $D_f^U(Y) = \beta(\alpha, S) \cdot D_f(Y)$. We refer the reader to [62] for the complete formulation of this demand function and the associated technical derivations.

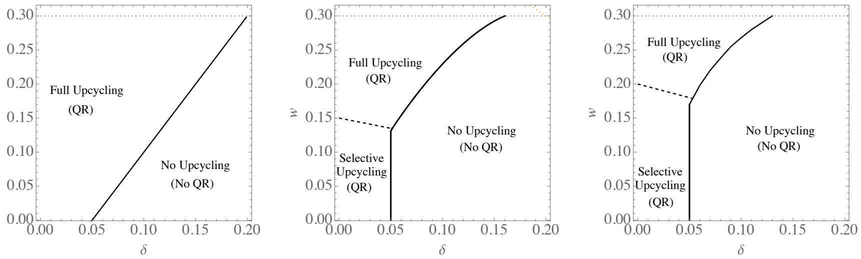
The firm's expected profit in the upcycling model can be modeled as

$$\mathbb{E}\Pi^U(x, q, q_\delta, S) = p_f \mathbb{E} \min\{D_f^U(Y), q + q_\delta\} - c_m x - cq - (c + \delta)\mathbb{E}q_\delta + w\mathbb{E}S. \tag{2}$$

In this profit function above, both q^δ and S are stage 2 decisions and depend on the realization of the market size Y.

Paralleling the notation in §2, we denote the optimal decisions that maximize $\mathbb{E}\Pi^U$ by $(x^U, q^U, q_\delta^U, S^U)$. We observe two key properties, illustrated by Figure 1. For the complete characterization of these decisions, please see [62].

The first observation from Figure 1 is that the presence of upcycling opportunities encourages the adoption of quick response. That is, the parametric regions under which the focal firm adopts quick response in the upcycling model (shown in Figure 1(a)-(c) for $w > 0$) are larger than that in the quick response model (corresponding to $w = 0$ in Figure 1). Intuitively, this is because the option of upcycling recovers the salvage value of leftover fabric and strengthens the option value of holding fabric in stage 1 (in preparation for quick response). Note that quick response increases deadstock fabric (by Proposition 2(2)) and thus the focal firm is also *more* likely to



(a) $\alpha = 1/6$ (no encroachment) (b) $\alpha = 0.3$ (c) $\alpha = 0.4$

Fig. 1: The optimal upcycling and quick response (QR) decisions under different values of α. In this figure, $Y \sim Uniform[0,1]$, $p_f = 0.6$, $c = 0.1$, $c_m = 0.3$, $p_s = 0.1$.

engage in upcycling when the option of quick response becomes available. Hence, quick response and upcycling options complement each other in the sense that the focal firm is more likely to adopt one if the other is accessible.

The second observation from Figure 1 is that as α increases (i.e., as the upcycling firm's product becomes more appealing to the focal firm's customers), the focal firm becomes less willing to engage in upcycling. In particular, comparing the three panels of Figure 1, we observe that the no-upcycling region becomes larger as α increases. Furthermore, even in regions where the focal firm engages in upcycling, it may refrain from selling all of its deadstock fabric to the upcycling firm (an outcome that we label as "*full upcycling*" in this figure) and instead sells only part of its deadstock fabric (labelled as "*selective upcycling*"). These outcomes arise from the focal firm's attempt to balance the positive salvage value it can recoup from upcycling against the negative demand encroachment effect that accompanies such an action.

Based on the above observations, we next explore the environmental implications of upcycling.

3.2.2 Environmental Impact of Upcycling

Downstream impact: We first characterize the impact of upcycling on finished goods production and waste. All results presented in §3.2.2 are based on the assumption that the market size Y follows a uniform distribution on $[0, 1]$. Please see [62] for a discussion of the results under other distributions.

Proposition 4 *Assume* $Y \sim Uniform[0,1]$ *and let* $\alpha \leq \frac{p_s}{p_f}$. *Compared to the quick response model,*

1. the focal firm produces fewer units in stage 1 in the upcycling model, i.e., $q^U \leq q^Q$.

2. there is less deadstock finished goods in expectation in the upcycling model, i.e., $\mathbb{E}[(q^U - D_f(Y))^+] \leq \mathbb{E}[(q^Q - D_f(Y))^+]$.

Proposition 4 presents the case where α is sufficiently low (so that demand encroachment does not occur), but similar results can be obtained numerically for $\alpha > \frac{p_s}{p_f}$ (when demand encroachment does exist). The results reveal that upcycling exerts a similar impact to that of quick response on the downstream supply chain. This is because upcycling encourages the focal firm to rely more on quick response, and accordingly reduces the amount of finished goods the firm produces in stage 1 and in turn, the amount of deadstock finished goods.

Upstream impact: Next we show that the impact of upcycling on the upstream supply chain depends on whether demand encroachment exists.

Proposition 5 *Assume* $Y \sim Uniform[0,1]$. *Compared to the quick response model,*

1. the focal firm acquires more fabric in the quick response model, i.e., $x^U \geq x^Q$*;*

2. when $\alpha \leq \frac{p_s}{p_f}$*, there is less deadstock fabric in expectation in the upcycling model, i.e.,* $\mathbb{E}[(x^U - q^U - q^U_\delta - S^U)^+] \geq \mathbb{E}[(x^Q - q^Q - q^Q_\delta)^+]$. *However, when* $\alpha > \frac{p_s}{p_f}$*, there may be more deadstock fabric in expectation in the upcycling model.*

Proposition 5(1) indicates that, similar to quick response, upcycling can motivate the focal firm to acquire more fabric. This result confirms the concern of practitioners that introducing a profitable option to treat deadstock fabric may increase fabric production and the environmental burden in the upstream supply chain.

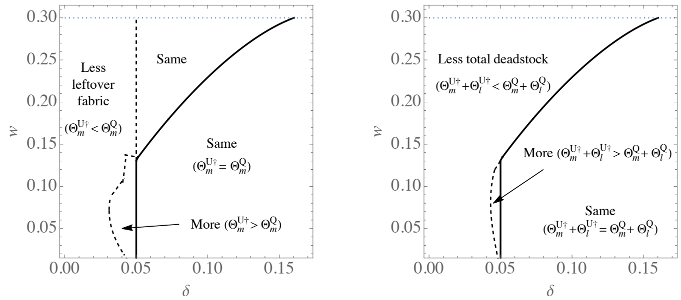
Proposition 5(2) shows that absent demand encroachment, upcycling effectively reduces deadstock fabric. This is because when upcycling does not hurt its demand, the focal firm engages in full upcycling by upcycling all available deadstock fabric. Note that the calculation of deadstock fabric in the upcycling model in Proposition 5(2) assumes that the upcycling firm uses up the deadstock fabric it acquires from the focal firm. This reflects practice where upcycling firms, driven by their business propositions, avoid fabric waste as much as possible.

In contrast, when demand encroachment exists, upcycling may not lead to a reduction in deadstock fabric. Figure 2(a) illustrates one such example. Comparing this figure with Figure 1(b) which shares the same parametric setting, we observe that upcycling can increase the amount of deadstock fabric when the focal firm engages in selective upcycling, in which case the amount of fabric upcycled could be less than the increase in fabric acquired.

Overall supply chain impact: We show that whether upcycling reduces the total amount of deadstock also depends on whether demand encroachment occurs.

Proposition 6 *Assume* $Y \sim Uniform[0,1]$. *Compared to the quick response model, when* $\alpha \leq \frac{p_s}{p_f}$*, there is less total deadstock in expectation in the upcycling model, i.e.,* $\mathbb{E}[(q^U - D_f(Y))^+] + \mathbb{E}[(x^U - q^U - q^U_\delta - S^U)^+] \leq \mathbb{E}[(q^Q - D_f(Y))^+] + \mathbb{E}[(x^Q - q^Q - q^Q_\delta)^+]$. *However, when* $\alpha > \frac{p_s}{p_f}$*, there may be more total deadstock in expectation in the upcycling model.*

The result under no demand encroachment (i.e., $\alpha \leq \frac{p_f}{p_f}$) directly follows from combining Proposition 4(2) and Proposition 5(2). The total deadstock comparison



(a) Leftover fabric (b) Total deadstock

Fig. 2: Impact of upcycling on deadstock outcomes under demand encroachment. In this figure, $Y \sim Uniform[0, 1]$, $p_f = 0.6$, $\alpha = 0.3$, $c = 0.1$, $c_m = 0.3$, $p_s = 0.1$.

under demand encroachment is depicted in Figure 2(b), which shows that the increase in deadstock fabric (illustrated in Figure 2(a)) may dominate the decrease in deadstock finished goods so that upcycling increases the total deadstock overall.

In sum, we find that upcycling can effectively reduce deadstock when the demand encroachment effect is small (or absent), but such a benefit always comes at the expense of worsened fabric production and environmental burden in the upstream. To comprehensively evaluate the overall impact of upcycling in the entire supply chain, we revisit the carbon emission example discussed at the end of §2. We find that in that example, introducing the upcycling option generally increases the overall carbon emission (see [62] for more details). The insight is that under environmental metrics that are heavily affected by fabric production (e.g., carbon emissions, water consumption, or pollution), upcycling is likely to exacerbate the overall environmental impact of the fashion supply chain.

4 Deadstock Recycling

Besides deadstock reuse, recycling represents another major approach to treat fashion deadstock. Recycling is the process of recovering raw material (e.g., cotton fiber or granules of synthetic material) from clothes and fabric through thermal and/or mechanical methods. Unlike deadstock upcycling which generates additional revenue for fashion brands, brands typically needs to pay for textile recycling services. This is because textile recycling requires specialized (and sometimes proprietary) technologies that can be costly [67, 13]. Hence, regulation is typically needed to ensure that fashion brands take part in recycling. One example is the Anti-Waste Law enacted in France in 2020 [65]. In the U.S., the state of California recently proposed the Responsible Textile Recovery Act that mandates extended producer responsibility of all apparel producers to collect and recycle their textile products

[21]. Nevertheless, some brands have voluntarily partnered with recycling facilities. For example, Reformation partners with SuperCircle (a textile collection, sorting and consolidation facility) in its *RefRecycling* program to recycle take-backs from consumers [53]. These initiatives could be driven by potential first-mover advantages under the current regulatory environment that is moving towards brands-financed recycling, or other benefits from establishing a circular business model such as improved brand reputation and access to innovative recycled materials.

As discussed in §1, there exists a large literature on recycling, yet very limited analysis that traces recycling's impact into raw material production stages. One exception is [11]; however, they study input material reduction as an alternative to, not as a consequence of, scrap recycling. In this section, we analyze the impact of recycling—in particular, regulatory mandated recycling—on fashion firms' production and fabric acquisition decisions. Specifically, we extend the models in §2-3 and assume that the focal firm is mandated to recycle any deadstock that is not upcycled, and incurs a unit cost of r_m and r_l to recycle deadstock fabric and finished goods, respectively. Hence, the focal firm's expected profit can be formulated as

$$\mathbb{E}\Pi^R(x,q,q_\delta,S) = \mathbb{E}\Pi^U(x,q,q_\delta,S) - r_m\mathbb{E}(x-q-S-q_\delta)^+ - r_l(q-D_f)^+ \quad (3)$$

where $\mathbb{E}\Pi^U$ is the focal firm's expected profit function in the upcycling model (see equation (2)).

Analysis of the optimal decisions that maximize $\mathbb{E}\Pi^R$ (see [62] for details) generates two main insights. First, mandatory recycling reduces the expected amount of deadstock generated. This is because the focal firm, in order to reduce the cost of recycling, either holds less inventory (in finished goods or fabric form) in stage 1 or upcycles more in stage 2.

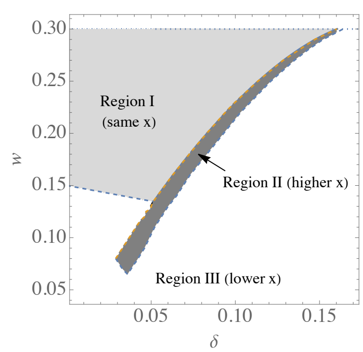


Fig. 3: The effect of deadstock ban on the focal firm's fabric acquired. In this figure, $r_l = r_m = 0.05$, and other parameters are the same as in Figure 1(b).

Second, depending on which of the two aforementioned cost reduction options the focal firm turns to, mandatory recycling could increase, decrease or have no impact on the focal firm's fabric acquisition decision, as illustrated by Figure 3. Specifically, when w is sufficiently high and δ is not too large (see Region I in Figure 3), the firm finds it optimal to reduce production (i.e., finished goods inventory) in stage 1 to mitigate the recycling cost, and keeps its fabric acquisition decision unchanged. When w is high and δ is moderate (see Region II in Figure 3), mandatory recycling motivates the firm to upcycle more (e.g., to switch from no or selective upcycling to full upcycling), which in turn increases its fabric acquisition amount. Finally, in the remaining region (i.e., Region III in Figure 3), it is optimal for the firm to focus on acquiring less fabric inventory in stage 1 to reduce the recycling cost.

The key takeaway from the above results is that a regulatory mandate that holds fashion brands responsible for recycling can effectively reduce deadstock as well as fabric acquisition. In other words, mandated recycling could be a way to resolve the tradeoff between downstream waste reduction and worsened upstream overproduction—a treadeoff that is unavoidable in other approaches such as quick response and upcycling.

We close this section by acknowledging a few downsides associated with mandatory recycling, compared to the other approaches discussed so far. First, textile recycling remains technically challenging and therefore can be a less effective and/or more expensive approach of treating deadstock than upcycling. For example, certain synthetic fabric such as spandex, lycra, or elastane cannot be recycled and has to be landfilled if not upcycled [39]. Polyester is almost impossible to recycle in a cost-effective manner [83]. Recycling of natural fabric such as cotton often incurs significant quality degradation that greatly limits the usage of the resulting fibers [27]. Moreover, most clothes are made of mixed fibers (for example, cotton is often mixed with elastane or spandex to make jeans), and separating them is notoriously difficult [13]. Second, most recycling technologies—especially those for synthetic fabric—involve thermal processes and thus are energy intensive and can worsen carbon emissions [13]. Third, upholding a regulatory mandate requires additional implementation and monitoring costs, compared to approaches such as quick response and upcycling that leverage fashion brands' economic incentives. Policy makers should be mindful of these drawbacks and the tradeoffs therein when designing regulations that promote one approach over another.

5 Discussion

In this chapter, we study the fashion waste and overproduction problem from a supply chain perspective that accounts for not only downstream operations related to finished products but also the upstream production of raw materials. We demonstrate such a perspective through a dual-decision setting where a fashion firm jointly optimizes finished goods production and fabric acquisition decisions. We show that simply tracing fashion firms' decisions one step further upstream in the supply chain—beyond the traditional focus of finished goods production—yields important new insights. In particular, we show that waste reduction in the downstream does not necessarily alleviate overproduction in the upstream. Rather, popular waste reduction approaches such as quick response and upcycling can worsen textile overproduction and even increase the overall environmental footprint of the fashion supply chain.

On a higher level, our study highlights a fundamental challenge associated with waste reduction approaches. That is, approaches that add economic value for fashion firms (e.g., quick response and upcycling) can incentivize voluntary waste reduction, but at the same time may increase the firms' demand for resources. In other words, reduced waste does not necessarily translate into reduced "want" in the supply chain. By contrast, waste reduction approaches that impose costs on fashion brands (e.g., recycling) can lead to more prudent acquisition and production decisions, but require external regulatory mandates to take effect. We note that similar tradeoffs have been discussed in other contexts. For example, it has been shown that food waste reduction efforts can inadvertently encourage more food consumption and production due to price drops, which may undermine the environmental benefit of such efforts [56].

From a policy perspective, our analysis shows that curbing fashion waste and overproduction may require a combination of different policy instruments. Incentive-based instruments such as subsidizing quick response and upcycling (featured in policy recommendations such as [33] and [37]) could have adverse effects on the upstream supply chain and thus may need to be coupled with tools that directly target reducing the environmental impact of the upstream textile industry, e.g., pollution control regulation. Recycling mandates such as Extended Producer Responsibility legislation could potentially curb overproduction at the source, yet may result in less effective waste treatment outcomes given the current textile recycling technologies and infrastructure. Hence, additional policies that monitor the recycling processes and their output may be necessary. In addition, policy makers may consider providing incentives that encourage technology innovation and infrastructure development in textile recycling. In all, curbing fashion waste and overproduction is at the nexus of technology, policy and business innovations and requires a holistic view that spans the entire fashion supply chain from raw material provision to disposal.

There are rich directions that can be explored to gain further insights into the impact of supply chain operations on the environmental impact of fashion. Going upstream, it will be interesting to incorporate the perspectives of raw material suppliers and examine how their incentives affect overproduction and waste outcomes. Other fruitful directions include probing the complexity of the deadstock supply chain and the associated business opportunities for traditional as well as upcycling companies. Going downstream, a comprehensive study of fashion consumers' behavior and how it interacts with firms' product provision decisions such as variety and frequency can generate practical insights into the root causes of overproduction and overconsumption in fashion. In addition, a closer investigation of textile recycling practices can offer valuable policy recommendations that are much-needed given the current regulatory trend towards Extended Producer Responsibility for fashion products.

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