Journal of Chemical Health Risks

www.jchr.org

JCHR (2026) 16(1), 78-86 | ISSN:2251-6727

EPQ Model Evolution: A Review of Fuzzy Demand, Deterioration, Rework, and Environmental Aspects

Heena Dattatraya Buradkar[1] Gopal Kumar Gupta[2]

[1]Symbiosis Institute of Technology Nagpur Campus, Symbiosis International (Deemed University) Pune, India - 440008

[2]Symbiosis Institute of Technology Nagpur Campus, Symbiosis International (Deemed University) Pune, India - 440008

(Received: 25 November 2025 Revised: 27 December 2025 Accepted: 01 January 2026)

KEYWORDS

fuzzy modeling, rework in imperfect production, sustainability considerations, backordering policies, and dynamic costing methods

ABSTRACT: A thorough examination of developments in Economic Production Quantity (EPQ) inventory models is provided in this study of the literature, with an emphasis on adding practical complexity to improve applicability in the real world. Traditional EPQ frameworks, developed under deterministic assumptions, often fall short when applied to uncertain and dynamic industrial environments. Over the years, researchers have extended EPQ models by incorporating fuzzy logic to manage uncertainty in demand and deterioration, and by embedding mechanisms for rework, backordering, trade credit, and sustainability. Although there has been significant advancement, current research generally considers these factors separately. A substantial research gap persists in the integration of fuzzy environments with other essential components like rework processes, screening errors, and environmental im- pacts within unified frameworks. This review emphasizes the necessity for detailed EPQ models that reflect the intricacies of actual systems, and it outlines future research avenues for creating integrated, resilient, and flexible inventory models in uncertain conditions.

1. **Introduction**:

The notable variant of the traditional Economic Order Quantity (EOQ) model, the Economic Production Quantity (EPQ) model is intended for use in scenarios where businesses produce their own goods instead of obtaining them from outside vendors. The EPQ model, which is based on Harris' (1913) EOQ concept, determines the ideal production lot size to save overall expense, which includes setup costs, holding costs, and, in some situations, shortage costs. Classical EPQ models, such as those explored by (Chung, 2003) and later expanded by (Huang, 2007), (Huang Y.-F. a.-F., 2008), were centered on deterministic parameters under idealized assumptions. Researchers have gradually incorporated more realistic constraints, such as setup cost functions in the study (Nobil, 2022), rework processes (Taleizadeh, 2024), (Cárdenas-Barrón, L. E., 2008), (Cárdenas-Barrón, L. E., 2009) and backorders (Nguyen, H. N., Godichaud, M., & Amodeo, L., 2023), to capture complexities in actual production environments. Conventional inventory models typically compute features like demand rate, holding cost, and defective rate using exact numerical data. However, these factors are rarely known with precision in real-world erratic markets, supplier concerns, or unclear managerial projections.

To deal with such uncertainties, researchers developed fuzzy set theory in inventory modelling. In 1965 Zadeh created a fuzzy logic, which enabled decision makers to work with inaccurate data by defining variables as ranges or linguistic terms (like" high demand" or" about 100 units") instead of precise integers. Fuzzy models have been created to address the uncertainty surrounding demand rates, deterioration rates, and cost in EPQ. Recent advances have utilized fuzzy set theory to tackle parameter uncertainty, particularly in regard to demand and deterioration rates, as seen in the work of (De Kumar, 2003), (Appadoo, 2021), (Hsieh, 2002). The EPQ model developed by (Chandramohan, 2023) considered environmental, social, and epidemic factors. The decision robustness of these models is enhanced through the use of fuzzy numbers and approximation method such as the Macluarins series, as detailed (Jana, 2025).

1. **Background**

The classical EPQ model, which assumes predictable demand, an unlimited production rate, and perfect objects. Enhanced the model by incorporating trade credit regulations and relaxing the instantaneous replenishment assumptions (Chung, 2003) (Huang Y.-F. , 2007). Expanded on it by incorporating rework operations, which are critical in industries where damaged goods are widespread (Cárdenas-Barrón, L. E., 2008) (Cárdenas-Barrón, L. E., 2009),

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JCHR (2026) 16(1), 78-86 | ISSN:2251-6727

(Taleizadeh, A. A., Naghavi-Alhoseiny, M. S., Cárdenas-Barrón, L. E., & Amjadian, A., 2024). To overcome uncertainty in production systems, various academics used fuzzy set theory. Fuzzy production-inventory model optimization was proposed by (Hsieh, 2002) (De Kumar, 2003) investigated the relationship between fuzzy demand and deterioration rates and used back-ordering under fuzzy situations (Wang, 2009)]. More advanced fuzzy modeling approaches have since emerged, such as possibility moments (Jana, 2025), (Appadoo, 2021) .On the sustainability front, (Yee, 2023)proposed an EPQ model that accounts for water waste and carbon emissions. Proposed a model that considers pandemic effects, social concerns, and product deterioration (Chandramohan, 2023).Used a lock fuzzy game theory technique to investigate pollution-sensitive EPQ systems in the study (Bhattacharya, 2023).

The components of Expectancy, Quality, and Perception are funneled into the creation of an improved EPQ (Economic Production Quantity) model, as shown in Figure 1. In inventory modeling, human-centric and qualitative elements are seen as essential to creating realistic and flexible production strategies, and this representation is in according to these tendencies. The expected advantage or satisfaction that decision-makers attach to inventory policies is known as expectation. It affects the confidence in implementing specific production plans and frequency of replenishment. Quality emphasizes how crucial it is to incorporate inspection procedures, defect rates, and flawed production processes into the EPQ structure, this is well backed by current research on imperfect production systems. Subjective assessments like perceived degradation, time sensitivity, or demand response are all part of perception. More and more, these variables are being modeled to represent real behavior in unpredictable settings.

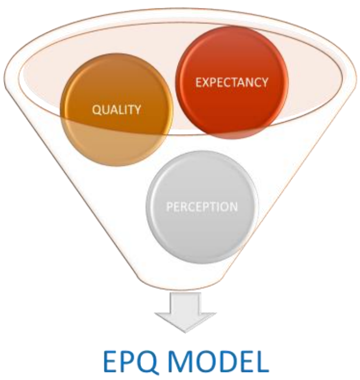

Figure 1: EPQ MODEL

2. Paper Outline:

This systematic survey paper is composed of different sections. Section I (Introduction and Background). Section II (Survey Literature): Classical EPQ Extensions, Fuzzy Logic in EPQ Models, Rework and Imperfect Production, Sustainability and Energy Considerations Back ordering, Trade Credit, and Inventory Policy, Mathematical Improvements and Dynamic Costing. Section III (Research Gap): Discussing the potential research gaps in the selected literatures. Section IV (Conclusion): Concluding the study with future scope.

3. Literature Survey:

A generalized framework often used in EPQ-based inventory systems is shown in Figure 2, It begins with determining the goal and recognizing pertinent system constraints. After the constraints are established, the EPQ model is developed to compute the ideal order quantity. Appropriate adjustments are made based on the nature of demand, whether it is constant or fluctuating. The following actions consist of determining reorder points, calculating total cost, and assessing the appropriateness of the inventory level. This systematic approach is characterized by its iterative nature and aligns with methodologies suggested by prior researchers.

3.1 Classical EPQ Extensions:

The intricacy of production in the real world is often not well represented by the traditional Economic Production Quantity (EPQ) model, which is predicated on idealistic assumptions. Extensions to this paradigm have emerged to make it more practical. A growing importance on integrating real-world complications including deteriorating sustainability, fuzzy surroundings, and dynamic systems behavior is reflected in recent development in Economic Production Quantity (EPQ) models. Examined traditional EOQ computation techniques once more, providing important insights into straightforward but reliable analytical process in the study (Chiang, 2024). Developed a green EPQ model in the area of sustainability that takes greenhouse gas emissions and wastewater into account, aligning inventory decisions with environmental objectives (Yee Y. M., 2023). Provided two solutions presented for idle versus shutdown states to maximize energy utilization, connecting backordering choices with energy implications in EPQ systems (Nguyen, H. N., Godichaud, M., & Amodeo, L., 2023). Produced a contribution by combining backordering, lot-sizing, pricing, and rework in a practical production setup in the study (Taleizadeh, A. A., Naghavi-Alhoseiny, M. S., Cárdenas-Barrón, L. E., & Amjadian, A., 2024).

3.2 **Fuzzy Logic in EPQ Models:**

A novel fuzzy optimization method involving Newton's interpolating polynomial-based defuzzification and max-min operator was used the best course of action for inventory management by solving a nonlinear constrained EPQ model for an imperfect production process with item deterioration, Type-I and Type-II screening errors, safety stock during production and screening time, and non-randomly varying constant demand in the study. By combining Game theory and a lock fuzzy system, (Bhattacharya, K., & De, S. K.,

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JCHR (2026) 16(1), 78-86 | ISSN:2251-6727

2023)[proposed a pollution sensitive EPQ inventory model under two scenarios- with and without failure induced deterioration, where the crisp model was converted into a fuzzy game using Gaussian probabilistic strategies and lock fuzzy numbers in order to optimize cost and pollution levels. By representing uncertain characteristics like demand, pro- duction rate, and time using trapezoidal fuzzy numbers, investigate the incorporation of fuzzy set theory into production inventory models in the study (Hsieh, 2002). Proposed a fuzzy chance con- strained programming (CCP) model and a fuzzy expected value (EVM) model to address the shortcomings of the traditional EPQ model in the study (Wang, 2009) . Created an EPQ model with fuzzy demand and deterrence rate, as well as output loss from manufacturing machines, for a more realistic production scenario using fuzzy membership functions and sensitivity analysis on (De Kumar, 2003).

3.3 Rework and Imperfect Production:

Economic production quantity (EPQ) models have recently evolved to more fully account for the realities of imperfect production and the need for rework, which represents a substantial shift from the conventional perception of faultless manufacturing. Presented fundamental guidelines for managing rework based on time in production cycles on (Jamal, 2004). Building on this, offered simplified algebraic formulation for these models, integrating rework, planned back-orders and shipment scheduling into EPQ frameworks in the study (Huang Y. F., 2007), (Wang, X., & Tang, W., 2009), (Khan, 2017), (Chung, K. J., Cárdenas-Barrón, L. E., & Ting, P. S., 2014), (Cárdenas-Barrón L. E.-G., 2014). In order to improve the model's applicability under actual manufacturing restrictions, Created a EPQ models that took into consideration rework, scrap, machine breakdowns, and different delivery policies in this study (García-Laguna, 2010), (Su, 2014), (Gani, 2015), (Taleizadeh A. A.-K.-B., 2017) , (Taleizadeh, A. A., Naghavi-Alhoseiny, M. S., Cárdenas-Barrón, L. E., & Amjadian, A., 2024). To improve allocation and cycle length decisions, researcher's studied production planning on single and multiple machines with imperfect quality and classified rework classified (Nobil, A. H., Sedigh, A. H. A., & Cárdenas-Barrón, L. E., 2016), (Cárdenas-Barrón L. E.-G., 2025). In stochastic lead time supply chain, (Shafiee-Gol, 2016) combined inspection errors and learning effect, emphasizing that Type -I error significantly raise system cost. Partial back-ordering, degradation and performance dependent screening were used in other studied by (Najafi, M., Ghodratnama, A., & Pasandideh, S. H. R., 2018), (Mishra, U., Tijerina-Aguilera, J., Tiwari, S., & Cárdenas-Barrón, L. E., 2021), (Dolai, 2021) to account for production dynamics . In order to increase profitability through co- operative planning, (Salas-Navarro, 2019) proposed by a collaborative EPQ model for a two-echelon supply chain with probabilistic. In order to handle demand uncertainty, screening errors, and deterioration in imperfect production systems, researchers (Wang, 2009), (Chung K. J.-B., 2014), (Mishra, 2021), (Jana, 2025) have more recently used fuzzy logic and stochastic elements.

3.4 Sustainability and Energy Considerations:

To meet the increasing demand for sustainability, enhancement, and overall efficiency in production and inventory systems. Researchers have built upon traditional EPQ frameworks to integrate real-world complexities, including imperfect production, rework, carbon emission cost, energy consumption, and decision making in the face of uncertainty. Under single-setup multi-delivery (SSMD) policies. (Cárdenas-Barrón L. E.-G., 2012) introduced vendor–buyer coordination models that take carbon emission costs into account. They showed that this integration reduces joint total cost and enhances environmental performance. The stochastic EPQ model created by (Shafiee-Gol, 2016) includes variable lead times, inspection errors, and learning effects, highlighting how quality control affects supply chain sustainability. Tackled the time value of money in rework-based EPQ systems involving multiple shipments, advocating for synchronized operations to improve long- term profitability in the study (Taleizadeh A. A.-B., 2012).

Recent development in inventory management have enhanced the traditional Economic Production Quantity (EPQ) models by incorporating practical elements like cost limits, trade credit programs, and back-ordering. The field was greatly advanced by (Cárdenas-Barrón, L. E., 2010) who developed EPQ models that like into account pricing decisions, full or partial back ordering conditions, outsourced rework operations and imperfect goods. In order to make EOQ/EPQ models more accessible to practitioners without extensive mathematical training, (Cárdenas-Barrón, L. E., 2010)proposed a geometric algebraic method for obtaining closed form solutions that incorporate both linear and fixed backordering costs. In order to address the problem of deteriorating inventory in the setting of partial trade credit, (Shaikh, A. A., Cárdenas-Barrón, L. E., & Tiwari, S., 2018)provided a simplified closed form approach that reduced computing complexity. (Najafi, M., Ghodratnama, A., & Pasandideh, S. H. R., 2018) expanded the EPQ framework to include multi-product systems with partial backordering rework and scrap, all while being constrained by capacity and budget. For assessment, they made use of multi-criteria decision-making methods and GAMS optimization. Provided an analysis of EOQ/EPQ models with variable holding cost in their study (Alfares, H. K., & Ghaithan, A. M., 2019).

3.6 Mathematical Improvements and Dynamic Costing

The most recent development in inventory modeling have sought to enhance the conventional Economic Production quantity (EPQ) models using dynamic costing techniques and mathematical improvements to better represent the complexity of the real world. Since, (Cardenas-Barron, 2010)presented a geometric algebraic method for obtaining closed form EOQ/EPQ solutions including linear and fixed backordering costs, making the methodology accessible to practitioners without a high level of mathematical knowledge. Decreased the computational overhead frequently associated with iterative strategies by creating a

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JCHR (2026) 16(1), 78-86 | ISSN:2251-6727

closed form EOQ model for degrading products with partial trade credit in the study (Shaikh, 2018). Introduced a fuzzy economic model that takes safety stock and Type-I and Type II screening errors into account in the study (Jana, 2025). Constrained fuzzy Newton interpolation is used in this approach to maximize expenses when demand and cost conditions are unknown. The work of (Taleizadeh, A. A., Naghavi-Alhoseiny, M. S., Cárdenas-Barrón, L. E., & Amjadian, A., 2024) includes a pricing-based EPQ approach that combines backordering and rework, enabling the simultaneous optimization of backorder levels, lot size, and selling price. Expanded this research avenue by developing a multi-product EPQ model that incorporates budgetary and capacity constraints, partial backordering, and rework on (Najafi, M., Ghodratnama, A., & Pasandideh, S. H. R., 2018), (Nobil A. H.-B., 2020). This model was solved using GAMS and assessed with multi criteria decision making (MCDM) techniques. Emphasized the importance of incorporating variable holding costs and suggested that trade credit and stochastic parameters be added to improve realism in the study (Alfares, 2019)

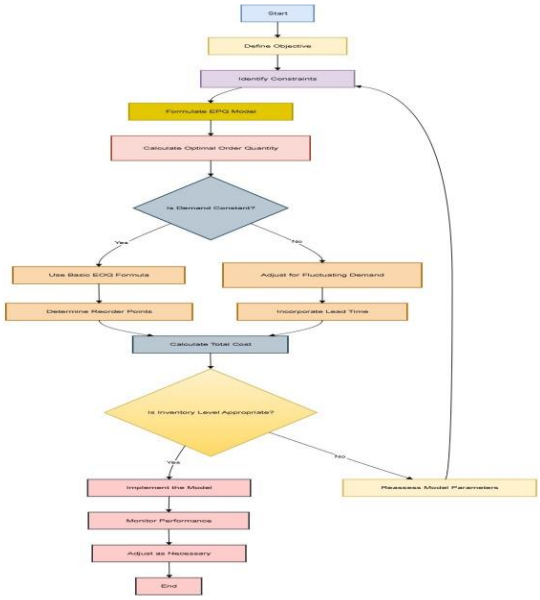

Figure 2: Inventory Model

Table 1: Comprehensive Literature Survey

Authors	Proposed Model	Technique	Limitations
Jana et al. (2025).	Type-I and Type-II screening mistakes are taken into account in the flawed EPQ model with safety stock	A method to constrained fuzzy Newton interpolation	Requires a significant amount of computing power and assumes certain fuzzy parameters
Yee et al. (2023).	Sustainable EPQ model taking wastewater and greenhouse gas emissions into account	Including environmental costs in the EPQ model	Environmental data might differ greatly; therefore, modelling sustainability variables can be challenging.
Nguyen et al (2023).	The EPQ model that takes energy use and backorders into ac- count	Energy variable integration in EPQ	Estimating realistic energy data could be challenging; model complexity would rise.
Taleizadeh et al. (2024).	Backorders, lot sizing, pricing, and rework in the EPQ model	Mathematical optimization with many objectives	Rework cost assumptions and a complicated optimization technique limit the applicability.
Chandramohan (2023).	Multi-objective EPQ for decaying objects with environmental and societal impacts caused by pandemics	Multi-criteria optimization method- ology	Restricted to epidemic situations; challenging to extrapolate over time
Nobil et al. (2022).	EPQ with setup time/cost function for multi-product sub- optimal production systems	In EPQ, cost function-based modeling	Unsuitable for systems with wildly fluctuating setup expenses or du- rations
Appadoo et al. (2021).	Supply chain modeling with fuzzy nonlinear possibilistic moments	Possibilistic fuzzy number theory in practice	Subjective fuzzy estimations are difficult to use in deterministic environments and de- grade precision.

Dolai, M., & Mondal, S. K. (2021).	Performance-based screening and preservation technology in an imperfect production system	Combined preservation analysis and screening	Restricted to particular preservation procedures, presupposes a predetermined pace of screening
Mishra et al. (2021).	Inventory model with manageable shortages and deterioration	Under degradation control, optimization	Demands exact management of deterioration in certain industries, shortages could not be practical.
Shaikh et al. (2018).	EPQ deteriorates exponentially under partial trade credit policies.	Closed form an analytical solution	Only applicable in specified degradation and credit conditions.
Nobil et al. (2020).	EPQ model for several products with budget constraints, joint pro- duction, and discrete delivery	Optimization of joint production policy	Managing several goods and constraints are really complex
Taleizadeh et al. (2017).	Backorders and outsourced rework in an EPQ model	Including an out-sourcing strategy in inventory modeling	Presupposes the availability of trustworthy rework outsourcing; it might not always be economical.
Cardenas-Barron (2011).	EOQ/EPQ with two different kinds of back- order expenses	Algebraic deduction and analytical geometry	Minimized practical sensitivity analysis in Favor of theoretical derivation
Najafi et al. (2018).	Single-machine, deterministic EPQ for several products with partial backordering, scrap, and rework	Optimization in mathematics with deterministic parameters	The stochastic flexibility of the model is limited and its complexity is increased by multiple products.
Khan et al. (2017.	EPQ with learning and screening errors during stochastic lead times	Probabilistic modelling involving screening and demand variability	Complex error estimation, requires historical data calibration.
Shafiee-Gol et al. (2016).	EPQ for many products, including price, discrete delivery, and rework	Integrated pricing and production model	Discrete delivery increases complexity; rework process assumptions may differ.
Nobil et al. (2016).	EPQ for imperfect systems including several machines and products.	Optimal allocation and utilization	Assumes constant machine reliability; co- ordination among ma- chines is difficult.
Taleizadeh et al. (2016).	EPQ includes rework, price, and numerous shipments.	Combined pricing and lot sizes model	The model becomes tough with extremely variable demand or shipment delays.
Pacheco-elazquez et al. (2016).	The EPQ model takes into account raw material costs and backorders.	Cost-based EPQ inventory model	Assumes linear cost functions, which may not account for real- world pricing variations.
Gani et al. (2015).	Fuzzy EPQ with planned backorders in a single-stage system.	Fuzzy set theory and inventory models	Model correctness is based on fuzzy estimation and may be less interpretable.
Pasandideh et al. (2015).	Multiproduct EPQ with an unsatisfactory system and warehouse development costs	Non-Linear Optimization Technique	High computational load for large-scale implementation.

Su et al. (2014).	Inventory model with reused raw materials and defective objects	Mathematical modeling and optimization for an inventory model	Assumes perfect reusability; limited actual feasibility
Chung et al. (2014).	Inventory with non-immediate receipt and decaying items	Calculus based Optimization technique.	The non-instantaneous assumption may hinder agility in fast- moving commodities.
Molamohamadi et al. (2014).	EPQ with allowed shortages under trade credit	The Cuckoo Search Algorithm (CSA) has been used to optimize the inventory model	Trade credit terms may vary between suppliers,which reduces model robust- ness
Chung et al. (2012).	EOQ/EPQ using linear and fixed backorder costs	Complete the algebraic solution technique.	Focused on theoretical validation and not applicable to practical datasets.
Huang (2007).	Retailer replenishment under a two-level trade credit.	Optimization Technique	Credit terms are deemed static and may not reflect evolving supplier relationships.
Chung et al. (2003).	EPQ with allowable payment delays	Mathematical optimization.	Assumes complete compliance with the trade credit terms

4. **Research Gap:**

In order to address issues like imperfect production, fuzzy uncertainty, dynamic holding costs, and environmental sustainability, the traditional EPQ model has undergone significant expansion in recent years. However, several important research gaps persist. The number of models concentrate on rework, while fuzzy logic and game theory have been utilized to model uncertainty (Jana, 2025), (Taleizadeh, A. A., Naghavi-Alhoseiny, M. S., Cárdenas-Barrón, L. E., & Amjadian, A., 2024). According to (Bhattacharya, K., & De, S. K., 2023), the absence of standardization in defuzzification techniques results in inconsistent outcomes. In addition, incorporation of energy use (Nguyen, H. N., Godichaud, M., & Amodeo, L., 2023),According to (Najafi, M., Ghodratnama, A., & Pasandideh, S. H. R., 2018), multi echelon supply chains are another area that lacks development, as most current studies assume either a deterministic demand or the absence of collaborative mechanisms.

5. **Conclusion:**

The wide body of literature on EPQ models has made significant progress by including factors like rework procedures, trade credit, sustainability considerations, and fuzzy environments. How- ever, these features are frequently investigated in isolation, resulting in fragmented models that may not fully capture the intricacies of real-world production processes. A full EPQ framework that incorporates fuzzy demand, degradation, energy and environmental considerations, rework mechanisms, and screening errors under dynamic cost structures is still unexplored. Addressing these gaps can lead to more robust, adaptive, and long-term inventory decisions. Future study should focus on constructing such integrated models utilizing modern mathematical tools and computational methodologies, which will increase their usefulness in unpredictable and dynamic production situations.

Acknowledgment:

The corresponding author, Heena Dattatray Buradkar, expresses gratitude to Symbiosis Inter- national (Deemed University), Pune (SIT Nagpur Campus) for providing financial support for this work. The author is also thankful for the anonymous comments and insightful reviews of the reviewers in shaping this article

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