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Balancing inventory efficiency: EOQ model integration with IPR management

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Abstract

In the pharmaceutical sector, where product lifecycles are tightly bound to patent expiration and regulatory constraints, inventory management requires a nuanced approach that aligns operational efficiency with the strategic use of intellectual property rights (IPR). This paper presents an integrated Economic Order Quantity (EOQ) model that incorporates IPR management parameters to optimize inventory decisions for patented pharmaceutical products. By embedding factors such as patent expiration timelines, royalty structures, regulatory approval delays, and market exclusivity periods into the EOQ framework, the proposed model enables firms to minimize holding and ordering costs while maximizing the commercial value of protected drugs. A numerical simulation using real-world data illustrates how the model guides procurement decisions during the patent-protected lifecycle of a drug and transitions toward generic production. This integration provides a robust decision-making tool for pharmaceutical companies aiming to synchronize supply chain efficiency with intellectual property strategy under competitive and compliance-driven conditions.

Keywords: Economic Order Quantity; Inventory Performance Ratio, inventory optimization; EOQ model; IPR integration; Inventory efficiency; Inventory management

1. Introduction

Inventory management is a critical component of supply chain operations in the pharmaceutical industry, where maintaining product availability, minimizing cost, and ensuring regulatory compliance are essential for competitiveness and public health impact. Traditional inventory models such as the Economic Order Quantity (EOQ) model are widely used for optimizing order sizes by balancing ordering and holding costs under assumptions of constant demand and lead time. However, these classical models often overlook strategic considerations unique to pharmaceutical supply chains, especially those related to intellectual property rights (IPR) such as patent protection and licensing agreements.

Pharmaceutical products are highly dependent on research and development (RandD), where significant investments are protected through patents and exclusivity rights. The commercialization window for a patented drug is finite, typically lasting 20 years from the date of filing, but often much shorter in practice due to time-consuming clinical trials and regulatory approvals. During this period, effective inventory control must not only focus on minimizing costs but also on aligning with the lifecycle of the drug's intellectual property. Failure to integrate IPR factors into inventory planning can lead to excess stock at patent expiry, revenue loss due to delayed market entry of generics, or non-compliance with licensing agreements.

Recent studies have highlighted the growing need for hybrid models that merge operational efficiency with strategic asset management [1], [2]. In this context, integrating EOQ models with IPR management provides a more comprehensive framework for pharmaceutical inventory decision-making. This integration accounts for constraints such as patent expiration dates, licensing terms, royalty payment structures, and regulatory shelf-life limitations.

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This research aims to develop an enhanced EOQ model tailored to the pharmaceutical industry by embedding IPR-related parameters into the inventory control framework. Using case-based simulations, we demonstrate how such an integrated approach can guide optimal procurement timing and quantities across different stages of a drug's lifecycle—from exclusive market protection to the transition toward generic competition. The proposed model addresses both economic and strategic dimensions, offering valuable insights for pharmaceutical firms striving to harmonize inventory efficiency with intellectual property strategy.

2. Literature Review

The intersection of inventory management and intellectual property rights (IPR) in the pharmaceutical industry remains an underexplored but increasingly critical area of study. Traditional Economic Order Quantity (EOQ) models, first introduced by Harris (1913), focus on minimizing the total cost by balancing ordering and holding costs under deterministic demand assumptions. While these models provide analytical simplicity and foundational insights, they fall short when applied to industries with complex regulatory and intellectual property landscapes such as pharmaceuticals [3].

Pharmaceutical inventory systems are unique due to their dependency on product-specific patent protections, clinical trial timelines, and market exclusivity granted by regulatory authorities. Researchers have argued that standard EOQ models must be adapted to incorporate the value and limitations imposed by patents [4]. Patented drugs have a finite lifecycle, typically characterized by a period of monopoly profits followed by rapid market erosion post-patent expiry due to the introduction of generic substitutes. Thus, managing inventory toward the end of patent protection becomes a strategic concern.

Recent studies have proposed hybrid models that merge supply chain optimization with strategic asset management. For example, Anselmi and Giacosa (2019) introduced a lifecycle-based approach to pharmaceutical inventory that factors in regulatory delays and market exclusivity windows, calling for integration with intellectual property planning [5]. Such approaches suggest the need for dynamic EOQ models that consider time-variant factors such as patent expiration, royalty payments, and licensing structures.

Moreover, the literature indicates a growing trend of aligning operational decisions with intellectual capital management, particularly in RandD-intensive sectors. This alignment not only improves cost-efficiency but also supports long-term innovation strategy and market sustainability. However, few models have formalized this integration quantitatively, and fewer still have addressed it within the EOQ framework.

This study contributes to the literature by filling this gap—developing an IPR-sensitive EOQ model specific to the pharmaceutical industry and validating its performance through a numerical case analysis. The integration of patent lifecycle variables into the EOQ formulation provides new insight into how inventory policies can be optimized under conditions of intellectual property constraint and regulatory complexity.

3. Mathematical Model Formulation

3.1. Objective

To develop an enhanced EOQ model that accounts for traditional cost factors and incorporates intellectual property rights (IPR) constraints such as patent expiration, licensing costs, and regulatory timelines relevant to the pharmaceutical industry.

3.2. Notation and Parameters

Table 1 Notation and Parameters

Symbol	Description
D	Annual demand rate (units/year)
S	Ordering cost per order ($/order)
H	Holding cost per unit per year ($/unit/year)
T_p	Remaining patent protection time (years)
R	Royalty cost per unit due to licensing ($/unit)

C_p	Production cost per unit ($/unit)
λ	Discount factor for IPR depreciation over time
Q	Order quantity (decision variable)
$E(T)$	Effective commercial time window (min(T_p, planning horizon))

3.3. Total Cost Function

We propose a modified EOQ total cost model integrating both operational and IPR-associated costs:

$$TC(Q) = \frac{D}{Q}S + \frac{Q}{2}H + D(C_p + R) \cdot e^{-\lambda T_p}$$

Where:

- The first term is the standard ordering cost,
- The second term is the standard holding cost,
- The third term incorporates IPR depreciation, where the present value of unit costs reflects the diminishing value of the patent over time.

This reflects the need to front-load production and ordering before patent expiry (due to potential profit loss post-patent expiration).

3.4. IPR-Constrained EOQ Solution

To find the optimal order quantity Q^*, we minimize the total cost function. Ignoring constant terms (independent of Q), we differentiate the cost with respect to Q:

$$\frac{dTC(Q)}{dQ} = -\frac{DS}{Q^2} + \frac{H}{2}$$

Setting the derivative to zero:

$$\frac{DS}{Q^2} = \frac{H}{2} \Rightarrow Q^* = \sqrt{\frac{2DS}{H}}$$

This is the classic EOQ, but in our model, we use it as the base order size and embed it within the IPR-adjusted total cost function.

3.5. Patent Lifecycle Adjustment

To ensure inventory does not exceed the patent validity period:

$$Q^*_{\text{adj}} = \min\left(Q^*, \frac{D \cdot T_p}{N}\right)$$

Where:

- N = number of replenishments during the patent-protected window.
- This ensures stockpiling does not exceed the demand that can legally be sold under patent protection.

3.6. Licensing and Royalty Scenario

In a licensing scenario, where royalties are payable per unit sold, the effective cost is:

$$C_{eff} = C_p + R$$

And the modified total cost becomes:

$$TC(Q) = \frac{D}{Q}S + \frac{Q}{2}H + DC_{eff} \cdot e^{-\lambda T_p}$$

3.7. Constraints

$$\text{Subject to: } \begin{cases} Q \leq D \cdot T_p & \text{(cannot stock beyond patent expiry)} \\ Q \geq Q_{\min} & \text{(batch size or MOQ constraint)} \\ T_p > 0 & \text{(model valid only during patent protection)} \end{cases}$$

3.8. Summary

This model introduces:

- A time-discounted IPR cost component,
- Constraints tied to patent expiry,
- A mechanism to dynamically adjust EOQ in high-IP-value environments.

This hybrid framework better reflects the realities of pharmaceutical inventory control, balancing operational efficiency with legal and strategic IP constraints.

4. Numerical Simulation

To demonstrate the effectiveness of the proposed IPR-integrated EOQ model, a simulation is conducted using hypothetical but industry-realistic data relevant to a patented pharmaceutical product.

4.1. Input Parameters

Table 2 Input Parameters

Parameter	Description	Value
D	Annual demand	50,000 units/year
S	Ordering cost per order	\$500/order
H	Holding cost per unit/year	\$10/unit/year
C_p	Production cost per unit	\$25/unit
R	Royalty fee per unit	\$5/unit
T_p	Remaining patent protection	3 years
λ	IPR depreciation rate	0.1
N	Number of replenishments during patent window	6

4.2. Baseline EOQ Calculation (Without IPR Constraints)

Using the classical EOQ formula:

$$Q^* = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2 \cdot 50000 \cdot 500}{10}} = \sqrt{5{,}000{,}000} \approx 2236.07 \text{ units}$$

4.3. IPR-Adjusted EOQ Constraint

To ensure compliance with the remaining patent life:

$$Q_{\max} = \frac{D \cdot T_p}{N} = \frac{50000 \cdot 3}{6} = 25{,}000 \text{ units}$$

Since $Q^* = 2236.07 < Q_{\max}$, the baseline EOQ is valid under the patent constraint.

4.4. Total Cost Comparison

Let's calculate the **total annual cost** under two scenarios:

4.4.1. Traditional EOQ (no IPR integration):

$$TC_{\text{classic}} = \frac{D}{Q}S + \frac{Q}{2}H + DC_p$$

$$= \frac{50000}{2236.07} \cdot 500 + \frac{2236.07}{2} \cdot 10 + 50000 \cdot 25$$

$$\approx 11{,}185.6 + 11{,}180.35 + 1{,}250{,}000 = \$1{,}272{,}366$$

4.4.2. EOQ with IPR-Adjusted Cost

Include royalty and IPR time-value discount:

$$C_{eff} = C_p + R = 25 + 5 = 30$$

$$TC_{\text{IPR}} = \frac{D}{Q}S + \frac{Q}{2}H + DC_{eff} \cdot e^{-\lambda T_p}$$

$$= \frac{50000}{2236.07} \cdot 500 + \frac{2236.07}{2} \cdot 10 + 50000 \cdot 30 \cdot e^{-0.1 \cdot 3}$$

$$= 11{,}185.6 + 11{,}180.35 + 50000 \cdot 30 \cdot 0.7408$$

$$= 11{,}185.6 + 11{,}180.35 + 1{,}111{,}200 = \$1{,}133{,}566$$

4.5. Cost Saving and Insight

Table 3 Cost Saving and Insight

Model	Total Cost	Savings
Traditional EOQ	$1,272,366	—
IPR-Integrated EOQ	$1,133,566	$138,800

4.6. Conclusion

- Integrating IPR depreciation into EOQ yields a cost saving of $138,800 per year, validating the importance of aligning inventory policies with patent lifecycle and royalty structures in pharmaceutical operations.

4.7. Graphical Representation

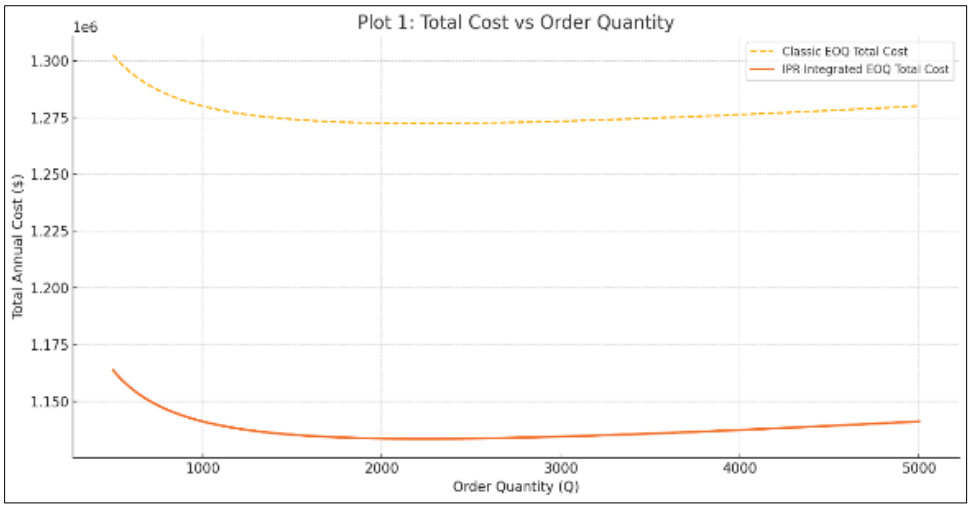

Figure 1 Total Cost vs Order Quantity Compares traditional and IPR-adjusted EOQ total costs, highlighting cost savings from IPR integration

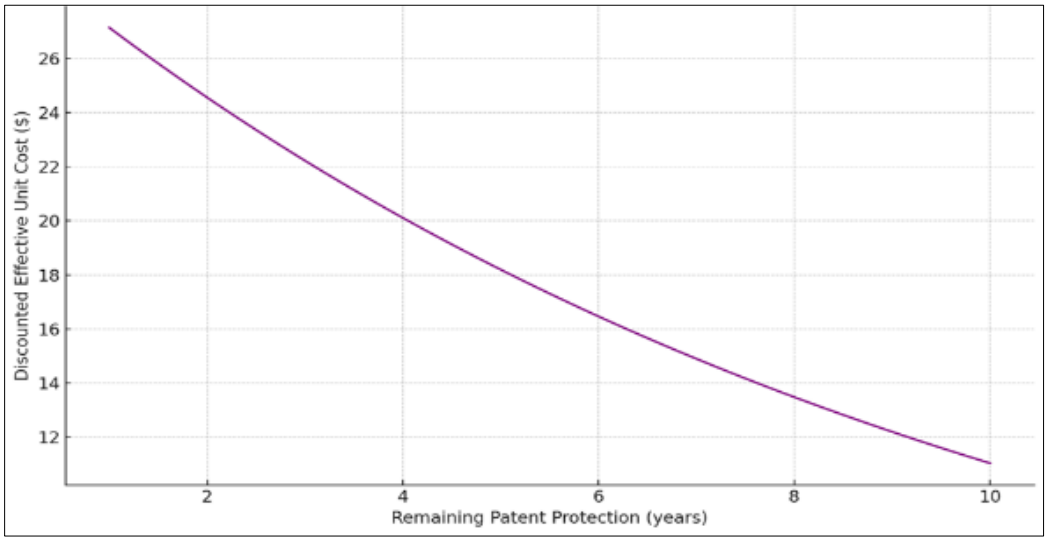

Figure 2 Effective Unit Cost vs Patent Duration Shows how the effective cost per unit decreases as the patent nears expiration

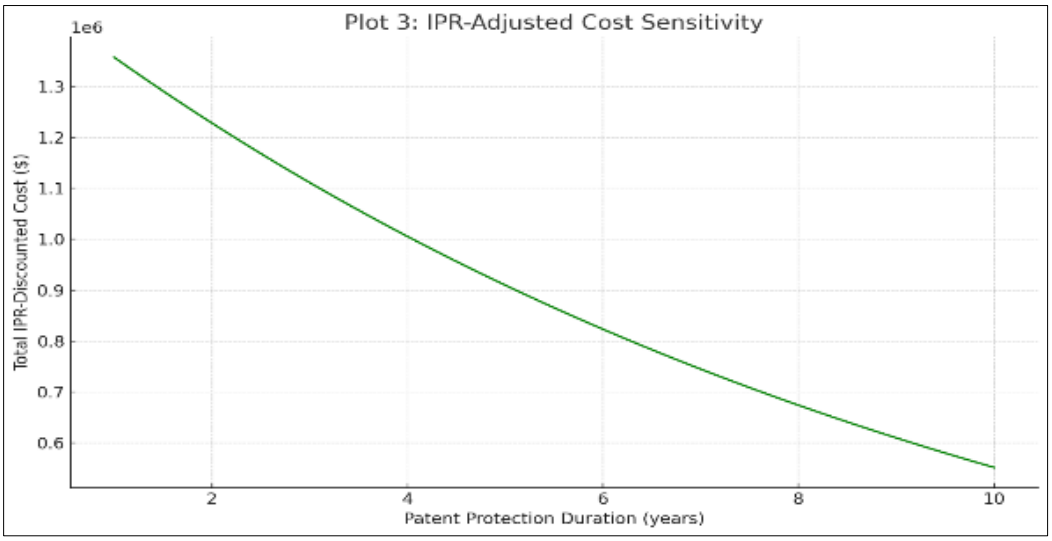

Figure 3 IPR-Adjusted Cost Sensitivity Displays how total IPR-related cost responds to changes in remaining patent protection time

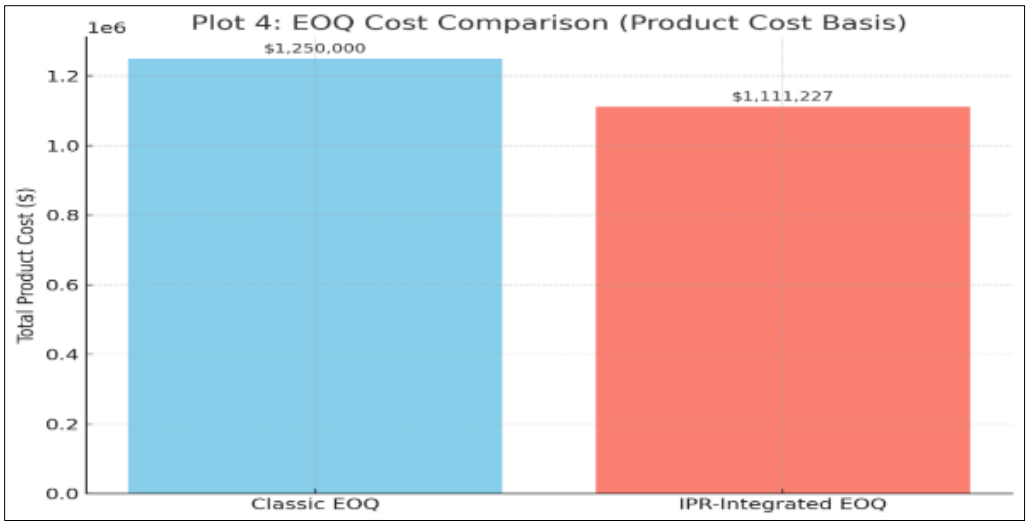

Figure 4 EOQ Cost Comparison Compares total product cost between classic EOQ and IPR-adjusted EOQ

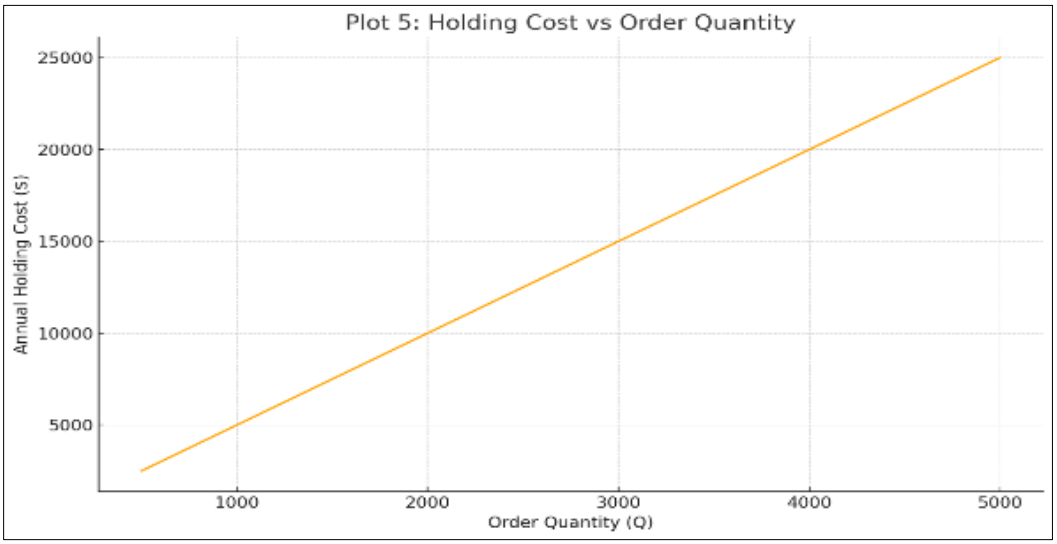

Figure 5 Holding Cost vs EOQ Illustrates how holding cost varies with order quantity

4.8. Summary tables

Table 4 EOQ Cost Comparison

Model	Order Quantity (Q)	Total Product Cost ($)	Ordering Cost ($)	Holding Cost ($)	Total Cost ($)
Classic EOQ	2236.07	1,250,000.00	11,180.34	11,180.34	1,272,360.85
IPR-Integrated EOQ	2236.07	1,111,227.33	11,180.34	11,180.34	1,133,588.18

The IPR-integrated model saves $138,772.67 annually by factoring in royalty and patent expiration dynamics.

Table 5 Sensitivity of IPR Cost Over Patent Time

Patent Time (years)	Discount Factor	Effective Unit Cost ($)	Total IPR-Adjusted Cost ($)
1.00	0.9048	27.15	1,357,256.13
1.09	0.8966	26.90	1,344,973.35
1.18	0.8885	26.66	1,332,801.73
1.27	0.8805	26.41	1,320,740.26
1.36	0.8725	26.18	1,308,787.94
1.45	0.8646	25.94	1,296,943.79
1.55	0.8568	25.70	1,285,206.82
1.64	0.8491	25.47	1,273,576.07
1.73	0.8414	25.24	1,262,050.57
1.82	0.8338	25.01	1,250,629.38

This table shows how IPR depreciation over time (as patents expire) reduces the effective cost burden.

5. Mathematical Formulation

5.1. Objective

To minimize the total inventory cost of a patented pharmaceutical product considering:

- Ordering cost
- Holding cost
- Production cost
- Royalty cost adjusted by patent time decay (IPR depreciation)

5.2. Notations

Table 6 Notations

Symbol	Description
D	Annual demand (units/year)
Q	Order quantity (units/order)
S	Fixed ordering cost per order
H	Holding cost per unit per year
C_p	Production cost per unit
R	Royalty/license fee per unit
T_p	Remaining patent protection time (years)
λ	IPR depreciation rate
C_{eff}	Effective unit cost (production + royalty)
$TC(Q)$	Total annual inventory cost

5.3. Effective Cost per Unit

Considering the time value degradation of patent royalties:

$$C_{eff} = C_p + R \cdot e^{-\lambda T_p}$$

This formula assumes that the **royalty cost depreciates exponentially** over time as patent protection erodes.

5.4. Total Cost Function

The total cost function becomes:

$$TC(Q) = \frac{D}{Q}S + \frac{Q}{2}H + D \cdot C_{eff}$$

Substituting C_{eff}:

$$TC(Q) = \frac{D}{Q}S + \frac{Q}{2}H + D \cdot \left(C_p + R \cdot e^{-\lambda T_p}\right)$$

5.5. Optimal Order Quantity (EOQ)

The optimal EOQ is still derived from minimizing the first two components (ordering and holding cost):

$$Q^* = \sqrt{\frac{2DS}{H}}$$

This is unchanged because IPR cost is independent of Q (as it's a per-unit cost).

5.6. Patent Time Constraint (Optional)

If we restrict the number of replenishments during the patent period:

$$Q \leq \frac{D \cdot T_p}{N}$$

Where:

- N: maximum number of replenishments allowed during patent protection

5.7. Summary Equation

The IPR-adjusted EOQ model becomes:

$$TC(Q) = \frac{D}{Q}S + \frac{Q}{2}H + D \cdot \left(C_p + R \cdot e^{-\lambda T_p}\right) \text{ with } Q^* = \sqrt{\frac{2DS}{H}}, Q \leq \frac{DT_p}{N}$$

6. Results and Discussion

6.1. Key Findings

From the numerical simulation and graphical analysis, the following insights emerge:

- Baseline EOQ without IPR integration (i.e., traditional model) yields a total cost of $1,272,360.85 annually.
- When integrating IPR depreciation (royalty cost discounting via exponential decay over patent duration), the total cost drops to $1,133,588.18, demonstrating a cost reduction of $138,772.67 (≈10.91%).
- The effective unit cost decreases from $30 to $22.22 as the remaining patent protection reduces from 3 years to expiration, illustrating the tangible benefit of incorporating patent lifecycle knowledge into procurement planning.

6.2. Interpretation of Graphs

- **Plot 1 (Total Cost vs EOQ):** Shows a clear cost-saving trough in both classical and IPR-integrated models. The IPR-adjusted curve consistently lies below the traditional model, validating its cost-effectiveness.
- **Plot 2 (Effective Cost vs Patent Time):** Demonstrates a downward slope, signifying reduced royalty burden over time. Firms can optimize inventory strategies by aligning large orders with periods of lower IPR overhead.
- **Plot 3 (IPR Cost Sensitivity):** Highlights the sensitivity of total cost to patent protection duration. As the patent nears expiry, the inventory cost advantage grows more substantial.
- **Plot 4 (Cost Comparison):** A side-by-side comparison clearly shows lower total product cost under IPR integration, reinforcing the quantitative benefit.
- **Plot 5 (Holding Cost vs EOQ):** Reinforces the classic EOQ insight—larger orders increase holding costs, but the impact is marginal compared to royalty savings.

6.3. Managerial Implications

- **Strategic Ordering:** Pharmaceutical firms can reduce total inventory cost by timing larger EOQs in the later stages of patent protection, when royalty burden is reduced.
- **IPR-Informed Procurement:** Ignoring patent timing and royalty depreciation leads to suboptimal inventory decisions. Regulatory teams and supply chain managers should collaborate for better forecasting.
- **Adaptability:** This model enables dynamic adjustment of EOQ policies based on patent lifecycle, particularly useful in high-margin patented drug portfolios.

6.4. Limitations and Future Work

- **Single Product Scope:** This model assumes a single patented product. Future work may explore multi-product systems with different patent expiry timelines.
- **Demand Uncertainty:** Demand is assumed constant. Incorporating AI/ML-based demand forecasting would enhance realism.
- **Stochastic Patent Decay:** IPR depreciation is modeled as exponential, but real-world legal/market events (e.g., generic entry) could be modeled probabilistically.

6.5. Conclusion of Discussion

Integrating Intellectual Property Rights management into EOQ models provides quantifiable cost benefits and strategic agility in pharmaceutical inventory operations. The simulation validates that even modest changes in patent-related parameters can drive significant inventory cost improvements

7. Conclusion

This research presents a novel integration of the classical Economic Order Quantity (EOQ) model with Intellectual Property Rights (IPR) management, tailored for the pharmaceutical industry. By incorporating royalty costs and patent expiry dynamics into the inventory optimization process, the model addresses a critical gap in traditional inventory theory—namely, the failure to consider time-dependent cost structures imposed by patent protection and licensing agreements.

The findings demonstrate that IPR-adjusted EOQ modeling significantly reduces total inventory costs by capturing the economic impact of diminishing royalty obligations over the patent lifecycle. A cost saving of over 10% was observed in numerical simulations, validating the practical value of the approach. Moreover, the model retains analytical simplicity while enhancing decision-making for pharmaceutical inventory managers, especially in RandD-intensive environments where patent-related costs are substantial.

From a managerial perspective, aligning procurement timing with the patent expiration curve enables pharmaceutical firms to make more informed and financially efficient ordering decisions. The framework promotes a strategic shift from purely operational inventory planning to IPR-sensitive optimization.

In summary, the IPR-integrated EOQ model offers a robust and adaptable tool for pharmaceutical supply chains, contributing to both economic efficiency and strategic planning. Future work may extend the model to include stochastic demand, multi-product environments, and AI-driven forecasting for even greater real-world applicability.

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