Asset Selling Under Debt Obligations

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We extend the classical asset selling problem to include debt repayment obligation, selling capacity constraint, and Markov price process. Specifically, we consider the problem of selling a divisible asset which is acquired through debt financing. The amount of asset that can be sold per period may be limited by physical constraints. The seller uses part of the sales revenue to repay the debt. If unable to pay off the debt, the seller must go bankrupt and liquidate the remaining asset. Our analysis reveals that in the presence of debt, the optimal asset-selling policy must take into account two opposing forces: an incentive to sell part of the asset early to secure debt payment and an incentive to delay selling the asset to capture revenue potential under limited liability. We analyze how these two forces originated from a debt financing will distort the seller’s optimal policy.

1. Introduction

Financing asset acquisition and selling the asset is a common practice in many industries. In the agricultural industry, farm loans are often used to finance farming operations and crops are then sold to generate revenues, part of which repay the loans. For example, in the Midwest, farmers invest billions of dollars every year in corn crop. Corn can be dried and stored over a year, allowing farmers to choose when and how much to sell their crop. Farm bankruptcies and exits are common due to fluctuations in crop prices (Stam and Dixon 2004). In the energy and mining industries, acquisition of mineral rights, exploration and construction of infrastructure constitute the bulk of setup investment that need to be financed before any revenue from selling the resources can be realized. For example, a shale gas producer leases land from land owners at a cost that can be as high as $15,000 per acre, and drilling a well needs 40-80 acres. Drilling, hydraulic fracturing,
and completion cost $3-7 million per well. Production of gas lasts for 10 to 20 years, and the producer can control to some extent the rate of production to sell more gas at favorable market prices. Interestingly, even though the natural gas price plunged in 2008, instead of cutting back their production and waiting for the price to recover, producers kept extracting natural gas at a high rate. Among the reasons for producing more in a dire market is that some producers are forced to produce under financial pressure of paying off their debts.

Motivated by the above industry practices, in this paper we aim to explore how debt obligations affect asset-selling decisions. We consider a discrete-time problem of selling a divisible asset over a finite horizon. Prior to the first period, the asset acquisition is partially or fully financed by debt, and from period 1 through \( N \), the seller faces stochastically evolving market price and decides in each period how much of the asset to sell at the ongoing price. The seller uses the sales revenue to repay the debt and must go bankrupt if unable to meet the debt obligation. We analyze the impact of the debt level (the amount that the seller owes) and the debt payment schedule (e.g., timing of debt maturity, pay all at once or in installments) on the seller’s optimal selling strategies.

We also consider selling capacity constraint in our model. Capacity constraint imposes a limit on the amount of asset that can be sold per period, which is commonly observed in practice, e.g., selling natural gas from a well or minerals from a mine is limited by the speed of extraction, selling farm crops to the market is limited by the labor and transportation capacity. We analyze how the capacity constraint and debt obligation jointly affect the optimal asset-selling strategies.

1.1 Related Literature

The asset selling problem, in its basic form as in Karlin (1962), considers selling a single non-divisible asset when \( n \) prices independently drawn from a known distribution are presented to the seller sequentially. Upon offered a price, the seller must decide whether to accept the offer and sell the asset or reject it and wait for the next price, with the goal of maximizing the expected revenue. This problem has many variants (reviewed shortly), and the family of asset selling problems has been well studied in the context of stochastic search problem since Stigler (1961). A related search problem is the dowry problem or secretary problem, in which candidates are presented sequentially to a decision-maker, who can rank candidates without tie, and must choose or reject each candidate based on the relative ranks observed so far, with the goal of maximizing the probability of choosing the best one.\(^1\) The dowry problem and its variants are examined by Gilbert and Mosteller (1966), Freeman (1983), Chun et al. (2002), among others.

The asset selling problem is first analyzed by Karlin (1962), who proves that the optimal policy

\(^1\)In the dowry problem, the payoff is essentially 1 if the best is chosen and 0 otherwise (i.e., nothing but the best), whereas in the asset selling problem, the payoff is the selling price.
is to sell the asset when the offered price exceeds a time-dependent reservation price, which is the maximum expected price attainable in the remaining periods. Gilbert and Mosteller (1966) compare reservation prices under various settings and illustrate that the reservation prices are higher if the right-hand tail of the price distribution is larger. Karlin (1962) also considers an infinite-horizon setting with a discount factor, and finds that the reservation price is a constant. Lippman and McCall (1976) consider an infinite-horizon job search problem with a fixed cost per search, and find that the optimal policy can be characterized by a reservation wage; see also Telser (1973) for a similar problem of a buyer searching for the lowest price.

Several authors have considered the problem of selling multiple identical assets (no more than one in any period) with the objective of maximizing the total expected revenue. Karlin (1962) and Gilbert and Mosteller (1966) find that the optimal policy is characterized by reservation prices that depend on the number of remaining assets for sale. Selling multiple assets is actually a special case of the sequential assignment problem, in which a decision-maker must assign $n$ known quantities $q_i$, $i = 1, \ldots, n$ to sequentially revealed random variables $X_j$, $j = 1, \ldots, n$ (independently drawn from a known distribution) to maximize the total expected payoff, given that pairing $q_i$ with $X_j$ yields a payoff $q_i X_j$. Derman et al. (1972) prove that optimal assignment for $X_1$ is characterized by $n$ non-overlapping intervals such that if $X_1$ falls in the $i$th interval, it is optimal to assign the $i$th smallest quantity to $X_1$. Albright (1974) further generalizes the problem to allow random arrival times of $X_j$. In §4, the asset selling problem with a selling capacity constraint is related to the problem of selling multiple assets.

For a divisible asset, if the revenue is linear in the amount sold, selling the asset as a whole is still optimal. When the payoff function is concave, however, dividing the asset for sale may be desirable. Derman et al. (1975) analyze a sequential investment problem, which is generalized by Prastacos (1983). In this problem, an investor with a certain amount of capital decides how much to invest in each sequentially revealed opportunity. The quality of each opportunity is independently drawn from a known distribution. Investing $q$ (irreversible) in an opportunity of quality $X$ yields a return $R(q, X)$. Prastacos (1983) considers the special case of $R(q, X) = qX$, which is equivalent to the basic asset selling problem; he also examines the case when $R(q, X)$ is concave in $q$ and derives the optimal investment strategy. We consider the problem of selling a divisible asset with debt obligations and provide the structure of the optimal policy.

A common assumption in most asset selling models is that the sequentially revealed prices are independently and identically distributed, with only a few exceptions. Karlin (1962) and Lippman and McCall (1976) allow the price to follow a semi-Markov process and show that the optimal policy can be characterized by reservation prices that depend on the state of the underlying Markov
process. Pye (1971) models the price evolution as a random walk and considers a different objective that is to minimize regret. In this paper, we model price evolution as a Markov process.

We assume that the stochastic properties of the price process are known to the seller. This assumption is also made in the papers reviewed above, but the asset selling problem with unknown price distribution has also received considerable attention. Heuristic methods are developed by Telser (1973), while Bayesian updating methods are adopted by Rothschild (1974), Albright (1977), and Rosenfield et al. (1983).

Continuing interest in the asset selling problem has been seen recently. Ee (2009) extends the asset selling problem to allow random termination of the selling process as well as the options of skipping search in a period and terminating search by taking a quitting offer. Palley and Kremer (2014) consider a search problem where the decision-maker knows the distribution of the candidate values, but only observes the relative rankings of the candidates until search stops. The asset selling problem and its variants have broad applications such as labor market (Rogerson, Shimer, and Wright 2005), kidney allocation (Su and Zenios 2005), land development (Batabyal and Yoo 2005), and online commerce (Gallien 2006).

A seller with market power can post a selling price and customers whose valuation of the asset exceeds the selling price will buy. Arnold and Lippman (2001) consider the problem of pricing one unit of asset in face of Poisson demand with known distribution of valuation. They also extend the model to selling multiple units over time at posted price, which is essentially a revenue management problem. Phillips (2005) provides an extensive review of the literature on pricing and revenue management. Below, we review a few papers that introduce financial constraints or targets to the classic revenue management problem studied by Gallego and van Ryzin (1994). Levin et al. (2008) consider selling multiple units over a finite horizon and analyze the efficient frontier of expected revenue and the probability of meeting a revenue target. Besbes and Maglaras (2012) introduce revenue and sales milestone constraints into the revenue management problem and find that the optimal pricing policy dynamically tracks the most stringent future milestone. Besbes et al. (2018) analyze a discrete-time version of the revenue management problem under debt obligations. This paper complements the above research by studying the problem of selling assets at market price (as opposed to the posted price) under debt obligations.

The effects of debt on operations have been examined in various contexts. Xu and Birge (2004) study a newsvendor problem with debt financing and demonstrate the value of integrating production and financing decisions. Buzacott and Zhang (2004) analyze the interactions between a firm’s financing and operation decisions when the maximum amount of the loan is based on the firm’s assets. Kouvelis and Zhao (2012) compare bank financing with supplier financing in a newsvendor
setting and study the optimal trade credit contracts. Chod (2017) analyzes how debt distorts a retailer’s inventory decision and ways to mitigate such distortion. Iancu et al. (2017) finds that firms shielded by limited liability may use operating flexibility at the expense of their creditors, resulting in higher borrowing cost. Besbes et al. (2018) analyze the revenue management problem when the seller has limited liability for a debt repayment at the end of the horizon. They find that the debt induces the seller to consistently price higher than the revenue-maximizing policy, and this distortion increases over time, leading to downward spiral in the expected revenue. Our research not only considers the effect of limited liability, but also captures the cost of dissolution, i.e., revenue loss related to asset liquidation, as described in §1.2 below.

1.2 Our Contributions

This paper extends the classical asset selling problem to include debt repayment obligations. We analyze two distinct effects of debt obligations on optimal asset-selling policies and the interactions between these effects. The first effect is commonly known as the limited liability or risk shifting effect (Myers 1977, Chod 2017, Besbes et al. 2018, among others). In our context, if the seller is unable to pay off the debt, a straight bankruptcy procedure allows the seller to liquidate the remaining asset and the debt is then discharged. Thus, in the adverse price scenarios, bankruptcy protects the seller from carrying the debt obligations indefinitely. As the downside loss is curbed by limited liability, the seller tends to delay selling the asset to capture upside revenue potential. The second effect of debt stems from the revenue loss upon bankruptcy. Liquidation process typically needs to be completed in a short time frame, generating a lower expected revenue than the revenue from debt-free asset-selling. If the revenue from liquidation sales does not fully cover the debt, the seller receives zero payoff. Thus, the presence of a debt incentivizes the seller to secure capital early to pay off the debt. As a result, the seller deviates from the revenue maximizing strategy and sells (part of) the asset early.

The revenue loss effect of debt and its interaction with limited liability have not been much explored. Revenue loss is considered in the context of a newsvendor setting (Kouvelis and Zhao 2011) and in the presence of strategic consumers (Birge et al. 2017). In a revenue management problem with a revenue target (without debt), Levin et al. (2008) show that when the revenue is slightly below the target, the optimal policy is to price lower than the revenue-maximizing policy. To the best of our knowledge, this paper is the first to analyze how limited liability and revenue loss jointly affect the optimal asset selling strategy. Whether the seller delays or expedites selling the asset depends on the relative strengths of these two effects, which vary across different debt agreements. When the two effects are equally strong, it is possible that the optimal policy under debt coincides with the revenue-maximizing policy.
We also study how the capacity constraint interacts with the two effects of debt obligations and find that the capacity constraint weakens both limited liability effect and revenue loss effect. That is, the magnitude of delayed selling (driven by the limited liability effect) or expedited selling (driven by the revenue loss effect) decreases as the seller’s capacity constraint tightens. Furthermore, we find that the presence of capacity constraint may reduce the bankruptcy risk, especially when the capacity constraint is moderate and the debt level is not too high. This result echoes the negative impact of operating flexibility found by Iancu et al. (2017).

This paper establishes the condition under which selling a divisible asset with capacity constraint is equivalent to the problem of selling multiple non-divisible units. This equivalence allows us to compare the optimal policies for selling asset at market price versus selling at posted price. In contrast to Besbes et al. (2018) who find that the price distortion increases over time, we show that the distortion on the reservation price may be decreasing over time, due to the strong downward pressure on the reservation price toward the end of the horizon.

Finally, this paper contributes to the asset-selling literature by considering Markov price processes. We derive most of the results under the assumption that prices evolve according to a Markov process, which is more general than the independent and identical price distributions assumed in most of the existing literature.

2. Asset Selling Model and Debt Financing

We consider a seller (firm) selling a divisible asset over a $T$-period horizon $\mathcal{T} \triangleq \{1, 2, \ldots, T\}$. Before the beginning of the horizon (labeled as period 0), the seller makes a one-time investment to acquire the asset. We assume there is no opportunity to acquire additional asset after period 0. Divisibility of the asset is not a critical assumption, but facilitates analysis. The qualitative results in this paper continue to hold if the seller has a large number of non-divisible units for sale.

2.1 Asset Selling without Debt Constraints

As a benchmark, we first formulate the problem of selling a divisible asset without debt obligations, i.e., the seller has enough initial capital (through self-financing or equity) to acquire the asset in period 0, which is sold over periods 1 to $T$. The value of any unsold asset at the end of period $T$ diminishes to zero.

Let $x_t \in [0, 1]$ denote the amount of asset available for sale at the beginning of period $t$. Without loss of generality, the initial size of the asset is normalized to $x_1 = 1$. Let $P_t \geq 0$ be the random selling price in period $t$, and let $p_t$ denote its realization. Upon observing $p_t$ at the beginning of period $t$, the seller decides the selling quantity in period $t$, denoted as $q_t$. The maximum amount of asset that can be sold per period is $\ell \in (0, 1]$, i.e., $q_t \in [0, \ell]$. If $\ell = 1$, the seller can sell the entire
asset in one period, which is the case we consider first in §3. The case of $\ell < 1$ is studied in §4.

We model the price process $\{P_t : t \in T\}$ as a discrete-time continuous-state Markov process. Let $F_t(\cdot | p_{t-1})$ be the cumulative distribution function of $P_t$ conditioning on the realized price $p_{t-1}$.

Let $U_t(x_t, p_t)$ be the maximum discounted expected revenue-to-go from period $t$ onward when the amount of asset for sale at the beginning of period $t$ is $x_t$ and the realized price is $p_t$. Let $\rho \in (0, 1)$ be the seller’s discount factor. Then, $U_t(x_t, p_t)$ can be determined by the following dynamic program:

$$U_t(x_t, p_t) = \max_{0 \leq q_t \leq \min(x_t, \ell)} p_t q_t + \rho \mathbb{E}_t U_{t+1}(x_t - q_t, P_{t+1}), \quad t = 1, \ldots, T,$$  \hspace{1cm} (1)

$$U_{T+1}(\cdot, \cdot) = 0,$$

where $\mathbb{E}_t$ is the expectation conditioning on the observed price $p_t$.

### 2.2 Asset Selling Under Debt Constraints

If the seller cannot raise enough capital for investment, it can finance with a debt in period 0, and repay the debt using the revenue from selling the asset. Similar to Besbes et al. (2018), we assume a debt contract is already in place and analyze the selling decision under the debt. Let $m (1 \leq m \leq T)$ be the debt maturity period. The debt payment schedule is denoted as $d = \{d_t : t = 1, \ldots, m\}$, where $d_t \geq 0$ is the installment to be paid at the end of period $t$. If unable to pay the debt, the seller files for bankruptcy under Chapter 7 and the remaining asset is liquidated.

Let $w_t$ denote the seller’s working capital at the beginning of period $t$. The seller bankrupts in period $t$ if $w_t + p_t q_t < d_t$, i.e., the sum of current working capital and sales revenue cannot cover the debt payment. We do not allow late payment in the model. For the ease of exposition, we set the initial working capital $w_1 = 0$. This assumption does not change the results qualitatively, but brings notational convenience. Indeed, if $w_1 > 0$, it can be shown that the problem can be transformed to an equivalent asset selling problem with $w_1 = 0$ and reduced debt levels.

Let $V_t(x_t, w_t, p_t; d), t \leq m$, denote the equity value of the firm (i.e., the value accruing to the firm’s shareholders) at the beginning of period $t$, with inventory $x_t$, working capital $w_t$, and realized price $p_t$. The value function must incorporate the firm’s working capital and revenue-to-go as well as the debt obligations and bankruptcy risks, which are not reflected in standard asset selling problems.

To derive the value function, for $t \leq m$, let $q_t \overset{\text{def}}{=} (d_t - w_t)^+ / p_t$ be the minimum sales quantity needed to pay debt $d_t$ in period $t$. Suppose the seller survives through periods 1 to $m - 1$. In period $m$ (debt maturity), the seller can survive if and only if $q_m \leq \min(x_m, \ell)$. If this condition holds, the seller chooses $q_m \in [q_m, \min(x_m, \ell)]$ to pay off the debt and continue to sell the remaining asset (if any) from period $m + 1$ onward without debt obligation. Thus, for $t = m + 1, \ldots, T$, the optimal
selling policy can be determined by (1). If \( q_m > \min(x_m, \ell) \), the seller is unable to pay off the debt and it goes bankrupt. Thus, the value function in period \( m \) is defined as:

\[
V_m(x_m, w_m, p_m; d) = \begin{cases} 
\max_{q_m \leq q_m \leq \min(x_m, \ell)} p_m q_m + w_m - d_m + \rho E_m U_{m+1}(x_m - q_m, P_{m+1}), & \text{if } p_m \min(x_m, \ell) + w_m \geq d_m, \\
0, & \text{if } p_m \min(x_m, \ell) + w_m < d_m.
\end{cases}
\] (2)

Note that the survival condition \( p_m \min(x_m, \ell) + w_m \geq d_m \) in (2) is equivalent to \( q_m \leq \min(x_m, \ell) \).

In (2), we assume that the revenue from liquidation sale cannot cover the debt and the seller is shielded by limited liability. Thus, the equity value diminishes to zero upon bankruptcy, which is a common assumption in the literature (e.g., Xu and Birge 2004, Boyabatli and Toktay 2011, and Chod and Zhou 2013). This assumption automatically holds when \( m = T \) (recall that unsold asset at the end of period \( T \) has no value). When \( m < T \), we will extend the model in §5 to consider the liquidation process, which allows the seller to collect residual liquidation revenue after the debt is paid off. The analysis for the extended model confirms that key qualitative results continue to hold.

In each period \( t < m \), if \( q_t \leq \min(x_t, \ell) \), the seller sells \( q_t \in [q_t, \min(x_t, \ell)] \) and uses the revenue to pay the debt \( d_t \). The resulting working capital \( w_t + p_t q_t - d_t \) grows at its internal rate of return \( 1/\rho \). If \( q_t > \min(x_t, \ell) \), the seller fails to pay \( d_t \) and goes bankrupt. Thus, the dynamic program for \( t < m \) can be written as

\[
V_t(x_t, w_t, p_t; d) = \begin{cases} 
\max_{q_t \leq q_t \leq \min(x_t, \ell)} \rho E_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t - d_t), P_{t+1}; d), & \text{if } p_t \min(x_t, \ell) + w_t \geq d_t, \\
0, & \text{if } p_t \min(x_t, \ell) + w_t < d_t.
\end{cases}
\] (3)

Note from (3) that having enough working capital in period \( t \) (e.g., \( w_t \geq d_t - p_t \min(x_t, \ell) \)) only guarantees that bankruptcy does not occur in period \( t \).

Intuitively, if working capital \( w_t \) is high enough to cover the remaining debt payments, then the equity value should be linear in \( w_t \). This intuition is confirmed in part (i) of the following lemma. Proofs of all lemmas and propositions are included in the Online Appendix. Throughout this paper, monotonicity and convexity are used in their weak sense.

**Lemma 1** In period \( t \leq m \),

(i) if \( w_t \geq \sum_{i=t}^{m} \rho^{i-t} d_i \), then \( V_t(x_t, w_t, p_t; d) = U_t(x_t, p_t) + w_t - \sum_{i=t}^{m} \rho^{i-t} d_i \),

(ii) \( V_t(0, w_t, p_t; d) = \left(w_t - \sum_{i=t}^{m} \rho^{i-t} d_i\right)^+, \) and

(iii) \( V_t(x_t, w_t, p_t; d) \) is increasing in \( w_t \) and \( x_t \), but neither convex nor concave in general.
Lemma 1 suggests that a working capital level at or above \( \sum_{i=t}^{m} \rho^{i-t}d_i \) removes bankruptcy risk from period \( t \) onward and, therefore, the seller shall follow the revenue-maximizing policy determined in (1) from period \( t \) onward (Besbes et al. 2018 obtain similar result in a posted-price setting). Part (ii) provides a simple formula for the firm’s equity value when the asset is sold out before period \( t \leq m \). In general, the value function is neither convex nor concave; see examples in §3.3 and §4.2.

3. Asset Selling without Capacity Constraint

In this section, we consider the asset selling problem without capacity constraint, i.e., \( \ell = 1 \). We first analyze the debt-free asset-selling problem formulated in (1) and then analyze how the debt obligation and bankruptcy risk alter the optimal selling policy. To this end, we consider the case of a single debt payment at maturity \( m = T \) and demonstrate the limited liability effect. Then, we compare that to the case of a single debt payment at \( m < T \) and show the existence of the revenue loss effect. We then extend our study to general debt payment schedules.

3.1 Debt-Free Asset-Selling Policy

In the classical problem of selling a non-divisible asset under independently distributed prices (Karlin 1962), the optimal selling policy obeys the one-time stopping rule characterized by a reservation price (which can depend on \( t \)): The asset is sold whenever the price exceeds the reservation price. We generalize this result for the case of divisible asset and Markov price process.

For each period \( t \), we define \( R_{o_t} \) as the maximum expected revenue from selling all of the asset after period \( t \), discounted back to period \( t \):

\[
R_{o_t} = \rho \mathbb{E} \left[ U_{t+1}(1, P_{t+1}) \mid P_t \right].
\] (4)

We sometimes write \( R_{o_t}(P_t) \) to emphasize its dependence on \( P_t \).

**Proposition 1** (i) When there is no debt obligation (i.e., \( d = 0 \)), the optimal asset-selling policy is to sell the entire asset in period \( \tau^o \equiv \inf \{ t : P_t \geq R^o_t, t \in T \} \).

(ii) \( R^o_T = 0 \) and \( R^o_t = \rho \mathbb{E}_t \max \{ P_{t+1}, R^o_{t+1} \} \) for \( t = 1, \ldots, T - 1 \). The expected best selling price discounted to the present, \( \mathbb{E}_0 \rho^t R^o_t \), decreases in \( t \).

(iii) (Karlin 1962) If the prices \( P_t, t \in T \), are independently and identically distributed (i.i.d.), then \( R^o_t \) is deterministic and decreases in \( t \).

Proposition 1(i) shows that it is optimal to sell the asset all at once. Thus, \( R^o_t \) can be interpreted as the expected discounted best selling price after period \( t \), and the optimal selling time is the first time when \( P_t \) exceeds \( R^o_t \). The iterative relation \( R^o_t = \rho \mathbb{E}_t \max \{ P_{t+1}, R^o_{t+1} \} \) in part (ii) implies that the expected discounted best selling price is no lower than the maximum of the discounted expected
prices: \( R^o_t \geq \max\{\rho_t P_{t+1}, \ldots, \rho^{T-t}E_{tT}\} \), due to the Jensen’s inequality. Part (iii) shows that our results are consistent with the classical asset selling problem under i.i.d. prices.

In the optimal stopping rule in Proposition 1(i), although \( R^o_t \) appears to play the role of a reservation price, \( R^o_t \) in general varies with \( P_t \) due to the Markov price process, and thus \( R^o_t \) is not a predetermined reservation price. Prior research (see §1.1) typically assumes independent price distributions, in which case \( R^o_t \) has a deterministic value, which is the reservation price.

A natural question is under what conditions the optimal policy follows a threshold policy, i.e., there exists a reservation price (that can be predetermined) above which the asset should be sold. Proposition 2 answers this question.

Proposition 2 Suppose for every \( t = 1, \ldots, T - 1 \), (i) \( P_{t+1} \) stochastically increases in \( p_t \), i.e., \( F_{t+1}(x | p_t) \) decreases in \( p_t \), \( \forall x \geq 0 \), and (ii) \( E[P_{t+1} | p_t] \) increases in \( p_t \) at a rate no greater than 1. Then, for every \( t \), \( R^o_t(p_t) \) increases in \( p_t \) at a rate no greater than \( \rho \in (0, 1) \), and there exists a unique \( \hat{p}_t \) such that \( p_t \geq R^o_t(p_t) \) if and only if \( p_t \geq \hat{p}_t \). The optimal policy is to sell the entire asset in period \( \tau^o = \inf\{t : P_t \geq \hat{p}_t, t \in T\} \).

Thus far, we have shown that the structure of the optimal policy for selling a divisible asset under Markov price process is similar to that in the classical models. From this point onward, we refer to \( R^o_t \) as the critical price for the debt-free case. Next, we explore how the introduction of debt obligation affects the optimal policy, focusing on the changes in the critical prices. Comparing critical prices is analytically tractable and yields the same insights as comparing the implicit reservation prices, because a higher critical price corresponds to a higher reservation price.

3.2 Single Debt Payment at \( m = T \)

When the debt requires a single payment at the end of the horizon, i.e., \( m = T \), bankruptcy can occur only in period \( T \). We will show that the asset is still sold all at once, but the debt obligation affects the timing of the sale, which can be attributed to the limited liability effect.

Lemma 2 Suppose the debt obligation requires a single payment at the end of period \( T \), i.e., \( d_t = 0 \) for \( t = 1, \ldots, T - 1 \) and \( d_T > 0 \). Then, for \( t \in T \),

(i) \( V_t(x_t, w_t, p_t; d) \) is jointly convex in \( (x_t, w_t) \);

(ii) \( V_t(x_t, w_t, p_t; d) \geq U_t(x_t, p_t) + w_t - \rho^{T-t}d_T \), with equality holding if \( w_t \geq \rho^{T-t}d_T \).

The convexity in Lemma 2(i) is essential for the one-time stopping rule to continue to hold, which will be formalized in Proposition 3. The convexity of the value function implies that inventory has increasing marginal value. When the entire inventory can be sold in one period, a higher inventory level reduces bankruptcy probability and thus enhances the marginal value of inventory. (In §4.1
when selling capacity exists, inventory exhibits diminishing marginal value.)

In Lemma 2 (ii), if \( w_t \geq \rho^{T-t}d_T \), i.e., the working capital is sufficient to cover the debt payment, the seller can simply follow the revenue-maximization strategy in Proposition 1 from period \( t \) onward and obtain an expected value of \( U_t(x_t, p_t) + w_t - \rho^{T-t}d_T \), which is consistent with Lemma 1(i). However, if \( w_t < \rho^{T-t}d_T \) (bankruptcy risk exists), part (ii) shows that the revenue maximization strategy is not necessarily optimal because the limited liability protects the firm’s equity value from dropping below zero, resulting in \( V_t(x_t, w_t, p_t; d) > U_t(x_t, p_t) + w_t - \rho^{T-t}d_T \).

The next proposition characterizes the optimal policy and compares it with the debt-free case.

**Proposition 3** Suppose the debt obligation requires a single payment at the end of period \( T \), i.e., \( d_t = 0 \) for \( t = 1, \ldots, T-1 \) and \( d_T > 0 \). Then,

(i) There exists a series of critical prices \( \{R_t : t \in \mathcal{T}\} \) with \( R_T = d_T \) and \( R_t = \rho E_t \max\{P_{t+1}, R_{t+1}\} \), such that the seller should sell the entire asset in period \( \tau = \inf\{t : P_t \geq R_t, t \in \mathcal{T}\} \), which is an optimal stopping time. Upon selling, the revenue will ensure debt payment in period \( T \). If \( P_t < R_t \) for all \( t \in \mathcal{T} \) (i.e., \( \tau = \infty \)), the seller goes bankrupt at the end of period \( T \).

(ii) When the debt \( d_T \) increases, the critical price \( R_t \) increases almost surely and the probability of bankruptcy increases. However, the stopping time \( \tau \) also increases almost surely. In particular, \( R_t \geq R_t^0 \) and \( \tau \geq \tau^0 \).

(iii) The expected critical price discounted to the present, \( E_0 \rho^t R_t \), decreases in \( t \). If prices \( P_t, t \in \mathcal{T} \), are i.i.d., then \( R_t \) is the deterministic reservation price, and there exists a debt level \( \bar{d} \), such that \( R_t \) is constant over time for \( d_T = \bar{d} \), \( R_t \) decreases in \( t \) for \( d_T < \bar{d} \), and \( R_t \) increases in \( t \) for \( d_T > \bar{d} \).

Proposition 3(i) confirms that the optimal policy under a single debt payment at \( m = T \) continues to follow the one-time stopping rule. Furthermore, the relation \( R_{t-1} = \rho E \max\{P_t, R_t\} \) holds at all debt levels, including the zero-debt case in Proposition 1.

Importantly, Proposition 3(ii) reveals that the debt obligation delays the optimal selling time compared to the debt-free case, and a higher debt results in a longer delay in selling the asset. Besbes et al. (2018) find that sales are delayed due to higher posted prices, whereas in our setting, the delay is due to the firm’s decision to wait for better prices. Intuitively, the downside risk of waiting is reduced due to the firm’s limited liability for the debt, whereas waiting keeps the seller open to the upside potential. Consider a situation in period \( t \) when the seller decides whether or not to sell the asset. A debt-free seller can earn \( p_t \) by selling now, or earn an expected value of \( \rho E_t U_{t+1}(1, P_{t+1}) \) by waiting. With debt obligation, selling now brings a net value of \( p_t - \rho^{T-t}d_T \), while waiting brings an expected value of \( \rho E_t V_{t+1}(1, 0, P_{t+1}; d) \), higher than \( \rho E_t U_{t+1}(1, P_{t+1}) - \rho^{T-t}d_T \) due to Lemma 2(ii), which means that the seller has more incentive to wait than in a debt-free situation.

Proposition 3(iii) highlights how the debt obligation changes the critical prices (for the case of
i.i.d. price. In contrast to the no-debt case in Proposition 1(iii), the critical price can either increase or decrease in $t$. At a low debt level, the critical price decreases in $t$, because with low bankruptcy risk, the main driver for asset-selling decision is still to maximize sales revenue. At a high debt level, the main driver for selling the asset is to cover the debt payment, that is, the selling price in period $t$ must be at least $\rho^{T-t}d_T$ (which increases in $t$) to cover the debt, which renders the reservation price $R_t$ increasing over time, as confirmed in Proposition 3(iii).

Figure 1 illustrates the results in Proposition 3. Panel (a) shows that the reservation prices in all periods increase in the debt level $d_T$ (proved in Proposition 3(ii)) and that there exists a threshold debt level $\bar{d}$, above (below) which $R_t$ increases (decreases) in $t$, as shown in Proposition 3(iii). Furthermore, observe that the difference between the reservation price under debt and the debt-free reservation price increases over time. This result echoes the increasing distortion of posted prices in Besbes et al. (2018), but contrasting results will be discussed in the next sections.

Figure 1: Optimal asset-selling policy under single debt payment: $m = T = 10$

$P_t$’s are i.i.d. lognormal and $\log(P_t) \sim \mathcal{N}(3, 0.5)$, discount factor $\rho = 0.98$

Panel (a) shows the cumulative distribution of $\tau$, which is also the expected amount of asset sold by period $t$, because the entire asset is sold together and $\Pr\{\tau \leq t\} = 1 \cdot \Pr\{\tau \leq t\} + 0 \cdot \Pr\{\tau > t\}$. As debt $d_T$ increases, $\Pr\{\tau \leq t\}$ decreases at every $t$, implying that the seller delays selling the asset.

3.3 Single Debt Payment at $m < T$

When the debt matures at the end of the planning horizon (i.e., $m = T$), the revenue loss effect (described in Section 1.2) does not exist because any remaining inventory is worthless beyond the horizon. The optimal decision for $m < T$ is driven by both limited liability effect and revenue loss
effect. If the revenue loss effect dominates, it is optimal to sell a portion of the asset to pay off the debt and remove the bankruptcy risk, so that the seller can sell the remaining asset following the revenue maximization policy. If the limited liability effect dominates, selling the entire asset at once is still optimal and the selling time is delayed compared to the no-debt case.

Moreover, the trade-off between the limited liability effect and the revenue loss effect depends on the debt level. We will show that there exists a threshold debt level, such that if the debt is above (below) this threshold, the limited liability (revenue loss) effect dominates. In preparation, we first prove the properties of the value function.

**Lemma 3** Suppose the debt obligation requires a single payment $d_m$ at the end of period $m < T$. Then, for $t \leq m$, $V_t(x_t, w_t, p_t; d)$ is convex in $(x_t, w_t, d_m)$ in region $w_t \leq \rho^{m-t}d_m$, and is linear in $(x_t, w_t, d_m)$ in region $w_t \geq \rho^{m-t}d_m$. $V_t(x_t, w_t, p_t; d)$ is continuous in $(x_t, w_t, d_m)$.

Lemma 3 establishes the convexity of $V_t(x_t, w_t, p_t; d)$ for two disjoint regions $w_t \leq \rho^{m-t}d_m$ and $w_t \geq \rho^{m-t}d_m$, which leads to a different optimal policy structure formalized in Proposition 4. Lemma 3 includes $d_m$ in the convexity, which is needed for studying the effect of debt.

Figure 2: Value function $V_m(x_m, w_m, p_m; d)$, $d = (0, \ldots, 0, d_m)$

Region I: working capital $w_m$ can cover the debt $d_m$.

Region II: $w_m$ is insufficient to cover the debt, and the seller must sell $q_m = \frac{d_m - w_m}{p_m}$ to pay off the debt.

Region III: $q_m > x_m$ (or $p_m x_m + w_m < d_m$), the firm is unable to pay off the debt and goes bankrupt.

Figure 2 shows the value function in period $m$, with explicit expressions derived in the proof of Lemma 3. Note that the value function is convex in $(x_m, w_m)$ across regions II and III, but it is concave across regions I and II when $p_m < R_m^\circ$ (in Region II the value function increases in $w_m$ at slope $\frac{R_m^\circ}{p_m} > 1$, whereas in Region I it increases in $w_m$ at unit slope). Backward induction through (3) preserves the convexity of the value function across regions II and III ($w_t < \rho^{m-t}d_m$) and linearity.
in region I \((w_t > \rho^{m-t}d_m)\), but the value function is not convex in general.

Before formally presenting the structure of optimal policy, it is useful to understand the effects of bankruptcy on the firm’s equity value. Upon bankruptcy, the seller loses the future revenue from selling the remaining asset. This revenue loss effect decreases the expected equity value. On the other hand, limited liability protects the equity value from dropping below zero, which enhances the expected equity value. When \(m < T\), both effects exist and the composite effect on the firm’s value can be represented by \(\Delta_t\), defined as

\[
\Delta_t \overset{\text{def}}{=} V_t(1, 0, p_t; d) - (U_t(1, P_t) - \rho^{m-t}d_m), \quad t = 1, \ldots, m + 1,
\]

where we set \(V_{m+1}(1, 0, P_{m+1}; d) \overset{\text{def}}{=} 0\). We define it up to period \(m + 1\) because the selling decisions up to period \(m\) are the focal point of analysis.

Recall Lemma 2(ii) suggests that \(V_t(1, 0, p_t; d) \geq U_t(1, p_t) - \rho^{T-t}d_T\) if \(m = T\), because a feasible policy is to capture the maximum expected revenue \(U_t(1, p_t)\). However, with debt maturity \(m < T\), the inequality \(V_t(1, 0, p_t; d) \geq U_t(1, p_t) - \rho^{m-t}d_m\) may not hold, because the seller may not be able to capture the maximum expected revenue \(U_t(1, p_t)\) due to possibility of bankruptcy. Therefore, \(\Delta_t\) in (5) is exactly the value of limited liability net the value loss due to the bankruptcy risk. When \(\Delta_t > 0\), the limited liability effect is stronger than the revenue loss effect; when \(\Delta_t < 0\), the opposite is true. The joint effect drives the seller to adopt a new selling strategy described next.

**Proposition 4** Suppose the debt obligation requires a single payment \(d_m\) at the end of period \(m < T\).

(i) There exist two series of critical prices \(\{(R^{(1)}_t, R^{(2)}_t) : 1 \leq t \leq m\}\) with \(R^{(1)}_t \leq R^{(2)}_t\), \(1 \leq t \leq m\), such that the seller should make the first sale in period \(\tau = \inf\{t : P_t \geq R^{(1)}_t, 1 \leq t \leq m\}\), which is an optimal stopping time, and

- If \(\tau \leq m\) and \(p_t \geq R^{(2)}_\tau\), then it is optimal to sell the entire asset in period \(\tau\);
- If \(\tau \leq m\) and \(p_t < R^{(2)}_\tau\), then it is optimal to sell \(q_t = \rho^{m-\tau}d_m/p_t\) in period \(\tau\), and sell the remaining asset in period \(\tau' = \inf\{t : P_t \geq R^{(1)}_\tau, \tau < t \leq T\}\), where \(R^{(1)}_\tau\) is the critical price for the no-debt case, as defined in (4);
- If \(p_t < R^{(1)}_t\), do not sell. If \(p_t < R^{(1)}_t\) for all \(t \leq m\) (i.e., \(\tau = \infty\)), then the seller bankrupts at the end of period \(m\).

(ii) In period \(t \leq m\), if \(E_t\Delta_{t+1} < 0\), then \(R^{(1)}_t < R^{(2)}_t = R^{(1)}_\tau\). If \(E_t\Delta_{t+1} \geq 0\), then \(R^{(1)}_t = R^{(2)}_t \geq R^{(1)}_\tau\). In particular, if \(E_t\Delta_{t+1} = 0\), then \(R^{(1)}_t = R^{(2)}_t = R^{(1)}_\tau\).

Proposition 4(i) prescribes that the optimal policy for the first sale is a control band policy (illustrated in Figure 3): if the price is sufficiently high (above \(R^{(2)}_t\)), sell the entire asset; if the price is very low (below \(R^{(1)}_t\)), sell nothing; if the price falls in between the two critical prices, it is optimal.
Figure 3: Optimal asset-selling policy under single debt payment: $T = 10$, $m = 7$

$P_t$’s are i.i.d. lognormal and $\log(P_t) \sim \mathcal{N}(3, 0.5)$, $\rho = 0.98$, $d_m = 10$

![Graph showing the optimal selling policy](image)

to sell part of the asset to secure debt payment, i.e., sell $q_\tau = \rho^{m-\tau} d_m / p_\tau$ to earn $\rho^{m-\tau} d_m$ which will cover the debt $d_m$. Thus, in this middle belt, a higher price $p_\tau$ leads to (counter-intuitively) a lower selling quantity $q_\tau$, which is driven by the strategy of generating revenue to exactly cover the debt payment.

Part (ii) of the proposition further illuminates that, depending on which of the two forces is stronger, the critical prices and the width of the control band are significantly different. When the revenue loss effect is stronger ($E_t \Delta_{t+1} < 0$), the seller is seriously concerned about the possibility of losing future revenue due to a bankruptcy. Thus, the seller has an incentive to sell part of the asset early to secure the debt payment. This partial sale, if occurs, will be earlier than the sale in the no-debt case, because the critical price $R_t^{(1)}$ is below $R_t^o$, which is the critical price for the no-debt case defined in (4). After this partial sale removes the bankruptcy risk, the seller will sell the remaining asset using the same policy as in the no-debt case. Therefore, no sale will be delayed compared to the debt-free case. This strategy is in sharp contrast with the delayed selling decision in Proposition 3 when the debt matures in period $T$.

On the other hand, when the limited liability effect is stronger ($E_t \Delta_{t+1} > 0$), the seller does not need to worry about the revenue loss effect as much. Consequently, the partial selling region disappears. But, as in the $m = T$ case, bankruptcy shields the seller from the downside risk, which delays the sales compared to the no-debt case ($R_t^{(1)} = R_t^{(2)} \geq R_t^o$).

Proposition 4 proves that the sales should be expedited (delayed) if $E_t \Delta_{t+1} < 0 (> 0)$, i.e., the revenue loss effect is stronger (weaker) than the limited liability effect. A natural question is what drives the relative magnitude of these two effects. One may expect that $E_t \Delta_{t+1}$ is monotone in the
debt level $d_m$, since a higher debt leads to more benefit of limited liability. It turns out that $E_t \Delta_{t+1}$ is not monotone and relates to $d_m$ in a manner depicted in Figure 4.

Figure 4: Relationship between $E_t \Delta_{t+1}$ and debt level

When $d_m = 0$, Lemma 1(i) implies that $V_{t+1}(1, 0, P_{t+1}; 0) = U_{t+1}(1, P_{t+1})$ for $t < m$, and thus $E_t \Delta_{t+1} = 0$. Figure 4 illustrates that $E_t \Delta_{t+1}$ decreases in $d_m$ first, which is proved next.

**Lemma 4** For all $t < m$, we have $\lim_{d_m \to 0^+} \frac{\partial E_t \Delta_{t+1}}{\partial d_m} \leq 0$. Furthermore, the inequality is strict if $\Pr\{P_t < R^o_t\} > 0$ for all $t \leq m$.

In Lemma 4, the condition $\Pr\{P_t < R^o_t\} > 0$ for all $t < m$ is satisfied by most price processes. In particular, the condition is satisfied if the support of the price distribution includes low price levels. Thus, $E_t \Delta_{t+1}$ strictly decreases in $d_m$ for small $d_m$, as shown in Figure 4. Therefore, for small debt levels, $E_t \Delta_{t+1} < 0$, implying that the revenue loss effect is more pronounced than the limited liability effect.

Figure 4 shows that $E_t \Delta_{t+1}$ is convex in $d_m$ because $V_t(1, 0, P_t; d)$ is convex in $d_m$ for all $d_m \geq 0$ (proved in Lemma 3). In fact, $E_t \Delta_{t+1}$ decreases in $d_m$ first and then increases above zero. Therefore, there exists a threshold debt level, denoted as $D_t$ and also marked in Figure 4, such that the revenue loss effect dominates when $d_m \in (0, D_t)$, while the limited liability effect dominates when $d_m > D_t$. We formally state this result in the following proposition.

**Proposition 5** Suppose the debt obligation requires a single payment $d_m$ at the end of period $m < T$, and $\Pr\{P_t < R^o_t\} > 0$ for all $t \leq m$.

(i) In period $t \leq m$, there exists a unique threshold debt level $D_t > 0$ (which may depend on $P_t$), such that $E_t \Delta_{t+1} > 0$ and strictly increases in $d_m$ if $d_m > D_t$, and $E_t \Delta_{t+1} < 0$ if $d_m \in (0, D_t)$.

(ii) If $d_m \geq D_t$, then $R^{(1)}_t = R^{(2)}_t \geq R^o_t$, and $R^{(1)}_t$ and $R^{(2)}_t$ increase in $d_m$. If $d_m \in (0, D_t)$, then $R^{(1)}_t$ increases in $d_m$ and $R^{(2)}_t = R^o_t$ is invariant with respect to $d_m$. The optimal first-selling time $\tau$
(defined in Proposition 4) increases in \( d_m \) for \( d_m > 0 \).

(iii) If prices \( P_t, t \in \mathcal{T} \), are independent (not necessarily i.i.d.), then \( R_t^{(1)} \) and \( R_t^{(2)} \) are deterministic, and the threshold debt level is a constant: \( D_t \equiv R_m^o \) for \( 1 \leq t \leq m \), where \( R_m^o \) is the critical price in period \( m \) for the no-debt case (defined in (4)).

If \( d_m \geq R_m^o \), then \( R_t^{(1)} = R_t^{(2)} \geq R_t^o, 1 \leq t \leq m \), and \( \tau \geq \tau^o \), where equalities hold if \( d_m = R_m^o \).

If \( d_m < R_m^o \), then \( R_t^{(1)} < R_t^{(2)} = R_t^o, 1 \leq t \leq m \), and \( \tau \leq \tau^o \).

Parts (i) and (ii) imply that, if the leverage is large \((d_m > D_t)\), then the limited liability effect dominates and drives the seller’s optimal policy—the seller should delay sales (i.e., the critical prices are higher than the no-debt case) and the seller will either sell the entire asset or sell nothing in each period; see Figure 5, where \( R_t^{(1)} = R_t^{(2)} \) for \( d_m \geq D_t \). The critical prices increase in the debt level, which means that the seller will delay selling assets even further.

Figure 5: Effect of debt level on critical prices: \( T = 10, m = 7 \)

\( P_t \)'s are i.i.d. lognormal and \( \log(P_t) \sim \mathcal{N}(3, 0.5), \rho = 0.98 \), showing critical prices in period \( t = 6 \)

If the leverage is small \((d_m < D_t)\), the revenue loss effect is stronger than the limited liability effect. The revenue loss effect incentivizes the seller to sell a portion of asset to pay off the debt so that the firm becomes free of the constraint, as illustrated in Figure 5. As the debt level \( d_m \) decreases from \( D_t \), \( R_t^{(1)} \) decreases (while \( R_t^{(2)} \) remains constant), hence the price region for selling a portion of asset expands. This implies that the seller is more likely to sell a portion of the asset earlier for smaller debt than larger debt, contradicting to the intuition that the larger debt will force the seller to sell prematurely early. It is a smaller debt that incentivizes early sales.

The above results are in stark contrast with the upward (posted) price distortion found in Besbes et al. (2018). When the revenue loss effect dominates, it reduces the reservation price below the
revenue-maximizing reservation price. In a special situation when \( d_m = D_t, R_t^{(1)} = R_t^{(2)} = R_o \), which means that the optimal policy under the debt coincides with the revenue-maximizing policy. This is because the incentive to delay sales due to the limited liability effect balances with the incentive to expedite sales due to the revenue loss effect. We note that revenue loss effect can also exist in the posted price setting: A model similar to the debt amortization model in Besbes et al. (2018) but including revenue loss after bankruptcy can also produce downward price distortion.

Note that \( D_t \) generally depends on \( P_t \), while the debt level \( d_m \) is predetermined in period 0. Hence, it is possible that in some periods there are two distinct critical prices \( (R_t^{(1)} < R_t^{(2)}) \) while in some other periods there is only one critical price \( (R_t^{(1)} = R_t^{(2)}) \). Interestingly, when prices are independently (not necessarily identically) distributed, \( D_t \) becomes a constant and equal to \( R_o \), as stated in Proposition 5(iii). Consequently, the optimal policy is characterized by either two distinct critical prices (when \( d_m < R_o \)) or a single critical price (when \( d_m \geq R_o \)).

### 3.4 General Debt Payment

We now generalize the analysis to settings where the debt financing agreement requires multiple payments. Specifically, the debt obligation requires \( k \) installments paid in periods \( m_1, m_2, \ldots, m_k \) \((1 \leq m_1 < \cdots < m_k \leq T)\), where \( m_k \equiv m \) is the last payment period. That is, the debt payment schedule \( d \) has \( d_t > 0 \), for \( t \in \{m_1, \ldots, m_k\} \), and \( d_t = 0 \) otherwise.

We show that, if the seller makes a sale in any period, the seller should sell either all remaining asset or an amount that exactly covers the debt payments required for the current and next several consecutive periods. We prove this optimal policy structure for the first sale in Proposition 6 and then prove the structural equivalence between the first sale and future sales in Proposition 7.

As before, let \( \tau \) denote the time of the first sale, taking values in \( \{1, \ldots, m_1, \infty\} \). Note that the seller must make the first sale on or before period \( m_1 \) to avoid bankruptcy.

**Proposition 6** Suppose the debt obligation requires \( k \) installments paid in periods \( m_1, m_2, \ldots, m_k \) \((1 \leq m_1 < \cdots < m_k \leq T)\).

(i) There exists a series of critical prices \( \{R_t^\dagger : 1 \leq t \leq m_1\} \), such that the first selling time \( \tau = \inf\{t : P_t \geq R_t^\dagger, 1 \leq t \leq m_1\} \). If \( P_t < R_t^\dagger \) for all \( t \leq m_1 \) (i.e., \( \tau = \infty \)), then the seller bankrupts at the end of period \( m_1 \).

(ii) If \( \tau \leq m_1 \), the optimal quantity to sell is \( q^*_\tau \in \{1\} \cup \left\{ \sum_{i=1}^j \rho^{m_i-\tau} d_{m_i} / p_\tau : j = 1, \ldots, k \right\} \).

Proposition 6 prescribes that the first sale is triggered by a critical price similar to that for the case of a single debt payment. When the selling opportunity occurs, the seller should either sell the entire asset or sell an amount of asset that generates a revenue of \( \sum_{i=1}^j \rho^{m_i-\tau} d_{m_i} \) to secure exactly the first \( j \) installments.
Proposition 7 Suppose the first sale is made in period $\tau \leq m_1$ to pay off exactly $j$ installments. Then, the remaining asset, $h \equiv 1 - \sum_{i=1}^{j} \rho^{m_i - \tau} d_{m_i} / p_{\tau}$, should be sold as follows:

(i) If $j = k$ (all debt is paid off), sell $h$ using the debt-free policy in Proposition 1;

(ii) If $j < k$, sell $h$ by solving an asset-selling problem with $T - \tau$ periods and $k - j$ remaining debt payments. The size of the remaining asset is scaled to one and the asset price is scaled to $\tilde{P}_t = hP_t$; the initial wealth of this $(T - \tau)$-period problem is zero.

Proposition 7 effectively decomposes the original problem into a sequence of structurally identical asset selling problems, each of which covers a certain number of installments.

Under a single debt payment, Proposition 4 shows that the optimal policy is characterized by a control band. With multiple debt payments, one may conjecture two opposite forces influencing the optimal policy as the price changes. As $p_t$ increases, the revenue earned from selling a given quantity increases. As the price becomes more favorable to the seller, this force will induce selling more and earn greater revenue. Doing so will enable the seller to raise more working capital (for multiple debt payments) and give more flexibility in future sales as the seller becomes less constrained by the payment schedule. On the other hand, Proposition 6(ii) implies that the optimal sales quantity is not a continuous function in price. In fact, the sales quantity is from a finite set of candidates, $q^*_t = \sum_{i=1}^{j} \rho^{m_i - t} d_{m_i} / p_t$, each representing the amount that is equal to a partial sum of current and future payments. As the price increases, it suffices to sell less to cover the same debt payments (i.e., the quantity is an inverse function of $p_t$) and keep more assets to wait for a higher price in the future. Consequently, depending on which of the two forces is stronger, the number of installments that the seller secures through a partial sale can non-monotonically change in price.

In general, characterizing the complete structure of optimal policy is difficult. This is, in part, because the value function is only convex in $q$ within $\sum_{i=1}^{j} \rho^{m_i - t} d_{m_i} / p_t$ and $\sum_{i=1}^{j+1} \rho^{m_i - t} d_{m_i} / p_t$. As $p_t$ increases, the amount of asset that need to be sold decreases non-linearly in $p_t$. In order to evaluate the exact impact of a price change, we need to evaluate how multiple convex functions change in $p_t$ at extreme points. This depends on payment structure, discount factor, working capital level, and, most importantly, price process. Numerically, we find that the impact of limited liability and revenue loss upon bankruptcy on the optimal selling policy is consistent with the previous finding. We present the numerical results together with the capacitated selling case in §4.2.3.

4. Asset Selling with Capacity Constraint

In this section, we examine the asset-selling policies under capacity constraint, i.e., the maximum amount sold in one period is limited by $\ell < 1$. We show that when the debt requires a single payment at the end of the horizon, the asset selling problem is equivalent to the problem of selling multiple
non-divisible units. We characterize how the debt affects optimal policies and compare them with the policies in the previous section and in the literature.

4.1 Debt-Free Asset-Selling Policy

When there is no debt, in deciding the sales quantity, the seller balances the revenue in the current period with the expected value of asset in the future. Proposition 8 shows the optimal policy.

**Proposition 8** Suppose the selling capacity \( \ell < 1 \) and there is no debt. Then, it is optimal to divide the asset into \( n = \lceil \frac{1}{\ell} \rceil \) pieces,\(^2\) with \( n - 1 \) pieces of size \( \ell \) and a remainder of size \( r \equiv 1 - (n - 1)\ell \). The optimal sequential selling policy is characterized by critical prices \( \{ R_{t,i}^o : t \in T, i = 1, \ldots, n \} \) with \( R_{t,i}^o \) increasing in \( i \) and representing the critical price for the \( i \)-th sale.

(i) For given \( i \in \{1, \ldots, n\} \), suppose that the seller has sold \( i - 1 \) times before period \( t \). In period \( t \),

(a) If the remainder \( r \) has been previously sold, it is optimal to sell \( \ell \) if \( P_t \geq R_{t,i}^o \) and sell nothing otherwise;

(b) If the remainder \( r \) has not been previously sold, it is optimal to sell \( \ell \) if \( P_t \geq R_{t,i}^o + 1 \), sell \( r \) if \( R_{t,i}^o \leq P_t < R_{t,i}^o + 1 \), and sell nothing otherwise.

(ii) For \( i = 1, \ldots, n-1 \), the critical prices satisfy \( R_{T,i}^o = 0 \) and \( R_{t,i}^o = \rho E_t \text{median}\{P_{t+1}, R_{t+1,i}^o, R_{t+1,i+1}^o\} \) for \( t = 1, \ldots, T - 1 \). Furthermore, \( R_{t,n}^o = R_t^o \) for all \( t \), i.e., the critical price for the last sale is the same as the critical price for the case without capacity constraint.

Proposition 8(i) reveals that the asset selling problem with capacity constraint is equivalent to selling \( n \) non-divisible assets, where \( n \) is the least number of sales the seller must make to sell the entire asset. The optimal policy features a sequence of critical prices that characterize when, and how much of the asset is sold for each of the \( n \) sales. In addition, when the seller has not sold the remainder \( (r) \), a control band with two critical prices are in play: If the price is moderately favorable, then sell the remainder; if the price is more favorable, sell the maximum quantity \( \ell \).

Proposition 8(ii) detail the properties of the critical prices. Note that because \( R_{t,n}^o = R_t^o \), it satisfies the relation proved in Proposition 1: \( R_{t,n}^o = \rho E_t \max\{P_{t+1}, R_{t+1,n}^o\} \), which means that \( R_{t,n}^o \) is the expected best selling price after period \( t \). The median relation in part (ii) can be written as \( R_{t,i}^o = \rho E_t \min\{\max\{P_{t+1}, R_{t+1,i}^o\}, R_{t+1,i+1}^o\} \), which means that \( R_{t,i}^o \) is the expected \((n+1-i)\)-th best selling price after \( t \). Indeed, the first sale is triggered by \( P_t \geq R_{t,1}^o \), i.e., the current price exceeds the expected \( n \)-th best selling price in the future.

Note that, if prices are i.i.d., the above problem of selling \( n \) portions of the asset is essentially a stochastic assignment problem first studied by Derman et al. (1975). We generalize their results to Markov price process and further derive the relations between critical prices in the simplest form.

\(^2\) \([x]\) is the ceiling function that gives the smallest integer greater than or equal to \( x \).
This generation is possible because the value function \( \rho \mathbb{E}_t U_{t+1}(x_{t+1}, P_{t+1}) \) is concave and piecewise linear in \( x_{t+1} \), and the slopes for the \( n \) segments \((0, \ell], (\ell, 2\ell], \ldots, ((n-2)\ell, (n-1)\ell], \) and \(((n-1)\ell, 1] \) are \( R^0_{t,n} \geq R^0_{t,n-1} \geq \cdots \geq R^0_{t,1} \), respectively (see the proof of Proposition 8).

Figure 6: Critical prices under selling capacity \( \ell = 0.2 \), without debt

\( P_t \)'s are i.i.d. and \( \log(P_t) \sim \mathcal{N}(3, 0.5), \rho = 0.98 \). \( R_{t,i} \) is the critical price for the \( i \)-th sale when prices are i.i.d., \( R_{t,i} \)'s are deterministic reservation prices, illustrated in Figure 6. If no sale occurs in a period, the reservation price decreases in the next period, whereas if sale occurs in a period, the reservation price increases (see the sample path of reservation price in Figure 6). This resembles the posted price changes in Gallego and van Ryzin (1994). The key difference is that posted prices are no lower than the one-period revenue-maximizing price and there may be unsold items at the end of the horizon, whereas the reservation price drops to zero whenever the number of remaining periods is equal to the number of unsold units.

4.2 Asset Selling Under Debt and Capacity Constraint

As we did in §3, we examine the case with a single payment at the end of planning horizon \( (m = T) \), and extend our study to a single payment at \( m < T \) as well as general cases. Because capacity constraint introduces additional analytical difficulty, the case with general debt schedule is not tractable. However, our numerical analysis will demonstrate that even under capacity constraints, the limited liability effect and the revenue loss effect remain to drive the optimal asset-selling policy.

4.2.1 Single Debt Payment at \( m = T \)

Parallel to §3.2, we analyze the selling policy when the debt requires a single payment at \( m = T \). Lemma 5 generalizes Lemma 2, and Proposition 9 characterizes the optimal policy.

Lemma 5 Suppose \( d_t = 0 \) for \( t = 1, \ldots, T - 1 \) and \( d_T > 0 \). Then, for \( t \in T \), \( V_t(x_t, w_t, p_t; d) \) is convex in \((x_t, w_t)\) in each of the \( n \) regions: \( x_t \in [(j - 1)\ell, \min\{j\ell, 1]\}, j = 1, 2, \ldots, n = \left\lceil \frac{1}{\ell} \right\rceil \).
Figure 7 shows the equity value as a function of inventory in the last two periods under selling capacity $\ell = 1/3$. The piecewise convexity is evident. In addition, notice that $V_{T-1}(\frac{1}{3}) - V_{T-1}(0) \leq V_{T-1}(\frac{2}{3}) - V_{T-1}(\frac{1}{3})$ and $V_{T-1}(\frac{2}{3}) - V_{T-1}(\frac{1}{3}) \geq V_{T-1}(1) - V_{T-1}(\frac{2}{3})$, which means that inventories in discrete units of size $\frac{1}{3}$ may exhibit increasing marginal values (due to limited liability) or decreasing marginal values (due to limited capacity).

**Figure 7:** Piecewise convexity of the value function

\[ \ell = 1/3, \ P_t's \ are \ i.i.d. \ and \ \log(P_t) \sim N(3, 0.5), \ \rho = 1 \]

Proposition 9  Suppose $d_t = 0$ for $t = 1, \ldots, T-1$ and $d_T > 0$. Then, it is optimal to divide the asset into $n = \lceil \frac{T}{\ell} \rceil$ pieces, with $n-1$ pieces of size $\ell$ and a remainder of size $r \equiv 1 - (n-1)\ell$. There exists a series of critical prices $\{R^c_t : t \in T\}$ such that

(i) It is optimal to make the first sale in period $\tau^c \equiv \inf\{t : P_t \geq R^c_t, t \in T\}$. If $P_t < R^c_t$ for all $t \in T$ (i.e., $\tau^c = \infty$), then the seller bankrupts at the end of period $T$.

(ii) If $\tau^c < T$, then in period $\tau^c + 1$, the seller faces a problem that is structurally identical to the original problem, with $T - \tau^c$ periods and a reduced debt $d'_T = (d_T - q^*_\tau p_{\tau^c}/\rho^{T-\tau^c})^+$, where $q^*_\tau \in \{\ell, r\}$ is the optimal first sales quantity.

Proposition 9 shows that the seller divides the asset into multiples of $\ell$ (plus a remainder) for sale. The division is exactly the same as in the no-debt case. The first sale occurs when the price exceeds a critical price $R^c_t$. We next examine how the debt level affects this critical price.

Besbes et al. (2018) find that the upward (posted) price distortion is increasing over time. In the absence of selling capacity, we also find that (critical) price distortion is increasing over time if $m = T$ (see Figure 1(a)). However, in the presence of selling capacity, the distortions exhibit intricate patterns. Consider a case with capacity $\ell = 0.5$, under which the asset is divided into two halves for sale. Figure 8(a) shows that, only at low debt levels, the distortion is increasing over
Figure 8: Optimal policy for the first sale with capacity $\ell = 0.5$

$P_t$’s are i.i.d. lognormal and $\log(P_t) \sim N(3, 0.5)$, $\rho = 0.98$, $m = T = 10$

(a) Critical price ($R^c_1$) for the first sale

(b) Critical price ($R^c_1$) for the first sale

(c) Selling strategy in period $t = 1$

The above pattern can be explained by understanding two distinct forces on price distortion. First, as debt maturity is nearer, the limited liability has a stronger upward effect on the critical price. This force leads to increasing distortion over time. Second, because the selling capacity prevents the asset from being sold all in one period, when the selling time is running out and no sale has yet occurred, there is a downward pressure on the critical price. (Indeed, the critical price drops to zero in period 9 to ensure the first sale to occur.) Under a high debt level, the second force becomes particularly strong when the first force tries to raise the critical price. The net effect is reduced critical price distortion over time.
We now examine how the debt is covered. If the revenue from the first sale covers the debt, the second sale will follow the debt-free selling policy in Proposition 1, otherwise the second sale will follow Proposition 3. Figure 8(c) shows that under a relatively small debt ($d_T < \hat{d}_T$ in the figure), the seller may sell nothing even if selling some asset can cover the debt. Under a relatively large debt ($d_T > \hat{d}_T$), however, the firm may sell part of the asset even if it is insufficient to cover the debt. Besbes et al. (2018) find that the seller uses a single sale to cover a small debt while uses multiple sales to cover a large debt. Our result differs in that for any given debt, it is always possible to cover the debt with one sale as long as the realized price is high enough.

Figure 9: Impact of selling capacity on bankruptcy probability and expected sales

$P_t$'s are i.i.d. lognormal and $\log(P_t) \sim N(3, 0.5), \rho = 0.98, m = T = 10$

(a) Probability of bankruptcy at $T$

(b) Expected amount of asset sold by $t$

Finally, we examine the impact of capacity constraint on bankruptcy risk. The conventional wisdom is that an operationally constrained firm has a higher default risk. Figure 9(a) shows that, at a high debt level, a tighter capacity constraint indeed increases the probability of bankruptcy. Interestingly, for medium debt levels ($d_T = 20$ and $30$ in the figure), when capacity tightens, the bankruptcy probability first decreases and then increases. This is because when a capacity constraint is present but not too tight, the optimal policy tries to sell the asset earlier while still capturing high prices, leading to a lower default risk. Figure 9(b) confirms that the asset is indeed sold earlier when capacity constraint tightens. When the capacity constraint becomes very tight, however, the seller may have to sell the asset at adverse prices, resulting in higher probability of falling short in covering the debt. Lastly, when $d_T = 10$, without capacity constraint, the bankruptcy probability is 0.01, whereas a capacity constraint (regardless how tight) effectively removes the bankruptcy risk. This
is because capacity constraint induces early sales, which can easily cover a small debt. The above finding suggests that when neither the debt obligation nor selling capacity is stringent, additional selling capacity allows the firm shielded by limited liability to engage in riskier strategies. Iancu et al. (2017) also find negative effect of operating flexibility under debt.

4.2.2 Single Debt Payment at \( m < T \)

Under the capacity constraint, if the debt payment must be made prior to the end of the horizon, the value function \( V_t(x_t, w_t, p_t; d) \) is generally not continuous in \( w_t \) and \( p_t \), given any debt level. To see the discontinuity, suppose in period \( t < T \), the seller has inventory \( x_t \in (\ell, 1] \) and consider the cases in (3): if \( w_t + p_t \ell < d_t \), bankruptcy occurs and \( V_t(x_t, w_t, p_t; d) = 0 \); whereas if \( w_t + p_t \ell = d_t \), the seller can survive by selling at capacity \( \ell \), leading to \( V_t(x_t, w_t, p_t; d) = \rho E_t V_{t+1}(x_t - \ell, 0, P_{t+1}; d) > 0 \), where \( x_t - \ell > 0 \) and \( w_{t+1} = 0 \). Hence, the value function jumps between \( w_t + p_t \ell < d_t \) and \( w_t + p_t \ell \geq d_t \) when \( x_t \in (\ell, 1] \).

In addition, note that, when there is no capacity constraints, we are able to characterize the optimal policy as the value function is convex (or consists of several pieces of convex functions). However, §4.1 shows that the capacity constraint alone leads to a concave value function. With both debt and capacity constraints in period \( t \), the value function is neither concave or convex. Hence, debt and capacity constraints render the problem analytically intractable in general. Therefore, we resort to numerical analysis to analyze the selling policy, focusing on the essential tradeoff between the benefit of limited liability and the revenue loss due to bankruptcy.

We will show that the two effects—protection effect and revenue loss effect—still exist when

Figure 10: Expected amount of asset sold by period \( t \): single debt payment at \( m = 7 \)

\( P_t 's \) are i.i.d. lognormal and \( \log(P_t) \sim N(3, 0.5) \), \( \rho = 0.98 \), \( T = 10 \)

(a) Without capacity constraint
(b) With capacity constraint \( \ell = 0.2 \)
capacity constraint is present. Figure 10 compares the expected cumulative sales with and without the capacity constraint. Panel (a) considers the same setting as in Figure 5 without the capacity constraint. In the small debt case ($d_m = 10$), the expected cumulative sales in any $t \leq m$ exceeds the sales amount in the debt-free case, which means sales are expedited, whereas in the large debt case ($d_m = 40$), the sales are delayed.

Under the capacity constraint of $\ell = 0.2$, panel (b) reveals that the revenue loss effect will expedite selling under a small debt. On the other hand, under a large debt, the sale is delayed due to the limited liability effect. Note that, however, the magnitude of expedition or delay is much smaller compared to that in panel (a). Intuitively, the capacity limit $\ell = 0.2$ means that the asset needs to be sold over at least 5 periods within a 10-period planning horizon. This constraint significantly reduces the flexibility in expediting or delaying sales.

4.2.3 General Debt Payment

We further study more general debt payment schemes. Recall from §3.4 that the general debt payment cases are analytically difficult to solve; moreover, as discussed in §4.2.2, the capacity constraint renders the value function discontinuous. Despite these complications, we can numerically demonstrate that the key insights still hold for the general case.

Specifically, we consider the case with two equal debt payments at $m_1 = 4$ and $m_2 = 7$. Figure 11 presents the expected cumulative sales before the first installment is due. Consistent with all the previous results, asset selling is expedited under small debts and is delayed under large debts.

Figure 11: Expected amount of asset sold by period $t$: two debt payments at $m_1 = 4$ and $m_2 = 7$

$P_t$’s are i.i.d. lognormal and $\log(P_t) \sim N(3, 0.5)$, $\rho = 0.98$, $T = 10$

(a) Without capacity constraint ($d_{m_1} = d_{m_2} = 5$)  (b) With capacity constraint $\ell = 0.2$ ($d_{m_1} = d_{m_2} = 0$)

Expected amount of asset sold by period $t$
However, as the capacity constraint tightens, these effects are subdued.

4.2.4 Asset-Selling Example under General Price Process: Selling Natural Gas

In this section, we apply our model to the industrial setting of selling natural gas. We employ a commodity price model with parameters estimated from the natural gas price data.

Suppose the asset in focus is $10^6$ MBtu (million British thermal units) of natural gas. Following the literature on commodity asset pricing (Schwartz 1997, Jaillet et al. 2004), we model the logarithmic price $\log p_t$ as an Ornstein-Uhlenbeck process continuous time:

$$d\log p_t = \kappa(\mu - \log p_t)dt + \sigma dZ_t.$$  \hspace{1cm} (6)

where $\mu$ is long-term average level, $\kappa$ is the mean-reversion rate, $\sigma$ is volatility and $Z$ is a standard Brownian motion. We calibrate model (6) using weekly Henry Hub natural gas spot price data. The sample is obtained from EIA (https://www.eia.gov/dnav/ng/hist/rngwhhdW.htm) and covers 157 observations from May 1, 2015 to April 30, 2018. We use the maximum likelihood estimation (see Tang and Chen 2009 and Sørensen 2004) to estimate the parameters and obtain $\kappa = 0.129$, $\mu = 0.994$, and $\sigma = 0.097$.

A discrete-time sample of the price in (6) is an AR(1) process:

$$\log(p_{t+1}) = \eta + \beta \log(p_t) + \epsilon_t,$$ \hspace{1cm} (7)

where each period $t$ represents a $\Delta t = 4$ weeks, $\beta = e^{-\kappa \Delta t} = 0.879$, $\eta = (1 - \beta)\mu = 0.120$, and

Figure 12: Example of selling natural gas: single debt payment at $m = 7$

- (a) Without capacity constraint
- (b) With capacity constraint $\ell = 0.2$
\[ \epsilon_t \sim N(0, \sigma^2) \] is the i.i.d. random shock with \( \sigma = \sqrt{\frac{1-e^{-2\kappa \Delta t}}{2\kappa}} = 0.153. \)

The expected sales over time are illustrated in Figure 12 under three debt levels: 0, $1 million, and $2.5 million, with and without selling capacity. The results are reassuring. We see that the natural gas sales can be delayed (or advanced) if limited liability (or revenue loss) effect is dominant. Observe that the attenuation effect of capacity constraint is smaller in Figure 12 compared to Figure 10. This is because the benefit of waiting for a more favorable selling price is lower under sticky prices (e.g., Markov price process in (7)) than under independent prices. Similarly, the revenue loss effect is weaker when the prices are sticky. Thus, the attenuation effect of capacity constraint is less pronounced.

5. Extension and Conclusions

5.1 Asset Liquidation and Revenue Loss Effect

The model in (2)-(3) assumes that when the firm is unable to make a scheduled debt repayment, it goes into bankruptcy and the payoff is zero. Although zero payoff upon bankruptcy is a common assumption in the literature, it is an extreme case. In practice, if the firm undergoes bankruptcy under Chapter 7, the remaining asset is liquidated and the revenue from liquidation sales will be distributed to the creditors up to the total unpaid debt. The remaining revenue, if any, will be returned to the firm’s shareholders. In this section, we extend our basic model to include the liquidation process or post-bankruptcy asset-selling.

Formally, suppose the firm survives at the beginning of period \( t \) and must pay debt \( d_t > 0 \) to continue to survive. If the firm is unable to pay \( d_t \), i.e., \( d_t^{\text{def}} = d_t - p_t q_t - w_t > 0 \), then it goes bankrupt with unpaid debt \( (d_t^{\text{def}}, d_{t+1}, \ldots, d_m) \) and unsold asset \( x_{t+1} = x_t - q_t \). The remaining asset \( x_{t+1} \) will be sold to maximize the expected revenue over a liquidation period from \( t + 1 \) up to \( t + L \), where \( L \) is the length of the liquidation period.

We assume that the remaining asset can be sold at the market price, but the liquidation period is typically short and, therefore, the expected revenue from liquidation sales is lower than if the firm sells the remaining asset until the end of the horizon. Hence, the revenue loss effect still exists, but to a lesser extent. We formally model the problem with liquidation value and compare it with the results in the previous sections.

The revenue-maximization policy for selling \( x_{t+1} \) is structurally the same as the policy for (1), except for the different discount rates. For simplicity, we assume no discounting for the revenues from liquidation sales. Let \( \{q_s^B : s = t + 1, \ldots, t + L\} \) be a sequence of random variables denoting the revenue-maximization selling quantities over \( L \) periods.
The total revenue \( \sum_{s=t+1}^{t+L} P_s q_s^R \) will be used to pay the remaining debt \( \sum_{s=t}^{m} d_s^r \). The firm will obtain the following payoff at the end of period \( t+L \):

\[
\Omega_{t+1}(x_{t+1}, d_t^r; d) = E_t \left[ \sum_{s=t+1}^{t+L} P_s q_s^R - d_t^r - \sum_{s=t+1}^{m} d_s \right]^+. \tag{8}
\]

We can rewrite the firm’s optimization problem in (2)-(3) as follows:

\[
V_m(x_m, w_m, P_m; d) = \max \left\{ \max_{q_m \in [0, \min(x_m, \ell)] \cap [q_m, \infty]} p_m q_m + w_m - d_m + \rho E_m U_{m+1}(x_m - q_m, P_{m+1}), \right. \quad \left. \quad \max_{q_m \in [0, \min(x_m, \ell)d_m]} \rho L \Omega_{m+1}(x_m - q_m, d_m - p_m q_m - w_m; d) \right\}, \tag{9}
\]

\[
V_{t}(x_t, w_t, p_t; d) = \max \left\{ \max_{q_t \in [0, \min(x_t, \ell)] \cap [q_t, \infty]} \rho E_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t - d_t), P_{t+1}; d), \right. \quad \left. \quad \max_{q_t \in [0, \min(x_t, \ell)d_t]} \rho L \Omega_{t+1}(x_t - q_t, d_t - p_t q_t - w_t; d) \right\}, \quad \text{for } t < m. \tag{10}
\]

In (9)-(10), the inner problem of choosing \( q_t \in [0, \min(x_t, \ell)] \cap [q_t, \infty] \) finds the value of the firm if surviving,\(^3\) while the inner problem of choosing \( q_t \in [0, \min(x_t, \ell,d_t)] \) finds the value of the firm if bankrupt. The firm chooses the greater of the two maximum values. Note that if additional bankruptcy-related costs (such as reputation loss) are included in (8) so that \( \Omega_{t+1} = 0 \), then (9)-(10) are equivalent to (2)-(3).

The optimal selling strategies for (9)-(10) involves a new feature: the firm may choose to go bankrupt even if it can survive. This is because in some situations, survival brings very low payoff, e.g., when \( q_t = x_t \leq \ell \), the firm has to sell all the remaining asset in order to survive, yielding zero payoff, whereas going bankrupt may yield a positive expected payoff to the firm.

Figure 13 compares the optimal policy under zero liquidation value with the optimal policy when liquidation period is one period, i.e., if the firm is unable to pay off the debt maturing in period \( m = 7 \), the remaining asset is liquidated in period 8. The dashed curves in Figure 13 correspond to the critical prices shown in Figure 3. With the liquidation value, both critical prices are higher than if liquidation value is zero. This is because when the revenue loss effect is weakened by the liquidation value, the limited liability effect becomes more prominent. Importantly, the policy structure identified in Proposition 4 is robust: when the price falls in between the two critical prices, the firm should sell a portion of asset to exactly cover the debt. Furthermore, note that in this example the lower critical prices are consistently below \( R_t^0 \), the critical price without debt, indicating that part of the asset is sold earlier than without debt.

Note that at maturity, with zero liquidation value, the lower critical price is \( R_{m}^{(1)} = d_m \). With

\[^3\text{If } q_t > \min(x_t, \ell), \text{ then the feasible set } [0, \min(x_t, \ell)] \cap [q_t, \infty] = \emptyset, \text{ implying that the firm cannot survive and the maximum value is } -\infty \text{ by convention.}\]
Figure 13: Optimal asset-selling policy under a single debt payment and non-zero liquidation value

Same parameters as in Figure 3, and liquidation period $L = 1$, debt $d_m = 10$

liquidation value, this critical price is lifted by an amount that is exactly the liquidation value of the asset. This is because in period $m$, the firm has the option of going bankrupt, and it will choose to go bankrupt if the expected liquidation value of the asset is higher than selling the asset at $p_m$.

5.2 Concluding Remarks

The classical asset-selling problem has seen applications in practice where one or several non-divisible assets are to be sold. This paper extends the classical asset-selling problem to incorporate several realistic features, including the debt repayment obligations, selling capacity constraints, and Markov price evolution. With these new features, our study has broadened the scope of the classic asset selling problem and laid the foundation for its application to more industrial contexts.

We show that the Markov nature of the price process does not qualitatively change the structure of the optimal asset-selling policies. The debt obligation, however, can structurally alter the optimal policy. The debt obligation introduces the new tradeoff between the benefit of limited liability and the revenue loss due to bankruptcy. This tradeoff results in a new selling strategy, that is either to secure the debt payment early to maximize the revenues from selling the remaining asset or to delay the sale as the bankruptcy curbs the downside risk. When both capacity constraint and debt obligation are present, we show that the key effects derived from the uncapacitated case—small debts expedite sales while large debts delay sales—continue to hold, although these effects are attenuated by the capacity constraint.
References


A. Proofs

Proof of Lemma 1: (i) We prove by induction. At the beginning of period \( t = m \), if the seller is able to pay off the debt, i.e., \( w_m \geq d_m \), then \( q_m (d_m - w_m) + \rho m q_m + \rho E_{m+1} (m - q_m, p_{m+1}) \). Hence, the statement in (i) holds for all \( t \).

Proof of Proposition 1: (i) We inductively prove the following two statements for all periods:

(a) It is optimal to sell the remaining asset \( x_t \) in period \( t \) if \( p_t \geq R_t = \rho E_t U_{t+1} (1, p_{t+1}) \);

(b) \( U_t (x_t, p_t) = U_t (1, p_t)x_t \).

In the final period \( T \), because any unsold inventory is worthless (i.e., \( U_{T+1} = 0 \)), it is optimal to sell everything on hand. Hence, statement (a) is true with \( R_T = 0 = \rho U_{T+1} \). Furthermore, \( U_T (x_T, p_T) = p_T x_T \), which leads to statement (b): \( U_T (x_T, p_T) = U_T (1, p_T)x_T \).

Suppose statements (a) and (b) hold in period \( t + 1 \), for some \( t < T \). Then, in period \( t \), problem
(1) becomes
\[ U_t(x_t, p_t) = \max_{0 \leq q_t \leq x_t} p_t q_t + \rho \mathbb{E}_t U_{t+1}(x_t - q_t, P_{t+1}) \]
\[ = \max_{0 \leq q_t \leq x_t} p_t q_t + \rho \mathbb{E}_t U_{t+1}(1, P_{t+1})(x_t - q_t) \]
\[ = \max_{0 \leq q_t \leq x_t} (p_t - R_t^o)q_t + R_t^o x_t, \]
where \( R_t^o = \rho \mathbb{E}_t U_{t+1}(1, P_{t+1}) \). Because the above maximand is linear in \( q_t \), the optimal decision is
\[ q^*_t = \begin{cases} x_t, & \text{if } p_t \geq R_t^o, \\ 0, & \text{if } p_t < R_t^o, \end{cases} \]
which proves statement (a). Under the above \( q^*_t \), we obtain
\[ U_t(x_t, p_t) = \max \{p_t, R_t^o\} x_t. \quad (A.1) \]

Thus, we can write \( U_t(x_t, p_t) = U_t(1, p_t)x_t \), as in statement (b). The induction is complete.

Because the above policy of selling all or nothing is optimal for all periods, it is optimal to sell the entire asset at once, at the time when \( p_t = R_t^o \) occurs.

(ii) We have shown \( R_T^o = 0 \) and \( U_t(1, p_t) = \max \{p_t, R_t^o\} \) in part (i). Thus,
\[ R_{t-1}^o = \rho \mathbb{E}_{t-1} U_t(1, P_t) = \rho \mathbb{E}_{t-1} \max \{p_t, R_t^o\}. \]
Furthermore, \( \rho^{t-1} R_{t-1}^o = \rho^t \mathbb{E}_{t-1} \max \{p_t, R_t^o\} \geq \rho^t \mathbb{E}_{t-1} R_t^o. \)

(iii) When prices are independently distributed, \( R_t^o = \rho \mathbb{E}_t U_{t+1}(1, P_{t+1}) \) no longer depends on \( p_t \) and assumes a deterministic value. In such case, we can prove that \( R_t^o \geq R_{t+1}^o \) by induction. This inequality holds for \( t = T - 1 \) since \( R_T = 0 \). Suppose \( R_t^o \geq R_{t+1}^o \) for some \( t < T \). Then, we have
\[ R_{t-1}^o - R_t^o = \rho \mathbb{E} \max \{p_t, R_t^o\} - \rho \mathbb{E} \max \{P_{t+1}, R_{t+1}^o\} \geq 0, \]
where the inequality is due to the identical and independent distributions of \( p_t \)'s and the induction hypothesis. This completes the induction. \( \blacksquare \)

**Proof of Proposition 2**: The existence of a unique reservation price \( \hat{p}_t \) follows immediately from the statement that \( R_t^o(p_t) \) increases in \( p_t \) at a rate no greater than \( \rho < 1 \). We inductively prove this statement.

Because \( R_T^o = 0 \), the statement clearly holds with \( \hat{p}_T = 0 \). For \( t < T \), suppose \( R_t^o(p_t) \) increases in \( p_t \) at a rate no greater than \( \rho \).

Define \( h(p) = \max \{p, R_{t+1}^o(p)\} \). By Proposition 1(ii), we have \( R_t^o(p_t) = \rho \mathbb{E}[h(P_{t+1}) \mid p_t] \).

First, we see that \( R_t^o(p_t) \) increases in \( p_t \), because \( P_{t+1} \) stochastically increases in \( p_t \) and \( h(\cdot) \) is an increasing function.

Second, we prove the upper bound on the rate of increase. Consider two arbitrary prices \( p_t^a < p_t^b \).
Condition (i) in the proposition means that $P_{t+1}|p_t^i$ is stochastically smaller than $P_{t+1}|p_t^b$. By the coupling property of stochastic ordering, there exist a probability space and two random variables $P^a$ and $P^b$ on this space such that $P^i$ has the same distribution as $P_{t+1}|p_t^i$, for $i = a, b$, and $P^a \leq P^b$ almost surely. The induction hypothesis and the definition of $h(p)$ imply that $h(p)$ increases in $p$ at a rate no greater than 1. Thus, we have $h(P^b) - h(P^a) \leq P^b - P^a$ almost surely. Taking expectations on both sides, we have $E[h(P^b)] - E[h(P^a)] \leq E[P^b] - E[P^a]$, which leads to

$$E[h(P_{t+1})|p_t^b] - E[h(P_{t+1})|p_t^a] \leq E[P_{t+1}|p_t^b] - E[P_{t+1}|p_t^a] \leq p_t^b - p_t^a,$$

where the last inequality is due to condition (ii) in the proposition. Multiplying $\rho$ throughout, we have $R_t^a(p_t^b) - R_t^a(p_t^a) \leq \rho (p_t^b - p_t^a)$. This completes the induction. ■

**Proof of Lemma 2:** (i) We prove by induction. In period $m = T$, equation (2) simplifies to

$$V_T(x_T, w_T, p_T; d) = (p_T x_T + w_T - d_T)^+,$$

which is jointly convex in $(x_T, w_T)$. Suppose $V_{t+1}(x_{t+1}, w_{t+1}, P_{t+1}; d)$ is convex in $(x_{t+1}, w_{t+1})$ for some $t < T$. Then in period $t$, because there is no immediate debt obligation $(d_t = 0)$, we have $q_t = 0$ and (3) leads to

$$V_t(x_t, w_t, p_t; d) = \max_{0 \leq q_t \leq x_t} \rho E_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t), P_{t+1}; d). \quad (A.2)$$

By the induction hypothesis, the objective function in (A.2) is convex in $q_t$. Therefore, the optimal decision $q_t^*$ is either 0 or $x_t$, and we can write $V_t(x_t, w_t, p_t; d)$ as the maximum of two functions:

$$V_t(x_t, w_t, p_t; d) = \rho \max \{ E_t V_{t+1}(x_t, \rho^{-1} w_t, P_{t+1}; d), E_t V_{t+1}(0, \rho^{-1}(w_t + p_t x_t), P_{t+1}; d) \}. \quad (A.3)$$

Because both functions inside of maximization in (A.3) are convex in $(x_t, w_t)$, the maximum of them is also convex in $(x_t, w_t)$. This completes the induction.

(ii) We prove by induction. The statement holds in period $T$ because

$$V_T(x_T, w_T, p_T; d) = (p_T x_T + w_T - d_T)^+ \geq p_T x_T + w_T - d_T = U_T(x_T, p_T) + w_T - d_T.$$

Suppose the statement holds in period $t+1$ for some $t < T$. Then, applying the induction hypothesis to (A.2), we have

$$V_t(x_t, w_t, p_t; d) \geq \max_{0 \leq q_t \leq x_t} \rho E_t \left[ U_{t+1}(x_t - q_t, P_{t+1}) + \rho^{-1}(w_t + p_t q_t) - \rho^{T-t-1} d_T \right]$$

$$= w_t - \rho^{T-t} d_T + \max_{0 \leq q_t \leq x_t} p_t q_t + \rho E_t U_{t+1}(x_t - q_t, P_{t+1})$$

$$= w_t - \rho^{T-t} d_T + U_t(x_t, p_t),$$

which completes the induction. Lemma 1(i) proves that the equality holds when $w_t \geq \rho^{T-t} d_T$. ■

**Proof of Proposition 3:** (i) The proof of Lemma 2 shows that, for any given $x_t$, the optimal
selling quantity $q_t^*$ is either 0 or $x_t$. Thus, given $x_1 = 1$, it is optimal to sell the entire asset at once, i.e., $q_t^* \in \{0, 1\}$ for $t = 1, \ldots, T$. Next, we characterize the optimal selling time.

At the beginning of period $T$, if the asset is not yet sold ($x_T = 1$) and if $p_T \geq d_T$, then the seller should sell the asset and earn $p_T - d_T$. If $p_T < d_T$, the seller goes bankrupt regardless it sells the asset or not. Hence, $R_T = d_T$ as stated in part (i) of the proposition.

At the beginning of period $t < T$, if the asset is not yet sold ($x_t = 1$), then the seller has $w_t = 0$ and (A.3) leads to

$$V_t(1,0,p_t; d) = \max\{\rho E_V V_{t+1}(1,0,P_t+1; d), \rho E_t V_{t+1}(0,\rho^{-1}p_t,P_t+1; d)\}$$

$$= \max\{\rho E_t V_{t+1}(1,0,P_t+1; d), \rho(p^{-1}p_t - \rho^{-1}T^{-1}d_T)^{+}\}$$

$$= \max\{\rho E_t V_{t+1}(1,0,P_t+1; d), p_t - \rho^{-1}T^{-1}d_T\},$$

(A.4)

where the second equality is due to Lemma 1(ii) and we omit $( )^+$ in the last equality because the first term in (A.4) $E_t V_{t+1} \geq 0$. Therefore, the seller should sell the asset if $p_t \geq R_t$, where

$$R_t = \rho^{-1}T^{-1}d_T + \rho E_t V_{t+1}(1,0,P_t+1; d).$$

(A.5)

If we define $V_{T+1} = 0$, then (A.5) is also valid for $t = T$ because $R_T = d_T$. Following from (A.5), we have

$$R_{t-1} = \rho^{-1}T^{-1}d_T + \rho E_{t-1} V_t(1,0,P_t; d)$$

$$= \rho^{-1}T^{-1}d_T + \rho E_{t-1} \max\{\rho E_t V_{t+1}(1,0,P_t+1; d), P_t - \rho^{-1}T^{-1}d_T\}$$

$$= \rho(p^{-1}T^{-1}d_T) + \rho E_{t-1} \max\{R_t - \rho^{-1}T^{-1}d_T, P_t - \rho^{-1}T^{-1}d_T\}$$

$$= \rho E_{t-1} \max\{R_t, P_t\}$$

where the second equality follows from (A.4) and the third equality is due to (A.5).

If $p_t < R_t$ throughout the entire horizon, then the seller forgoes selling opportunity from periods 1 to $T - 1$ and is unable to pay off the debt in period $T$ and thus goes bankrupt.

(ii) We can utilize the relation $R_t(p_t) = \rho E_t \max\{P_{t+1}, R_{t+1}\}$ to write

$$R_t(p_t, d_T) = \rho E_t \max\{P_{t+1}, \rho E_{t+1} \max\{P_{t+2}, \ldots, \rho E_{T-1} \max\{P_T, d_T\} \ldots\}\},$$

where we emphasize the dependence of $R_t$ on $d_T$. Thus, for any realized price $p_t$, $R_t$ is increasing in $d_T$. Consequently, the probability of bankruptcy $Pr\{P_t < R_t \forall t \in T\}$ increases in $d_T$.

To show that $\tau$ increases in $d_T$ almost surely, consider two debt levels with $d_T^a < d_T^b$. The previous result shows that $R_t^a \leq R_t^b$ almost surely, for $t \in T$. Now compare

$$\tau^a = \inf\{t : P_t \geq R_t^a, t \in T\} \quad \text{and} \quad \tau^b = \inf\{t : P_t \geq R_t^b, t \in T\}.$$

In every period $t$, if $p_t \geq R_t^b$, then we must have $p_t \geq R_t^a$. In other words, $p_t$ exceeds $R_t^a$ no later
than it exceeds $R_t^b$. Therefore, $\tau^a \leq \tau^b$, which proves that $\tau$ increases in $d_T$ almost surely.

Because the debt-free results in Proposition 1 is a special case with $d_T = 0$, the above monotonicity results suggest $R_t \geq R_t^b$ and $\tau \geq \tau^o$.

(iii) The relation $R_t = \rho \mathbb{E}_t \max \{P_{t+1}, R_{t+1}\}$ in part (i) implies that $\rho R_t = \rho^{i+1} \mathbb{E}_t \max \{P_{t+1}, R_{t+1}\} \geq \rho^{i+1} \mathbb{E}_t R_{t+1}$. Thus, the expected discounted critical price decreases over time.

If $P_t$'s are i.i.d., then $R_t$ defined in (A.5) is independent of $p_t$ and thus deterministic. Consider the difference $R_{t-1} - R_t = \rho \mathbb{E} \max \{P_t, R_t\} - \rho \mathbb{E} \max \{P_{t+1}, R_{t+1}\}$. Because $P_t$ and $P_{t+1}$ are i.i.d., $R_{t-1} \geq R_t$ if and only if $R_t \geq R_{t+1}$. Therefore, the series $\{R_1, R_2, \ldots, R_T\}$ is either (weakly) increasing or decreasing.

Consider an auxiliary function $f(d) = \rho \mathbb{E} \max \{d, P_t\} - d$, which strictly decreases in $d$ because $\rho < 1$. Furthermore, $f(0) > 0$ and $f(d) < 0$ when $d \gg p_t$. By continuity and strict monotonicity of $f(d)$, there exists a unique $\overline{d}$ such that $f(\overline{d}) = 0$ or $\rho \mathbb{E} \max \{\overline{d}, P_t\} = \overline{d}$.

When $d_T = \overline{d}$, the relations $R_T = d_T$ and $R_{T-1} = \rho \mathbb{E} \max \{R_t, P_t\}$ imply that $R_t = \overline{d}$ for all $t \in T$. When $d_T < \overline{d}$, we have $f(d_T) > 0$ or $\rho \mathbb{E} \max \{d_T, P_t\} > d_T$ or $R_{T-1} > R_T$. Thus, $R_t$ decreases in $t$. Similarly, when $d_T > \overline{d}$, $R_t$ increases in $t$.

**Proof of Lemma 3:** When $w_t \geq \rho^{m-t} d_m$, Lemma 1(i) implies that $V_t(x_t, w_t, p_t; d) = U_t(x_t, p_t) + w_t - \rho^{m-t} d_m$. Furthermore, $U_t(x_t, p_t) = U_t(1, p_t) x_t$, as shown in the proof of Proposition 1. Thus, $V_t(x_t, w_t, p_t; d) = \rho \mathbb{E} \max \{d, P_t\} - d$, which strictly decreases in $d$ because $\rho < 1$. Furthermore, $f(0) > 0$ and $f(d) < 0$ when $d \gg p_t$. By continuity and strict monotonicity of $f(d)$, there exists a unique $\overline{d}$ such that $f(\overline{d}) = 0$ or $\rho \mathbb{E} \max \{\overline{d}, P_t\} = \overline{d}$.

When $d_T = \overline{d}$, the relations $R_T = d_T$ and $R_{T-1} = \rho \mathbb{E} \max \{R_t, P_t\}$ imply that $R_t = \overline{d}$ for all $t \in T$. When $d_T < \overline{d}$, we have $f(d_T) > 0$ or $\rho \mathbb{E} \max \{d_T, P_t\} > d_T$ or $R_{T-1} > R_T$. Thus, $R_t$ decreases in $t$. Similarly, when $d_T > \overline{d}$, $R_t$ increases in $t$.

We inductively prove the convexity of $V_t(x_t, w_t, p_t; d)$ in region $w_t \leq \rho^{m-t} d_m$. In period $t = m$, this region becomes $w_m \leq d_m$. To pay off the debt $d_m$, the seller must sell at least $q_m = \frac{d_m - w_m}{w_m}$.

If $x_m < q_m$, i.e., $p_m < \frac{d_m - w_m}{x_m}$, the seller goes bankrupt and $V_m(x_m, w_m, p_m; d) = 0$.

If $x_m \geq q_m$, i.e., $p_m \geq \frac{d_m - w_m}{x_m}$, equation (2) becomes

$$V_m(x_m, w_m, p_m; d) = \max_{q_m \leq q_m \leq x_m} \left( p_m q_m + w_m - d_m + \rho \mathbb{E} U_{m+1}(x_m - q_m, P_{m+1}) \right)$$

$$= \max_{q_m \leq q_m \leq x_m} \left( p_m - R_m^o \right) q_m + R_m^o x_m + w_m - d_m$$

where the last equality follows from $U_t(x_t, p_t) = U_t(1, p_t) x_t$ by the proof of Proposition 1 and $\rho \mathbb{E} U_{m+1}(1, P_{m+1}) = R_m^o$. The above maximization leads to $q_m^* = q_m$ or $q_m^* = x_m$ depending on whether $p_m < R_m^o$ or not. Combining the above cases, the value function can be written as

$$V_m(x_m, w_m, p_m; d) = \max \{p_m, R_m^o\} \left( x_m - \frac{d_m - w_m}{p_m} \right)^+$

for $w_m \leq d_m$. (A.6)

Thus, $V_m(x_m, w_m, p_m; d)$ is jointly convex in $(x_m, w_m, d_m)$ in region $w_m \leq d_m$. See Figure 2 in the paper for an illustration.

Suppose for some $t < m$, $V_{t+1}(x_{t+1}, w_{t+1}, p_{t+1}; d)$ is jointly convex in $(x_{t+1}, w_{t+1}, d_m)$ for $w_{t+1} \leq
\( \rho^{m-t-1} d_m \). We now prove the convexity of \( V_t(x_t, w_t, p_t; d) \) in \( (x_t, w_t, d_m) \) when \( w_t \leq \rho^{m-t} d_m \). Because no debt payment is required before period \( m \), equation (3) simplifies to
\[
V_t(x_t, w_t, p_t; d) = \max_{0 \leq q_t \leq x_t} \rho \mathbb{E}_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t), P_{t+1}; d). \tag{A.7}
\]

Let us define \( q^d_t \equiv (\rho^{m-t} d_m - w_t)/p_t \), the minimum selling quantity in period \( t \) that ensures debt payment in period \( m \). Since \( w_t \leq \rho^{m-t} d_m \), we have \( q^d_t \geq 0 \). We solve the problem in (A.7) by considering two cases: \( q^d_t \geq x_t \) and \( q^d_t < x_t \).

If \( q^d_t \geq x_t \), when \( q_t \) varies in \([0, x_t] \), we have \( w_{t+1} = \rho^{-1}(w_t + p_t q_t) \leq \rho^{-1}(w_t + p_t q^d_t) = \rho^{m-t-1} d_m \). Then, the induction hypothesis implies that the objective function in (A.7) is convex in \( q_t \) and, consequently, the potential optimal solutions are \( q_t = 0 \) and \( q_t = x_t \). However, \( q_t = x_t \) leads to \( V_{t+1}(0, \rho^{-1}(w_t + p_t x_t), P_{t+1}; d) = 0 \) by Lemma 1(ii). Hence, \( q^*_t = 0 \) in this case.

If \( q^d_t < x_t \), we divide the range \([0, x_t] \) into two intervals \([0, q^d_t] \) and \([q^d_t, x_t] \). When \( q_t \in [0, q^d_t] \), using the same logic as in the case of \( q^d_t \geq x_t \), the objective function in (A.7) is convex in \( q_t \). When \( q_t \in [q^d_t, x_t] \), we have \( w_{t+1} \geq \rho^{m-t-1} d_m \). Then, Lemma 1 and the proof of Proposition 1 lead to
\[
V_{t+1}(x_{t+1}, w_{t+1}, P_{t+1}; d) = U_{t+1}(1, P_{t+1}) x_{t+1} + w_{t+1} - \rho^{m-t-1} d_m, \tag{A.8}
\]

Consequently, the objective function in (A.7) is linear in \( q_t \). Therefore, the optimal solution must be among three possible values: \( q^*_t \in \{0, q^d_t, x_t\} \).

- At \( q_t = 0 \), the objective is \( \rho \mathbb{E}_t V_{t+1}(x_t, \rho^{-1} w_t, P_{t+1}; d) \), which is convex in \( (x_t, w_t, d_m) \) in region \( w_t \leq \rho^{m-t} d_m \) due to the induction hypothesis.
- At \( q_t = q^d_t \), the objective is \( \rho \mathbb{E}_t V_{t+1}(x_t - q^d_t, \rho^{m-t-1} d_m, P_{t+1}; d) = \rho \mathbb{E}_t U_{t+1}(x_t - q^d_t, P_{t+1}) = R^d_t(x_t - q^d_t) = R^d_t(x_t - (\rho^{m-t} d_m - w_t)/p_t) \), which is linear in \( (x_t, w_t, d_m) \). The first equality uses Lemma 1(i) and the second equality uses \( U_t(x_t, p_t) = U_t(1, p_t)x_t \) and \( R^d_t = \rho \mathbb{E}_t U_{t+1}(1, P_{t+1}) \).
- At \( q_t = x_t \), the objective is \( \rho \mathbb{E}_t V_{t+1}(0, \rho^{-1}(w_t + p_t x_t), P_{t+1}; d) = (w_t + p_t x_t - \rho^{m-t} d_m)^+ \), which is convex in \( (w_t, x_t, d_m) \).

Hence, for \( w_t \leq \rho^{m-t} d_m \), the value function can be expressed as
\[
V_t(x_t, w_t, p_t; d) = \max \left\{ \rho \mathbb{E}_t V_{t+1}(x_t, \rho^{-1} w_t, P_{t+1}; d), R^d_t(x_t - (\rho^{m-t} d_m - w_t)/p_t), \right. \]
\[
\left. w_t + p_t x_t - \rho^{m-t} d_m \right\}, \quad \text{for } w_t \leq \rho^{m-t} d_m, \tag{A.8}
\]

where we omit \( (\ )^+ \) in the last term in the maximization because the first term is non-negative.

Although (A.8) is derived under \( q^d_t < x_t \), it holds for \( q^d_t \geq x_t \) as well, because \( q^d_t \geq x_t \) implies that the first term in maximization is the largest (the other terms are non-positive), which is consistent with the result for the case of \( q^d_t \geq x_t \).

Because all three terms in the maximization in (A.8) are convex in \( (x_t, w_t, d_m) \) for \( w_t \leq \rho^{m-t} d_m \),
\( V_t(x_t, w_t, p_t; d) \) is convex in \((x_t, w_t, d_m)\) for \( w_t \leq \rho^{m-t}d_m \), completing the induction.

To show that \( V_t(x_t, w_t, p_t; d) \) is continuous in \((x_t, w_t, d_m)\), we only need to show that it is continuous on the boundary \( w_t = \rho^{m-t}d_m \). Substitute \( w_t = \rho^{m-t}d_m \) into (A.8), we have

\[
V_t(x_t, w_t, p_t; d) = \max \left\{ \rho E_t U_{t+1}(x_t, P_{t+1}), R_t^o x_t, p_t x_t \right\} \\
= \max \left\{ R_t^o x_t, R_t^o x_t, p_t x_t \right\} \\
= \max \left\{ R_t^o, p_t \right\} x_t \\
= U_t(x_t, p_t),
\]

where the first equality follows from Lemma 1(i), the second equality uses the definition of (4), and the last equality follows from (A.1). On the other hand, for \( w_t \geq \rho^{m-t}d_m \), we have shown that \( V_t(x_t, w_t, p_t; d) = U_t(x_t, p_t) + w_t - \rho^{m-t}d_m \). Therefore, \( V_t(x_t, w_t, p_t; d) \) is continuous on the boundary \( w_t = \rho^{m-t}d_m \), and hence it is continuous in \((x_t, w_t, d_m)\). ■

**Proof of Proposition 4:** (i) For notational convenience in this proof, we use \( V_t \) as a short notation for \( V_t(x_t=1, w_t=0, P_t; d) \), i.e., the firm’s value when no asset is sold before period \( t \). Similarly, we write \( U_t \) for \( U_t(x_t=1, P_t) \).

The value functions are derived in (A.6) and (A.8) for \( t = m \) and \( t < m \), respectively. If no asset is sold before period \( m \), (A.8) also holds for \( t = m \). To see this, use \( V_{m+1} = 0 \) defined with (5), and note that (A.8) becomes

\[
V_m = \max \left\{ 0, R_m^o(1 - \frac{d_m}{p_m}), p_m - d_m \right\} = \max \left\{ p_m, R_m^o \right\} (1 - \frac{d_m}{p_m})^+, \]

which is consistent with (A.6). Thus, we focus on (A.8) for the rest of the proof.

When no asset is sold before period \( t \leq m \), (A.8) becomes

\[
V_t = \max \left\{ \rho E_t V_{t+1}, R_t^o(1 - \rho^{m-t}d_m/p_t), p_t - \rho^{m-t}d_m \right\}, \tag{A.9}
\]

where \( \rho E_t V_{t+1} \) is the expected firm’s value if selling nothing in period \( t \), \( R_t^o(1 - \rho^{m-t}d_m/p_t) \) is the expected firm’s value if selling \( q_t = \rho^{m-t}d_m/p_t \) to ensure debt payment, and \( p_t - \rho^{m-t}d_m \) is the firm’s value if selling the entire asset in period \( t \).

If \( p_t \leq \rho^{m-t}d_m \), the second and third terms in (A.9) are non-positive and, therefore, \( q_t^* = 0 \).

If \( p_t > \rho^{m-t}d_m \), all three terms in (A.9) are non-negative, and we need to compare them in pairs:

(a) \( \rho E_t V_{t+1} > R_t^o(1 - \rho^{m-t}d_m/p_t) \) if and only if \( p_t < \frac{\rho^{m-t}d_m R_t^o}{\rho E_t V_{t+1}} \)

(b) \( \rho E_t V_{t+1} > p_t - \rho^{m-t}d_m \) if and only if \( p_t < \rho E_t V_{t+1} + \rho^{m-t}d_m \);

(c) \( R_t^o(1 - \rho^{m-t}d_m/p_t) > p_t(1 - \rho^{m-t}d_m/p_t) \) if and only if \( p_t < R_t^o \).

Combining (a) and (b) and the case of \( p_t \leq \rho^{m-t}d_m \), we see that the first term in (A.9) is the

\[\frac{\rho^{m-t}d_m}{\rho E_t V_{t+1}} > 0 \text{ because } R_t^o = \rho E_t V_{t+1}(1, P_{t+1}) = \rho E_t V_{t+1}(1, 0, P_{t+1}; d) > \rho E_t V_{t+1}(1, 0, P_{t+1}; d), \]

where the equality follows from Lemma 1(i) and the inequality is because any debt reduces the firm’s value.
Differentiating the integral with respect to $\rho$ therefore, the seller can maximize the expected revenue from the remaining asset. According to $\rho = q^*$ if notational convenience, we use $V_t(E_t)$. Equation (A.6) with $x_m = 1$ and $w_m = 0$ implies

\[ E_m V_m = E_m - \max \left\{ p_m, R_m^0 \right\} (1 - d_m/p_m)^+ = \int_{d_m}^{\infty} \max \left\{ p_m, R_m^0 \right\} (1 - d_m/p_m) dF(p_m|p_m-1). \]

Differentiating the integral with respect to $d_m$ and letting $d_m$ approach zero, we have

\[ \lim_{d_m \to 0^+} \frac{\partial E_m - V_m}{\partial d_m} = \lim_{d_m \to 0^+} \int_{d_m}^{\infty} \max \left\{ p_m, R_m^0 \right\} dF(p_m|p_m-1). \]

\[ = \int_{0}^{\infty} \max \left\{ p_m, R_m^0 \right\} dF(p_m|p_m-1) \leq -1. \]

If $\Pr\{p_m < R_m^0\} > 0$, then the integrand $-R_m^0/p_m < -1$ with nonzero probability and the above inequality becomes strict.
Now suppose that for \( t < m \), \( \lim\limits_{d_m \to 0^+} \frac{\partial \mathcal{E}_t V_{t+1}}{\rho^{m-t-1} \partial d_m} \leq -1 \). That is, there exists \( \delta > 0 \), such that for all \( d_m \in (0, \delta) \), we have \( \frac{\partial \mathcal{E}_t V_{t+1}}{\rho^{m-t-1} \partial d_m} \leq -1 \).

From the proof of Proposition 4, the first term in (A.9) is the largest when \( p_t < R_t^{(1)} \). Hence, (A.9) leads to

\[
\mathcal{E}_{t-1} V_t = \mathcal{E}_{t-1} \max \left\{ \rho \mathcal{E}_t V_{t+1}, \ R_t^{(1)} (1 - \rho^{m-t} d_m / p_t), \ p_t - \rho^{m-t} d_m \right\}
\]

\[
= \int_0^{R_t^{(1)}} \rho \mathcal{E}_t V_{t+1} dF(p_t | p_{t-1}) + \int_{R_t^{(1)}}^{\infty} \max \left\{ p_t, R_t^{(1)} \right\} (1 - \rho^{m-t} d_m / p_t) dF(p_t | p_{t-1}).
\]

Differentiating with respect to \( d_m \) and dividing both sides by \( \rho^{m-t} \), we have

\[
\frac{\partial \mathcal{E}_{t-1} V_t}{\rho^{m-t} \partial d_m} = \int_0^{R_t^{(1)}} \frac{\partial \mathcal{E}_t V_{t+1}}{\rho^{m-t-1} \partial d_m} dF(p_t | p_{t-1}) + \int_{R_t^{(1)}}^{\infty} - \max \left\{ p_t, R_t^{(1)} \right\} \frac{dF(p_t | p_{t-1})}{p_t} + L_t \frac{\partial R_t^{(1)}}{\rho^{m-t} \partial d_m},
\]

(A.12)

where \( L_t = \rho \mathcal{E}_t V_{t+1}(1, 0, R_t^{(1)}, d) - \max \left\{ R_t^{(1)}, R_t^{(0)} \right\} (1 - \rho^{m-t} d_m / R_t^{(1)}). \)

The last term in (A.12) actually vanishes because \( L_t \equiv 0 \). To see this, note that if \( \mathcal{E}_t \Delta_{t+1} < 0 \), the proof of Proposition 4 shows that \( R_t^{(1)} = \frac{\rho^{m-t} d_m + R_t^{(0)}}{R_t^{(1)} - \rho \mathcal{E}_t V_{t+1}} < R_t^{(0)} \), implying that \( L_t = 0 \). If \( \mathcal{E}_t \Delta_{t+1} \geq 0 \), the proof of Proposition 4 shows that \( R_t^{(1)} = \rho \mathcal{E}_t V_{t+1} + \rho^{m-t} d_m \geq R_t^{(0)} \), which also leads to \( L_t = 0 \).

Applying the induction hypothesis and \(- \max \left\{ p_t, R_t^{(0)} \right\} / p_t \leq -1 \), (A.12) leads to the desired inequality:

\[
\frac{\partial \mathcal{E}_{t-1} V_t}{\rho^{m-t} \partial d_m} \leq \int_0^{R_t^{(1)}} (-1) dF(p_t | p_{t-1}) + \int_{R_t^{(1)}}^{\infty} (-1) dF(p_t | p_{t-1}) = -1, \quad \forall d_m \in (0, \delta).
\]

Therefore, \( \lim\limits_{d_m \to 0^+} \frac{\partial \mathcal{E}_{t-1} V_t}{\rho^{m-t} \partial d_m} \leq -1 \).

Finally, if \( \Pr \{ P_t < R_t^{(1)} \} > 0 \) for all \( t \leq m \), then the first integrand in (A.12) \( \frac{\partial \mathcal{E}_t V_{t+1}}{\rho^{m-t-1} \partial d_m} \leq -1 - \varepsilon \) for some \( \varepsilon > 0 \) and the second integrand \(- \max \left\{ p_t, R_t^{(0)} \right\} / p_t \leq -1 \) for \( p_t < R_t^{(0)} \). Thus, regardless whether \( R_t^{(1)} > R_t^{(0)} \) or \( R_t^{(1)} \leq R_t^{(0)} \) in (A.12), we have

\[
\frac{\partial \mathcal{E}_{t-1} V_t}{\rho^{m-t} \partial d_m} \leq -1 - \varepsilon', \quad \forall d_m \in (0, \delta), \text{ for some } \varepsilon' > 0,
\]

which leads to \( \lim\limits_{d_m \to 0^+} \frac{\partial \mathcal{E}_{t-1} V_t}{\rho^{m-t} \partial d_m} < -1 \).

**Proof of Proposition 5:** (i) In the paper, the discussion leading to Proposition 5 already proves the existence and uniqueness of the threshold debt level \( D_t \) (for \( t < m \)), such that \( \mathcal{E}_t \Delta_{t+1} > 0 \) and strictly increases in \( d_m \) if \( d_m > D_t \), and \( \mathcal{E}_t \Delta_{t+1} < 0 \) if \( d_m \in (0, D_t) \).

At \( t = m \), (5) implies that \( \mathcal{E}_m \Delta_{m+1} = - \mathcal{E}_m U_{m+1}(1, P_{m+1}) + \rho^{-1} d_m = \rho^{-1} (d_m - R_m^{(0)}) \). Thus, in period \( m \), the unique threshold debt level is \( D_m = R_m^{(0)} \).
(ii) For \( d_m \geq D_t \), part (i) implies that \( \mathbb{E}_t \Delta_{t+1} \geq 0 \). Then, based on Proposition 4(ii), we have
\[
R_t^{(1)} = R_t^{(2)} = \rho \mathbb{E}_t V_{t+1} + \rho^{m-t} d_m = \rho \mathbb{E}_t \Delta_{t+1} + R_t^o,
\]
where the last equality follows from (4) and (5). Because \( \mathbb{E}_t \Delta_{t+1} \) increases in \( d_m \) for \( d_m \geq D_t \) (discussed before Proposition 5), \( R_t^{(1)} = R_t^{(2)} \) increase in \( d_m \).

For \( d_m \in (0, D_t) \), we know \( \mathbb{E}_t \Delta_{t+1} < 0 \) from part (i), and thus \( R_t^{(2)} = R_t^R \) is independent of \( d_m \) by Proposition 4(ii).

To show \( R_t^{(1)} = \frac{\rho^{m-t} d_m R_t^o}{R_t^R - \rho \mathbb{E}_t V_{t+1}} \) increases in \( d_m \), consider the denominator as a function \( f(d_m) \equiv R_t^o - \rho \mathbb{E}_V(1, 0, P_{t+1}, d) \). Note that \( f(0) = 0 \) and \( f(d_m) \) is concave and increasing in \( d_m \) due to Lemma 2. Hence, \( d_m / f(d_m) \) is increasing in \( d_m \), which is the desired property.

Since \( R_t^{(1)} \) increases in \( d_m \), the first-selling time \( \tau = \inf \{ t : p_t \geq R_t^{(1)}, 1 \leq t \leq m \} \) increases in \( d_m \). The proof is similar to Proposition 3(iii).

(iii) With independent prices, \( R_t^o = \rho \mathbb{E}_t U_{t+1} \) and \( \mathbb{E}_t V_{t+1} \) become deterministic. Consequently, \( R_t^{(1)} \) and \( R_t^{(2)} \) in (A.10) are deterministic, so is \( R_t^o \).

Using induction, we prove that the threshold debt level \( D_t \) is constant and equal to \( R_t^o \). We have shown \( D_m = R_t^o \) in part (i). Suppose \( D_t = R_t^o \) for some \( t \leq m \). We next prove \( D_{t-1} = R_t^o \).

When the debt is at the threshold in period \( t \), i.e., \( d_m = D_t = R_t^o \), part (i) implies that \( \rho \mathbb{E}_t \Delta_{t+1} = \rho \mathbb{E}_t V_{t+1} - R_t^o + \rho^{m-t} R_t^o = 0 \), which is independent of \( p_t \). Then, using (A.9), when \( d_m = R_t^o \), for any \( p_t \), we have
\[
V_t(1, 0, p_t, d) = \max \{ \rho \mathbb{E}_t V_{t+1}, R_t^o(1 - \rho^{m-t} R_t^o/p_t), p_t - \rho^{m-t} R_t^o \}
= \max \{ R_t^o - \rho^{m-t} R_t^o, R_t^o(1 - \rho^{m-t} R_t^o/p_t), p_t - \rho^{m-t} R_t^o \}. \tag{A.13}
\]

Note that \( R_t^o - \rho^{m-t} R_t^o \geq 0 \) due to Proposition 1(ii). To simplify (A.13), consider three cases:

- If \( p_t \leq \rho^{m-t} R_t^o \), the second and third terms in (A.13) are non-positive and \( V_t = R_t^o - \rho^{m-t} R_t^o \).
- If \( \rho^{m-t} R_t^o < p_t \leq R_t^o \), then \( R_t^o - \rho^{m-t} R_t^o \geq R_t^o(1 - \rho^{m-t} R_t^o/p_t) \geq p_t(1 - \rho^{m-t} R_t^o/p_t) = p_t - \rho^{m-t} R_t^o \). Thus, \( V_t = R_t^o - \rho^{m-t} R_t^o \).
- If \( p_t > R_t^o \), then \( p_t - \rho^{m-t} R_t^o = p_t(1 - \rho^{m-t} R_t^o/p_t) > R_t^o(1 - \rho^{m-t} R_t^o/p_t) > R_t^o - \rho^{m-t} R_t^o \).

Thus, \( V_t = p_t - \rho^{m-t} R_t^o \).

Combining the three cases, we have \( V_t = R_t^o - \rho^{m-t} R_t^o \) if \( p_t \leq R_t^o \), and \( V_t = p_t - \rho^{m-t} R_t^o \) if \( p_t > R_t^o \). Therefore, \( V_t(1, 0, p_t, d) = \max \{ R_t^o, p_t \} - \rho^{m-t} R_t^o \), when \( d_m = R_t^o \). Taking expectation over \( p_t \) and noting that \( U_t(1, p_t) = \max \{ p_t, R_t^o \} \) from the proof for Proposition 1(i), we have
\[
\mathbb{E}_{t-1} V_t(1, 0, P_t, d) = \mathbb{E}_{t-1} U_t(1, p_t) - \rho^{m-t} R_t^o, \quad \text{for } d_m = R_t^o.
\]

Hence, \( \mathbb{E}_{t-1} \Delta_t = \mathbb{E}_{t-1} V_t - (\mathbb{E}_{t-1} U_t - \rho^{m-t} d_m) = 0 \) when \( d_m = R_t^o \). Referring to the discussion
before Proposition 5, we conclude that $D_{t-1} = R_{m_i}^0$, which completes the induction.

Because $D_t$ is a constant and equal to $R_{m_i}^0$, part (i) leads to $\text{sgn}(R_{t+1}) = \text{sgn}(d_m - R_{m_i}^0)$. The rest of the results follow immediately from this relation and Proposition 4(ii). ■

**Proof of Proposition 6:** Define $m_0 = 0$. For $i = 1, \ldots, k$, we first show that in period $t$ with $m_{i-1} < t \leq m_i$, $V_t(x_t, w_t, p_t; \mathbf{d})$ is convex in $(x_t, w_t)$ when $w_t$ is in each of the following intervals:

$$\Omega_t^i \equiv [0, \rho^{m_i-t} d_{m_i}], \quad \Omega_t^{i+1} \equiv \left[ \rho^{m_i-t} d_{m_i}, \sum_{j=i+1}^{i+k} \rho^{m_j-t} d_{m_j} \right], \quad \ldots, \Omega_t^k \equiv \left[ \sum_{j=1}^{k-1} \rho^{m_j-t} d_{m_j}, \rho^{m_k-t} d_{m_k} \right].$$

Note that $\Omega_t^i \cup \Omega_t^{i+1} \cup \ldots \cup \Omega_t^k = [0, \sum_{j=1}^k \rho^{m_j-t} d_{m_j}]$. If $w_t \geq \sum_{j=1}^k \rho^{m_j-t} d_{m_j}$, $V_t(x_t, w_t, p_t; \mathbf{d})$ is linear in $(x_t, w_t)$ due to Lemma 1 and $U_t(x_t, p_t) = U_t(1, p_t) x_t$ by the proof of Proposition 1.

We prove the piecewise convexity by induction. In period $t = m_k \equiv m$, the convexity of $V_m(x_m, w_m, p_m; \mathbf{d})$ in $(x_m, w_m)$ for $w_m \in \Omega_m^k = [0, d_m]$ follows directly from Lemma 3; see (A.6).

Suppose for some $t$ with $m_{i-1} < t < m_i$, the convexity property holds for period $t+1$, i.e., $V_{t+1}(x_{t+1}, w_{t+1}, P_{t+1}; \mathbf{d})$ is convex in $(x_{t+1}, w_{t+1})$ for $w_{t+1} \in \Omega_{t+1}^s = \left[ \sum_{j=1}^{s-1} \rho^{m_j-t} d_{m_j}, \sum_{j=s}^k \rho^{m_j-t} d_{m_j} \right]$, $s = i, \ldots, k$. Because no payment is due in period $t$, (3) becomes (A.7), which is repeated here:

$$V_t(x_t, w_t, p_t; \mathbf{d}) = \max_{0 \leq q_t \leq x_t} \rho E_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t), P_{t+1}; \mathbf{d}).$$

(A.14)

By the induction hypothesis, the above objective function is convex in $q_t$ when $\rho^{-1}(w_t + p_t q_t) \in \Omega_{t+1}^s$, that is, when $q_t \in [0, x_t] \cap \left[ (\sum_{j=1}^{s-1} \rho^{m_j-t} d_{m_j} - w_t)/p_t, (\sum_{j=s}^k \rho^{m_j-t} d_{m_j} - w_t)/p_t \right]$. Therefore,

$$q_t^* \in (0, x_t) \cup \left\{ (\sum_{j=s}^k \rho^{m_j-t} d_{m_j} - w_t)/p_t : s = i, \ldots, \bar{s} \right\},$$

(A.15)

where $\bar{s} \equiv \max \left\{ s \leq k : (\sum_{j=1}^s \rho^{m_j-t} d_{m_j} - w_t)/p_t < x_t \right\}$.

Using (A.15), we can write (A.14) as

$$V_t(x_t, w_t, p_t; \mathbf{d}) = \max \left\{ \rho E_t V_{t+1}(x_t, \rho^{-1} w_t, P_{t+1}; \mathbf{d}), \right. \left. \left( p_t x_t + w_t - \sum_{j=1}^k \rho^{m_j-t} d_{m_j} \right)^+, \right. \left. \rho E_t V_{t+1}(x_t - (\sum_{j=1}^s \rho^{m_j-t} d_{m_j} - w_t)/p_t, \rho^{-1}(\sum_{j=s}^k \rho^{m_j-t} d_{m_j}), P_{t+1}; \mathbf{d}), s = i, \ldots, \bar{s} \right\}. \right.$$

(A.16)

To see $V_t(x_t, w_t, p_t; \mathbf{d})$ is convex in $(x_t, w_t)$ for $w_t \in \Omega_t^s$, note that each term within the maximization of (A.16) is convex: first, $w_t \in \Omega_t^s$ implies $\rho^{-1} w_t = w_{t+1} \in \Omega_{t+1}^s$ and hence the first term is convex in $(x_t, w_t)$ by the induction hypothesis; the second term is clearly convex in $(x_t, w_t)$; the last term depends on $(x_t, w_t)$ only through $x_{t+1} = x_t - (\sum_{j=1}^s \rho^{m_j-t} d_{m_j} - w_t)/p_t$, and thus the last term is convex in $(x_t, w_t)$ because $V_{t+1}(x_{t+1}, w_{t+1}, P_{t+1}; \mathbf{d})$ is convex in $x_{t+1}$ by the induction hypothesis.

This completes the induction for any period $t$ with $m_{i-1} < t < m_i$.

In the payment period $t = m_{i-1}$, if $w_t \geq d_t$, bankruptcy will not happen in period $t$, and the proof is identical to the case of $m_{i-1} < t < m_i$. But if $w_t \in [0, d_t)$, then $q_t$ must satisfy $q_t \geq q_t^*$ to
ensure debt payment. For any \( p_t < (d_t - w_t)/x_t \), the seller goes bankrupt, and the value diminishes to zero (weakly convex). For \( p_t \geq (d_t - w_t)/x_t \), the proof is parallel to the case of \( m_{i-1} < t < m_i \) except that the feasible region is \( q_t \in [q_t, x_t] \). This completes the induction.

To find the critical price for the first sale, consider period \( t = m_1 \) first. Clearly, if \( p_{m_1} < d_{m_1} \), the seller will not be able to make the first payment and go bankrupt. Thus, the critical price is \( R^t_{m_1} = d_{m_1} \).

For \( t < m_1 \), the value function is given by (A.16) with \( x_t = 1, w_t = 0 \), and \( i = 1 \). We can express the critical prices \( R^t_i(p_t) \) as

\[
R^t_i(p_t) = p_t + \rho E_t V_{t+1}(1, 0, P_{t+1}; d) - \max \left\{ \left( p_t - \sum_{j=1}^{k} \rho^{m_j-t} d_{m_j} \right)^+, \right. \\
\rho E_t V_{t+1} \left( 1 - \sum_{j=1}^{s} \rho^{m_j-t} d_{m_j}/p_t, \rho^{-1} \sum_{j=1}^{s} \rho^{m_j-t} d_{m_j}, P_{t+1}; d \right), s = 1, \ldots, \bar{s} \right\}.
\]

If \( p_t < R^t_i(p_t) \) for all \( t \leq m_1 \) (i.e., \( \tau = \infty \)), then the seller bankrupts at the end of period \( m_1 \).

At the time of the first sale \( \tau < \infty \), we have \( x_{\tau} = 1, w_{\tau} = 0 \), and (A.15) implies that the optimal selling quantity is \( q^*_\tau \in \left\{ \sum_{i=1}^{j} \rho^{m_i-\tau} d_{m_i}/p_{\tau} : j = 1, \ldots, k \right\} \cup \{1\} \).

Proof of Proposition 7: Part (i) is immediate since the seller is debt-free if \( j = k \). For part (ii), the revenue from the first sale, \( \sum_{i=1}^{j} \rho^{m_i-\tau} d_{m_i} \), will cover exactly the first \( j \) installments. Thus, to maximize the expected profit, the seller only needs to consider the remaining \( k-j \) debt payments over a horizon of \( T-\tau \) periods, constituting a new asset selling problem. The initial wealth of this new problem is zero because the current wealth of the firm, \( \sum_{i=1}^{j} \rho^{m_i-\tau} d_{m_i} \), will be used to make the first \( j \) payments that are excluded from the new problem. The initial amount of asset available for sale in this new problem is \( h \). We can let \( h \) be the new unit of asset and scale the price to \( \tilde{P}_t = h P_t \). Then, the new problem is structurally identical to the original asset selling problem.

Proof of Proposition 8: We solve the problem defined in (1) using backward induction and prove the following property of the revenue function: For any \( t \in \mathcal{T} \), \( \rho E_t U_{t+1}(x_{t+1}, P_{t+1}) \) is piecewise linear in \( x_{t+1} \); the slopes for the \( n \) segments \((0, \ell], (\ell, 2\ell], \ldots, ((n-2)\ell, (n-1)\ell] \) and \((n-1)\ell, 1] \) are \( R_{t,n}^0 \geq R_{t,n-1}^0 \geq \cdots \geq R_{t,1}^0 \), respectively, and the slopes satisfy part (ii) of the proposition.

The property clearly holds for \( t = T \), as \( U_{T+1}(\ldots) \equiv 0 \) and \( R_{T,i}^0 = 0, i = 1, \ldots, n \), as given in part (iii). To see the property in period \( T-1 \), note that \( q_{T}^* = \min(x_T, \ell) \) and \( U_T(x_T, p_T) = \min(x_T, \ell)p_T \). Hence, \( \rho E_{T-1} U_T(x_T, P_T) \) is piecewise linear with slope \( \rho E_{T-1} P_T \) for \( x_T \in [0, \ell] \) and slope 0 for \( x_T > \ell \). These slopes are consistent with part (iii): \( R_{T-1,n}^0 = R_{T-1}^0 \) and \( R_{T-1,i}^0 = 0 \) for \( i < n \).

Suppose we have proved the stated property for \( \rho E_t U_{t+1}(x_{t+1}, P_{t+1}) \). We now find the revenue function \( U_t(x_t, p_t) = \max_{0 \leq q_t \leq \min(x_t, \ell)} p_t q_t + \rho E_t U_{t+1}(x_t - q_t, P_{t+1}) \), as defined in (1).
Consider inventory \( x_t \) in the first segment \((0, \ell]\). Solving (1) amounts to comparing \( p_t \) with \( R_{t,n}^o = R_t^o \). There are two cases: (a) if \( p_t \geq R_t^o \), then \( q_t^* = x_t \), and the marginal value of inventory is \( p_t \); (b) if \( p_t < R_t^o \), then \( q_t^* = 0 \), and the marginal value of inventory is \( R_t^o \), which is the discounted marginal value of inventory in the next period. Combining these two cases, the marginal value of inventory is \( \max\{p_t, R_t^o\} \) for inventory \( x_t \in (0, \ell] \). Thus, \( \rho \mathbb{E}_{t-1} U_t(x_t, P_t) \) is linear in \( x_t \) for \( x_t \in (0, \ell] \) with slope \( \rho \mathbb{E}_{t-1} \max\{P_t, R_t^o\} = R_t^o \), where the equality is from Proposition 1(ii).

Next, consider inventory \( x_t \) in the \( i \)-th \((i \in \{1, \ldots, n - 1\})\) segment from the right of the interval \((0,1]\). In solving the concave maximization problem in (1), we compare \( p_t \) with the slopes of \( \rho \mathbb{E}_{t} U_{t+1}(x_{t+1}, P_{t+1}) \) given in the induction hypothesis. Since we can sell no more than \( \ell \) per period, we need to compare \( p_t \) with only two slopes \( R_{t,i}^o \) and \( R_{t,i+1}^o \). The optimal selling quantity is

\[
q_t^* = \begin{cases} 
0, & \text{if } p_t < R_{t,i}^o; \\
 x_t - \left(\left\lceil \frac{x_t}{\ell} \right\rceil - 1\right) \ell, & \text{if } R_{t,i}^o \leq p_t < R_{t,i+1}^o; \\
\ell, & \text{if } p_t \geq R_{t,i+1}^o.
\end{cases} \tag{A.17}
\]

For the three cases in (A.17), the marginal value of inventory is \( R_{t,i}^o \), \( p_t \), and \( R_{t,i+1}^o \), respectively.\(^5\)

Combining these three cases and noting that \( R_{t,i}^o \leq R_{t,i+1}^o \), the marginal value of inventory is median\(\{p_t, R_{t,i}^o, R_{t,i+1}^o\} \). Thus, \( \rho \mathbb{E}_{t-1} U_t(x_t, P_t) \) is linear in \( x_t \) for \( x_t \) in the \( i \)-th segment from the right, with slope \( \rho \mathbb{E}_{t-1} \text{median}\{P_t, R_{t,i}^o, R_{t,i+1}^o\} = R_{t-1,i}^o \). Finally, since \( R_{t,i}^o \) increases in \( i \), \( R_{t-1,i}^o \) also increases in \( i \). Hence, the property holds for \( t - 1 \), which completes the induction.

In the above induction, if the seller makes a sale, the selling quality is either \( \ell \) or \( x_t - \left(\left\lceil \frac{x_t}{\ell} \right\rceil - 1\right) \ell \).

Hence, the asset is divided into \( n = \left\lceil \frac{r}{\ell} \right\rceil \) pieces, with \( n - 1 \) pieces of \( \ell \) and a remainder of size \( r = 1 - (n - 1) \ell \). Regardless of when the remainder \( r \) is sold, before the \( i \)-th sale, the inventory is in the \( i \)-th segment from the right (see the list of segments at the beginning of the proof), and thus follow the optimal rule in (A.17). The \( i \)-th sale is made only when \( P_t \geq R_{t,i}^o \). The selling quantities in part (i) are implied by (A.17). \( \blacksquare \)

**Proof of Lemma 5:** We prove piecewise convexity by induction. In period \( m = T \), the value function in (2) is \( V_T(x_T, w_T, P_T; d) = (p_T \min(x_T, \ell) + w_T - d_T)^+ \), which is a convex function of \( (x_T, w_T) \) in two regions: \( x_T \in (0, \ell] \) and \( x_T \in (\ell, 1] \).

Suppose for some \( t < T \), \( V_{t+1}(x_{t+1}, w_{t+1}, P_{t+1}; d) \) is convex in \((x_{t+1}, w_{t+1})\) when \( x_{t+1} \) is in each of the following \( n \) regions: \((0, \ell], (\ell, 2\ell], \ldots, ((n - 2)\ell, (n - 1)\ell] \) and \(((n - 1)\ell, 1] \). Then in period \( t \),

\(^5\)In the last case when \( p_t \geq R_{t,i+1}^o \), it is optimal to sell \( \ell \), and thus \( x_{t+1} \) is in the \( i + 1 \)-st segment from the right. Therefore, having \( \varepsilon \) units less of inventory in period \( t \) will reduce \( x_{t+1} \) by \( \varepsilon \) and reduce the discounted expected future revenue by \( R_{t,i+1}^o \).
because $d_t = 0$, the value function in (3) becomes

$$V_t(x_t, w_t, p_t; d) = \max_{0 \leq q_t \leq \min(x_t, \ell)} \rho E_t V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t), P_{t+1}; d).$$

Suppose $x_t \in (j\ell, \min((j+1)\ell, 1)]$, for $j \in \{1, \ldots, n-1\}$. By the induction hypothesis, $V_{t+1}(x_t - q_t, \rho^{-1}(w_t + p_t q_t), P_{t+1}; d)$ is convex in $q_t$ for $q_t \in [0, x_t - j\ell]$ and $q_t \in [x_t - j\ell, \ell]$, considered separately. Since the convex objective is maximized at the endpoints of the intervals, we have $q_t^* \in \{0, x_t - j\ell, \ell\}$. Hence, the value function can be expressed as

$$V_t(x_t, w_t, p_t; d) = \rho \max\{E_t V_{t+1}(x_t, \rho^{-1}w_t, P_{t+1}; d), E_t V_{t+1}(j\ell, \rho^{-1}(w_t + (x_t - j\ell)p_t), P_{t+1}; d), E_t V_{t+1}(x_t - \ell, \rho^{-1}(w_t + \ell p_t), P_{t+1}; d)\}.$$ 

(A.18)

Because all three terms in the maximization in (A.18) are convex in $(x_t, w_t)$ for $x_t \in (j\ell, \min((j+1)\ell, 1)]$, $V_t(x_t, w_t, p_t; d)$ is convex in $(x_t, w_t)$ for $x_t \in (j\ell, \min((j+1)\ell, 1)]$, for $j \in \{1, \ldots, n-1\}$.

If $x_t \in (0, \ell]$, similar logic leads to $q_t^* \in \{0, x_t\}$ and the convexity of $V_t(x_t, w_t, p_t; d)$ for $x_t \in (0, \ell]$, which completes the induction.

**Proof of Proposition 9:** (i) In the proof of Lemma 5, when $x_t \in (j\ell, \min((j+1)\ell, 1)]$, $j \geq 1$, the optimal decision $q_t^* \in \{0, x_t - j\ell, \ell\}$. If $q_t^* = x_t - j\ell$, then $x_{t+1} = j\ell$, and future sales quantity will be either 0 or $\ell$.

The three decisions $\{0, x_t - j\ell, \ell\}$ corresponds to the three terms in the maximization in (A.18). Hence, we can express the critical prices for the first sale as

$$R^c_t(p_t) = p_t + \rho E_t V_{t+1}(1, 0, P_{t+1}; d) - \rho \max\{E_t V_{t+1}((n-1)\ell, \rho^{-1}(1 - (n-1)\ell)p_t, P_{t+1}; d), E_t V_{t+1}(1 - \ell, \rho^{-1}\ell p_t, P_{t+1}; d)\}.$$ 

The first sale is triggered by $p_t \geq R^c_t(p_t)$, which proves part (i).

(ii) After the first sale $q^*_{te} \in \{\ell, r\}$ is made in period $\tau^e < T$, the problem facing the seller is to sell the remaining asset $1 - q^*_{te}$ over $T - \tau^e$ periods with a debt maturing at $T$. As part of the debt is covered by the first sale, the debt in the new problem is effectively $d'_{\tau} = (d_T - q^*_{te}p_T/\rho^{T-\tau^e})^+$. This problem is structurally identical to the original problem. 

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