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Managing risk and disruption in production-inventory and supply chain systems: a review

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Abstract

This paper presents a literature review on risk and disruption management in production-inventory and supply chain systems. The review is conducted on the basis of comparing various works published in this research domain, specifically the papers, which considered real-life risk factors, such as imperfect production processes, risk and disruption in production, supply, demand, and transportation, while developing models for production-inventory and supply chain systems. Emphasis is given on the assumptions and the types of problems considered in the published research. We also focus on reviewing the mathematical models and the solution approaches used in solving the models using both hypothetical and real-world problem scenarios. Finally, the literature review is summarized and future research directions are discussed.

Keywords: Production-inventory, supply chain, risk management, disruption management, literature review.

1. Introduction

Over the last half a century, one of the most widely studied research topics, in Operations Research and Industrial Engineering, is the production-inventory and supply chain system. Production and supply chain systems exist, in many organizations, in different forms and degrees, depending upon the size and nature of the organization, the products produced and supplied, and the size of the production facilities, wholesalers and retailers. A key issue for the success in any organization, under a supply chain environment, is to ensure the smooth functioning of each and every entity in the chain by managing risks and disruptions (both predictable and unpredictable) efficiently.

Recently, risk and disruption management has become an important topic in supply chain research. In reality, the risk factors involved in supply chain systems [1] are: disruption in production, supply, and transportation, and uncertainty in demand and supply. Imperfections in production system are also an important factor that has a significant impact on a company's performance. Without a proper response to all these factors, the entire system can be imbalanced and the organization can face massive financial loss, as well as loss of goodwill. An organization should apply an appropriate mechanism to minimize the impact of such risk and disruption in supply, production and distribution.

A number of studies have been conducted in the past to develop models for managing risk and disruption in production and supply chain systems. The literature basically presents various types of models, such as models on imperfect production processes, production-inventory management with disruptions, and supply chain management with disruptions. These models have been solved using different solution approaches, and some of them were applied to real-life cases. In this paper, we focus on reviewing the papers that incorporate risk and disruption in modelling production and supply chain systems.

The reminder of this review paper is organized as follows. After the introduction, Section 2 presents a review of different models of risk and disruption. The different solutions approaches used to solve these models are described in Section 3. The models applied to real-life cases are reviewed in Section 4. Finally, conclusions are drawn and future research directions are provided.

2. Models

In previous research, a good number of papers considered some real-life risk and disruption factors while modelling production-inventory and supply chain systems. We have categorized these works into four classes: (i) modelling for imperfect production process, (ii) modelling with disruption, (iii) modelling for supply chain risk, and (iv) modelling for disruption recovery.

2.1 Modelling for imperfect production process

Imperfect production processes are very common in practice. Process reliability is used to include the effect of imperfection in production systems that have a significant impact on costs and profits [2]. At first, process reliability was considered by Cheng [2] in a single period inventory system that was formulated as an unconstrained geometric programming model. Later it was extended in [3] by considering product demand as a fuzzy random variable. In the past, process reliability has been incorporated to determine the optimal product reliability and production rate that achieves the highest total integrated profit [4], in studying an unreliable supplier in a single-item stochastic inventory system [5] and in analyzing a production lot size with price and advertising demands under the effect of inflation [6]. Recently, Paul *et al*. [7] extended the model proposed in [2], assuming product demand and inventory holding cost as fuzzy random variables, by maximizing the graded mean integration value of total profit. Some other models with process reliability in production-inventory systems were reported in [8],[9],[10],[11],[12],[13],[14],[15], and [16] .

2.2 Modelling with risk and disruption

Disruption management strategies can be categorized into three main groups [17]: mitigation strategies, recovery strategies, and passive acceptance. Mitigation strategies act in advance of a disruption irrespective of whether disruptions actually occur or not [18]. Examples of mitigation strategies include: increasing amount of safety stock, multiple sourcing, expanding capacity, increasing visibility and setting up alternative transportation modes [18]. Recovery strategies include the actions, which are taken only after the occurrence of a disruption. This strategy may include: alternative sourcing, rescheduling of plans for future periods, and rerouting of transport systems [19]. Lastly, passive acceptance, that is accepting the risks without any action, may be more appropriate in certain circumstances when the costs of mitigation or recovery strategies outweigh their potential advantages. . In the literature, most of the researches focused of mitigation strategies to manage the risks due to disruption. Recently, some researches have been carried out by applying recovery strategies. In case of sudden disruption, recovery strategies could be more effective than mitigation strategies. In this paper, we focus on reviewing papers that study on production-inventory and supply chain models for managing disruptions and risks.

Figure 1 presents a typical supply chain system with different disruptions. We have classified disruption risk into four categories: (i) disruption in production, (ii) disruption in supply, (iii) disruption in transportation, and (iv) fluctuation in demand, which are shown in Figure 1. Production disruption includes any form of interruption in production that may be caused due to shortage of material, machine breakdown and unavailability, or any other form of disturbance (either accidental or man-made). A supply disruption can be defined as any form of interruption in the material supply that may be caused due to delay, unavailability, or any other form of disturbance. The transportation disruption includes any form of interruption in the transportation system that may be caused due to vehicle breakdown, road work, strike, and natural disasters like floods and earthquakes. Lastly, demand fluctuation can be defined as any kind of variation in product demand at the retailer end. Demand can be increased or decreased for a certain period of time.

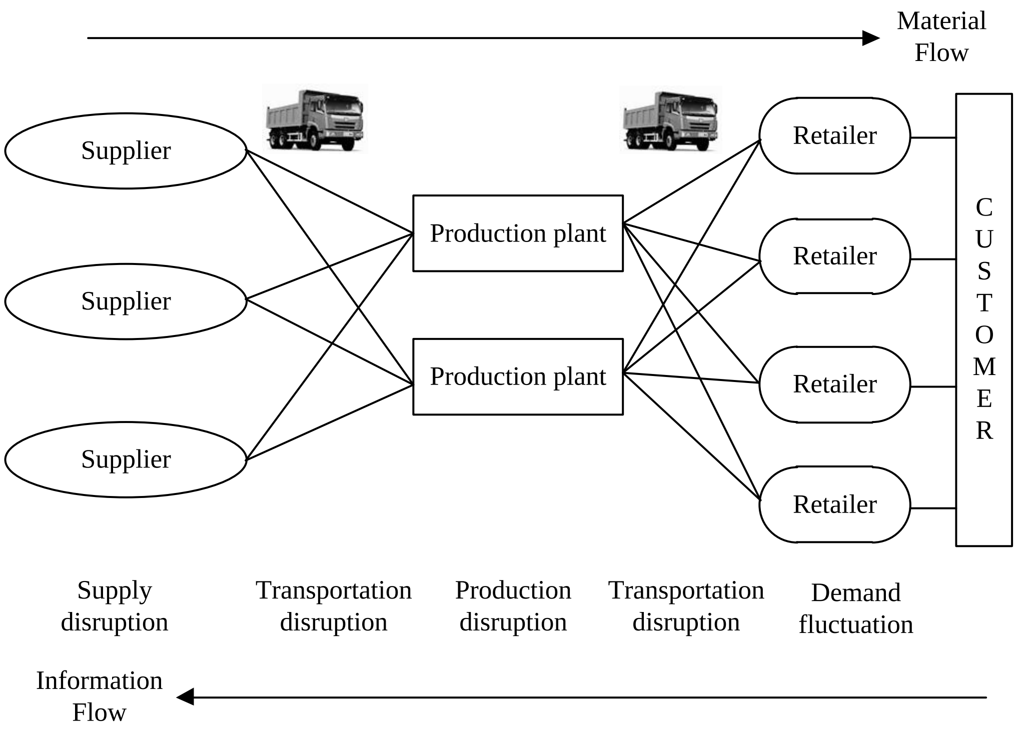

Fig. 1: Different disruptions in a manufacturing supply chain system

2.2.1 Disruption in production

Lin and Gong [20] analyzed the impact of machine breakdown on an Economic Production Quantity (EPQ) model, for deteriorating items in a single stage production system, that considered a fixed period of repair time. They minimized an expected total cost per unit time that included setup, maintenance, inventory, deterioration, and lost sales costs. Widyandana and Wee [21] extended the model of [20] under random machine breakdown and stochastic repair time using uniform and exponential distributions. An EPQ model with a Poisson distributed machine breakdown was used in [22] to determine an optimal production run time. They developed a cost function for a single stage production system, with and without breakdown, while assuming that some percentages of the products produced were defective, meaning that they must be either scraped or reworked. Moinzadeh and Aggrawal [23] considered a (s, S) production-inventory policy with random disruptions and exponentially distributed time between breakdowns in an unreliable bottleneck system. A two-stage supply chain, consisting of retailer and supplier, was considered in [24], where random disruption may occur at both the retailer and supplier ends, while assuming that unfulfilled customer demand will be lost. The proposed model minimizes an expected annual cost in finding the order quantity of the retailer. Schmitt and Snyder [25] developed an inventory model that considered two options: (i) an unreliable supplier and (ii) a reliable but expensive supplier.

For both cases, they considered disruption and recovery probability with yield uncertainty to find the optimal order and reserve quantities. Hishamuddin et al. [26] developed a production disruption recovery model in a single stage production-inventory system, which considered both back order and lost sales options. Chiu et al. [27] considered breakdown in equipment for developing an optimal replenishment policy for an economic production quantity (EPQ) inventory model. They assumed that the machine will go immediately to under repair whenever a breakdown occurs and the production resumes immediately after the machine is fixed and restored. Recently, Taleizadeh et al. [28] considered interruption in the manufacturing process to develop an economic production quantity (EPQ) inventory model. They studied a multi-product and single-machine EPQ model and permitted the shortage as backordered.

2.2.2 Disruption in supply

Supply disruption is another important consideration in production and inventory modelling. In inventory and supply chain disruption management, the highest numbers of papers deal with supply disruptions. In the early years, Parlar and Berkin [29] and Parlar and Perry [30] developed inventory models that considered supplier availability with deterministic product demand under a continuous review framework. Özekici and Parlar [31] considered back orders to analyze a production-inventory model under random supply disruptions. Weiss and Rosenthal [32] developed an optimal inventory policy for EOQ inventory systems which may have a disruption in either supply or demand. They considered that disruption is known a priori and it lasts for a random duration of time. Some other models for supply disruptions that considered deterministic or probabilistic product demand in their inventory models, can be found in [5], [17], [33], [34], [35], [36], and [37]. There are a few studies that considered both supply and demand disruptions with deterministic product demand, such as [38] and [39].

Recently, Hou *et al.* [40] studied a buy-back contract between a buyer and a backup supplier when the buyer's main supplier experiences disruptions and explored the main supplier's recurrent supply uncertainty through comparative studies. Pal *et al.* [41] considered two suppliers supplying raw materials to a manufacturer, where the main supplier may face supply disruption after a random time and the secondary supplier is perfectly reliable but more expensive than the main supplier, to develop a model in a multi-echelon supply chain. Snyder [42] introduced a simple but effective approximation for a continuous-review inventory model that considered supplier experiences as "wet" and "dry" (operational and disrupted) periods where the durations are exponentially distributed. Recently, Qi [43] considered two supplier concept; (i) supplier 1: primary supplier (cheaper) and (ii) supplier 2: backup supplier (expensive but reliable) to manage supply disruption for a single item continuous-review inventory problem. He considered two strategies to recover from a disruption; (i) If supplier 1 is available when the inventory level at the retailer reaches the reorder point, the retailer orders from supplier 1 and (ii) the retailer will reroute to the backup supplier if supplier 1 still does not recover from the disruption when the cap of waiting is reached. Hishamuddin et al. [44] applied the back order and lost sales concept to manage supply disruption in a two-stage supply chain, which consists of single supplier and single retailer. Some other recent works on managing supply disruption can be found in [45], [46], [47], [48], [49], and [50].

2.2.3 Disruption in transportation

In the literature, transportation disruption has got much less attention in comparison to production and supply disruptions. This type of disruption stops the flow of finished products to customers, whereas other types of disruption may also stop production of goods and supply of raw materials as well [19]. Giunipero and Eltantawy [51] discussed transportation disruptions in general, without specifying any strategies to deal with them. Wilson [52] investigated the effect of a transportation disruption on supply chain performance using a system dynamics simulation in a 5-echelon supply chain system, which is presented in Figure 2. Four types of disruptions were considered in the study: (i) transportation disruption between the warehouse and the retailer, (ii) transportation disruption between the tier 1 supplier (manufacturer) and the warehouse, (iii) transportation disruption between the tier 2 supplier and the tier 1 supplier, and (iv) transportation disruption between the raw material supplier and the tier 2 supplier. It was observed that the greatest impact occurs when transportation is disrupted between the tier 1 supplier and the warehouse.

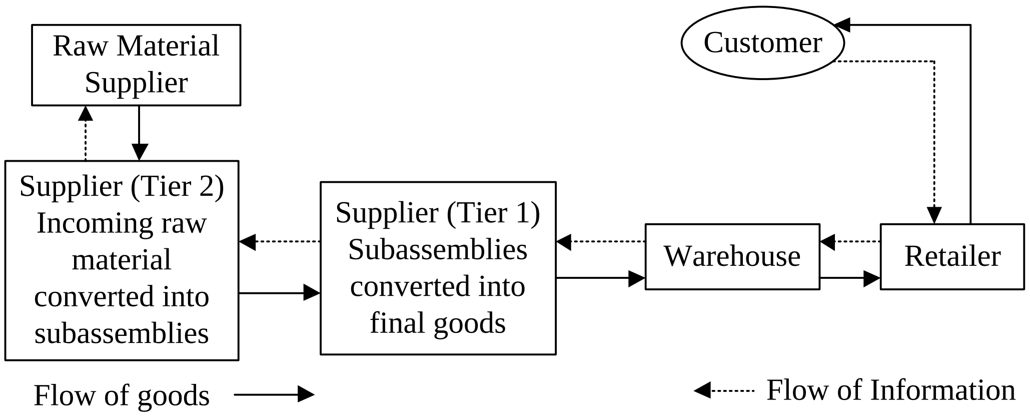

Fig. 2: Flow of goods and information: the tradition structure [52].

Zhang and Figliozzi [53] focused on the performance of international and domestic transport and logistics systems, as perceived by Chinese importers and exporters. They provided significant information regarding international freight transport chains, the impact of delays on supply chain operations and the subsequent costs, companies' delay and disruption planning, and managers' perspectives on future transport and logistics developments. Unnikrishnan and Figliozzi [54] formulated a mathematical model for a new type of freight network assignment problem in a dynamic environment with the presence of probable network disruptions or significant delays. Recently, Hishamuddin *et al.* [55] proposed a recovery strategy for managing transportation disruption in a two-echelon supply chain system that considered both back orders and lost sales options to recover after the occurrence of a sudden disruption.

2.2.4 Fluctuation in demand

A very few works have been found in the literature, which develop model for managing demand fluctuation in a supply chain system. Recently, Paul et al. [56] developed a mathematical model for managing sudden and short-term demand fluctuation, on a real-time basis, in a supplier-retailer coordinated system. They considered lost sales, back orders and production loss to develop the model. They also considered both a single and multiple fluctuations on a real-time basis.

2.3 Supply chain risk and disruption

Supply chain risk and disruption management is aimed at managing risks in complex and dynamic supply and demand networks [57]. There are some papers in the literature which focused on managing supply chain network disruption and risks. Tang [58] presented certain "robust" strategies, for mitigating supply chain disruptions, which possesses two strategies. The first strategy is to manage the inherent fluctuations efficiently, regardless of the occurrence of major disruptions, and the second strategy is for making a supply chain more resilient in the face of major disruptions. Craighead *et al.* [59] derived six propositions that related the severity of disruptions to the supply chain design characteristics of density, complexity, node criticality and to the supply chain mitigation capabilities of recovery and warning. Those propositions augmented extant knowledge as to what risk factors are present within a supply chain, how vulnerable a supply chain is to these risks, how resilient a supply chain is to some given risks, and what can be done to prevent or reduce the occurrences of severe supply chain disruptions. Xiao *et al.* [60] introduced a supply chain coordination model, with one manufacturer and two competing retailers, under demand disruptions. They found that an appropriate contractual arrangement can fully coordinate a supply chain and so a manufacturer can achieve a desired allocation of the total channel profit by varying the unit wholesale price and the subsidy rate. Manuj and Mentzer [61] proposed a comprehensive risk management and mitigation model for global supply chains, that brought together the concepts, frameworks, and insights from several disciplines – primarily logistics, supply chain management, operations management, strategy, and international business management. Wu *et al.* [62] presented a network-based modelling methodology to determine how changes or disruptions propagate in supply chains and how those changes or disruptions affect a supply chain system. The modelling approach provided insights to better manage supply chain systems that face disruptions and thus allow quicker response times, lower costs, higher levels of flexibility and agility, lower inventories, lower levels of obsolescence and reduced demand amplification throughout the chain. Recently, Atoei *et al.* [63] proposed a reliable supply chain network design model, by considering random disruptions in both distribution centers and suppliers, that determined the location of distribution centers by optimizing reliability as well as the transportation cost. Bradley [64] analyzed the differences between frequent and rare risks for supply chain disruptions, and proposed a new and improved risk measurement and prioritization method to account for the characteristics of rare risks. Some other supply chain disruption and risk management models can be found in [65],[66],[67],[68],[69],[70],[71],[72], [73], [74], [75], and [76].

A few papers have considered multiple sourcing strategies to manage supply chain disruption risks. Yu *et al.* [77] evaluated the impacts of supply disruption risks on the choice between the famous single and dual sourcing methods in a two-stage supply chain with a non-stationary and price-sensitive demand. They developed expected profit functions in the presence of disruption risks and then identified critical values of the key factors affecting the final choice. Xanthopoulos *et al.* [78] proposed news-vendor type inventory models for capturing the trade-off between inventory policies and disruption risks in a dual-sourcing supply chain. They developed models for both risk neutral and risk-averse decision-makers and obtained closed-form analytical solutions to determine the expected total profit of a retailer/wholesaler. Recently, Gong et al. [79] determined optimal ordering and pricing policies in each period over a planning horizon, and analyzed the impacts of supply source diversification. They showed that when both suppliers are unreliable, the optimal inventory policy in each period is a reorder point policy and the optimal price decreases from the starting inventory level of the period. They also reported that having supply source diversification or higher supplier reliability increases the firm's profit and reduces the selling price. Silbermayr and Minner [80] studied supply interruptions mitigation and management with sourcing from multiple suppliers. The study considered a supply chain with one buyer facing Poisson demand who can procure from a set of potential suppliers who are not reliable. They modelled the system as a Semi-Markov decision process where demands, lead times and availability of suppliers were stochastic. Some other models used multiple sourcing strategy to manage supply chain risk can be found in [81], [82], [83], [84], [85], and [86].

2.4 Modelling for disruption recovery

Disruption is a concern in production and supply chain environments because companies may face financial, as well as reputation losses, from such events. Due to disruption, the entire plan of an organization can be distorted, causing shortage of goods and unfulfilled customer demand. The development of an appropriate recovery policy can help to minimize losses and maintain the goodwill of a company. As of the literature, there exist limited studies that considered recovery planning from disruptions. If a system is disrupted for a given period of time (known as a disruption period), it is necessary to revise the production schedule (known as a recovery plan) for some periods in the future (known as a recovery time window) until the system returns to its normal schedule [26]. In some studies, it is assumed that the recovery time window must be specified by the management of the production system.

A few studies have developed recovery models to deal with a disruption after it occurs. Xia *et al.* [87] developed a general disruption management approach for a two-stage production and inventory control system that incorporated a penalty cost for deviations of the revised plan from the original one. They divided the disruption interval into three parts: pre-disruption, in-disruption, and post-disruption, for detailed analysis of the disruption effects. They developed a quadratic programming model that incorporated the concept of a disruption recovery time window. Eisenstein [88] introduced a flexible dynamic produce-up-to policy that is able to respond to disruption by adjusting the amount of idle time during recovery and re-established the target idle time as the schedule recovered.

A disruption recovery model, for a single disruption in a single stage and single item production system, has been developed in [26], for obtaining a recovery plan within a user defined time window, which was an extension of the model in [87]. The study considered back order, as well as the lost sales option. Later, they extended the concept for a transportation disruption recovery plan in a two-stage production and inventory system [55]. Recently, they proposed a supply disruption recovery model in a two-echelon supply chain system with single supplier and single retailer [44]. Recently, the concept of [26] was further extended to develop a real-time disruption management model, for managing both a single and multiple production disruptions in a single-stage [89] and two-stage [90] imperfect production-inventory system and for managing demand fluctuation in a two-stage supplier retailer coordinated system [56]. Some other disruption recovery models in the production-inventory and supply chain system can be found in [91], [92], [93], [94], [95], [96], [97], [98], and [99].

The model developed by Hishamuddin et al. [26], which was an extension of [87], enhanced the disruption recovery literature significantly. The model considered the disruption in the form of schedule interruption that is not known in priori. The model considered both back order and lost sales option and developed an efficient heuristic to determine the optimal recovery plan and the recovery cycles, after the occurrence of a disruption, are presented in Figure 3.

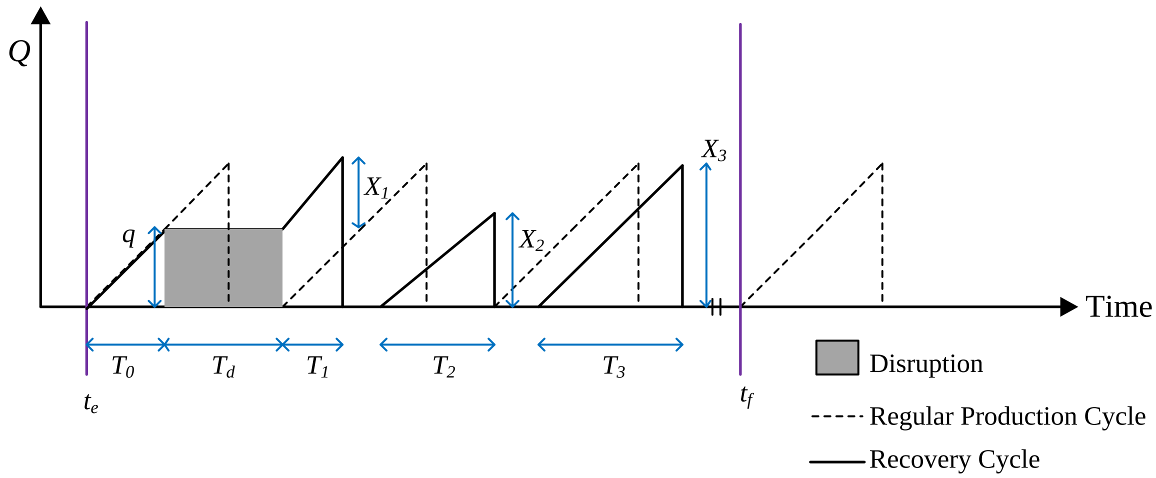

Fig. 3: Disruption recovery plan of Hishamuddin et al. [26].

They used following notations to formulate the model.

A	Set-up cost for a cycle
D	Demand rate for a product
H	Annual inventory holding cost
P	Production rate
Q	Production lot size in the original schedule
T_d	Disruption period
q	Pre-disruption production quantity in a cycle
T_0	Production time for q
u	Production down time for a normal cycle
t_e	Start of recovery time window
t_f	End of recovery time window
T	Production cycle time for a normal cycle
ρ	Production up time for a normal cycle
B	Unit back order cost per unit time
L	Unit lost sales cost
X_i	Production quantity for cycle i in the recovery window
T_i	Production up time for cycle i in the recovery window
S_t	Set-up time for a cycle
δ	Idle time for a cycle
n	Number of cycles in the recovery window

Finally, they developed the mathematical model, which was a constrained mathematical program and minimized the total cost. The final total cost function is presented in equation (1), which was subject to the constraints, presented in (2) – (6).

$$TC(X_i, n) = (A.n) + \left(\frac{H}{2P}\left(q^2 + 2qP.(T_d + S_t) + q.X_1 + \sum_{i=1}^{n} X_i^2\right)\right) + \left(B\left((X_1 + q)\left(T_d + S_t + \frac{X_1 + q}{P} - \frac{Q}{P}\right) + \sum_{i=2}^{n}\left(T_d + i.S_t + \sum_{j=1}^{i}\frac{X_j}{P} + \frac{q}{P} - i.\frac{Q}{P} - u(i-1)\right)\right)\right) + \left(L\left(nQ - (X_1 + q) - \sum_{i=2}^{n} X_i\right)\right) \quad (1)$$

$$X_1 \leq Q - q \quad (2)$$

$X_i \leq Q$; for $i = 2,3,\ldots, n$ (3)

$$\sum_{i=1}^{n} X_i \leq P(nT - nS_t - T_d) - q \quad (4)$$

$$X_1 + q + \sum_{i=2}^{n} X_i \geq nTD - (nQ - \sum_{i=1}^{n} X_i - q) \quad (5)$$

$$\sum_{j=1}^{i} X_j \geq i.Q + (i-1)P.u - P.T_d - P.iS_t - q \quad (6)$$

2.5 Summary of literature review for different models

The summary of the literature review for different models is presented in Table 1. It is observed that, most of the studies considered single risk factor while developing the model. Most of the models considered a simple supply chain network with only a single occurrence of disruption. In real-life, multiple disruptions can happen one after another as a series. A very few models have been found in the area of disruption recovery and most of them developed recovery model for a single disruption. So it can be said that there is a lack of quantitative disruption and risk management models to help the decision maker to make prompt and accurate decision.

Table 1: Summary of literature review for different models

Modelling type	Description	References	Remarks
Imperfect production	Production system is not 100% perfect and produces some defective items. The term, process reliability, is used for imperfect production system.	[2-16], [56], [89], [90], [95]	The models, developed for imperfect production process, extended the literature significantly. But in this competitive business era, the consideration of only process reliability is not sufficient to make the model realistic. Other risk factors, such as disruption in supply, production, and transportation and fluctuation in demand should be considered while developing a realistic production-inventory model.
Disruption management	**Production disruption:** Any form of interruption in the production that may be caused due to shortage of material, machine breakdown and unavailability, or any other form of disturbance (either accidental or man-made).	[20-28], [89-90], [95-96]	These papers developed models for managing production disruption mainly for a single-stage production-inventory system and also for managing only a single disruption. A very few developed the model for managing multiple disruptions.
	Supply disruption: Any form of interruption in the material supply that may be caused due to delay, unavailability, or any other form of disturbance.	[5], [17], [29-50]	These papers developed models for managing supply disruption mainly for a two-stage supply chain system with single supplier and single retailer and also for managing only a single disruption.
	Transportation disruption: Any form of interruption in the transportation system that may be caused due to breakdown, road work, strike, and natural disaster like flood, earthquake etc.	[19], [51-55]	Transportation disruption has got much less attention compare to production and supply disruptions. Most of studies developed model for a single disruption.
	Demand fluctuation: Any type of fluctuation in demand at the retailer end that may be caused due to seasonal variation, natural disaster etc.	[56]	This paper developed models for managing demand fluctuation for a two-stage supplier-retailer coordinated system with only single supplier and single retailer.
Supply chain risk	Managing risk in complex and dynamic supply and demand networks.	[57-86]	A plenty of papers have been found in the literature. They considered different risk factors, such as risk from different disruptions, sourcing, flexibility, and reliability. No study considered all risk factors together in a single study.
Disruption recovery	Development of appropriate recovery policy, after the occurrence of a disruption, on a real-time basis.	[19], [26], [44], [55-56], [87-99]	A very few studies have been found in the literature, which developed a recovery models after the occurrence of a sudden disruption. No study considered all disruptions together.

3. Solution approach

The solution approaches can be broadly classified as: (i) Traditional optimization approaches, (ii) Heuristic approaches, (iii) search algorithm approaches, and (iv) Simulation approaches. In the cases of solving complex models, research has focused on developing heuristics, rather than applying standard search algorithms. Many researchers have also used simulation techniques to make models closed to real-world processes.

3.1 Traditional optimization approach

If the supply chain problem is simple, then it can be solved by using a traditional optimization approach. A few examples of such approaches include: use of linear programming [100], geometric programming ([2], [3], [7]), quadratic programming [87], and the branch and bound method [101]. In real-life situations, supply chain risk and disruption management problem is a dynamic and complex problem. This limits the applicability of traditional optimization approaches to solve the risk and disruption management model.

3.2 Heuristic approach

Heuristics have the advantage of being simple to understand, easy to apply and are computationally very inexpensive [102]. Usually, heuristics were proposed when the corresponding mathematical model was too complex. Examples include: finding near optimal policies of a production-inventory system subject to exponentially distributed disruptions [23], managing production disruption in a single stage production-inventory system [26], dealing with transportation disruption in a two-echelon supply chain [55], and handling supply disruption in a two-echelon supply chain [44].

Abboud [103] developed an efficient algorithm that relaxed the constant recovery length assumptions made in [23]. Hishamuddin *et al.* [26] developed an efficient heuristic approach to determine the optimal values of the production quantities and number of recovery cycles for solving the recovery model of a single-stage production-inventory system. The heuristic consisted of three strategies: the total back order plan, the available capacity allocation, and the minimum back order requirement. Some other recent papers, which developed a heuristic, can be found in [104], [105], [106], [107], and [108].

3.3 Search algorithm approach

Search algorithms, such as: genetic algorithm (GA), simulated annealing (SA), ant colony algorithm (ACA), and particle swarm optimization (PSO) are also applied to solve the models developed in production-inventory and supply chain model. These are standard solution techniques to solve the model. Among the entire search algorithm, genetic algorithm was widely used. A few recent papers which used genetic algorithm can be found in [109], [110], [111], [112], and [113]. Other search algorithm, such as SA, ACA and PSO were also applied to solve the model developed in production-inventory and supply chain. Simulated annealing was used in [114], [115], and [116]. Ant colony algorithm was used in [117], [118], and [119]. Particle swarm optimization was used in [120], and [121].

3.4 Simulation approach

Simulation is defined as the imitation of the operation of a real-world process or system over time [122]. Simulation enables decision makers to improve operational efficiency and performance through its ability to incorporate the inherent uncertainties in a complex real system [123]. It is a very common tool in the literature, and used to evaluate the complex models of inventory and supply chains.

In this section, a brief review, of using simulation approach in inventory and supply chain risk management, is discussed. Wu and Olson [124] considered three types of risk evaluation models within supply chains: chance constrained programming (CCP), data envelopment analysis (DEA), and multi-objective programming (MOP) models. They modelled the various risks in the form of probability and simulation of specific probability distribution in a supply chain consisting of three levels and used simulated data with representative distributions. Longo and Mirabelli [125] presented an advanced modelling approach and a simulation model for supporting supply chain management. They considered two objectives. The first objective was to develop a flexible, time-efficient and parametric supply chain simulator starting from a discrete event simulation package and the second objective was to provide a decision making tool for supply chain management. They analyzed the effects of inventory control policies, lead times, customers' demand intensity and variability, on different supply chain performance measures. Pierreval et al. [126] performed a dynamic analysis of the behavior of an automotive industry supply chain through simulation, which was based on Forrester's system dynamic paradigms.

A few more examples of simulation use include: application of Monte Carlo simulation for quantifying supply chain disruption risk [127], reducing risk from both supply disruptions and demand uncertainty in a multi-echelon supply chain [128], and development of a second version of the supply chain operations reference model (SCOR), a simulation based tool for dynamic supply chain analysis [129]. The last model was also tested in a case company: Alfa Laval at Ronneby, Sweden – a manufacturer of heat exchangers. The tests analyzed the effect of supply disruptions in a single-product inventory system which involved a supplier, a retailer, and differentiated customers, by considering partial backordering when a stock out occurred [130]. Some other recent simulation studies can be found in [131], [132], [133], and [134].

Table 2: Summary of review for different solution approaches

Solution approach	Description	References	Remarks
Traditional optimization	This includes geometric programming, quadratic programming, and branch and bound technique etc.	[2-3], [7], [87], [100-101]	This approach is not suitable to solve dynamic and complex problem.
Heuristic	Heuristics are a subset of strategies to find the near optimal solutions.	[23], [26], [44], [55], [102-108]	This approach is simple to understand, easy to apply, computationally inexpensive and it requires less computational time.
Search algorithm	This is existing search algorithm, such as; genetic algorithm (GA), simulated annealing (SA), ant colony algorithm (ACA), and particle swarm optimization (PSO).	**GA:** [109-113] **SA:** [114-116] **ACA:** [117-119] **PSO:** [120-121]	This approach is an iterative method and it requires higher computational time.
Simulation	This is the operation of a process or system over time to make it closer to a real-world process.	[19], [122-134]	This approach makes the model closer to a real-world process when real-world data is not available.

The summary of the literature review for different solution approaches is presented in Table 2. It is observed that, most studies focused on using search algorithm to solve the models. A good number of works also have been found which developed heuristic and simulation approach to solve the complex models. In case of dynamic and complex problem, it is worth to develop a combined heuristic and simulation approach to make the model easy to implement and more closer to a real-world process.

4. Applications

In the recent years, the researchers have started to implement their models in a real-life case. Applying the developed models to real-life scenarios is a good way to judge their appropriateness, as it helps to show their usefulness and benefits. A few recent examples include: managing disruptions within the supply chain of a large US retailer [135], simulation study for risk assessment and management of a supply chain for an industrial case [136], development of a set of propositions about how companies manage supply risks in financial crises by using in-depth case studies conducted among eight European enterprises [137], application to an automotive spare parts manufacturer in Iran to manage supply chain disruption [138], design of a robust supply chain against disruption and application in a real-life case study from the agri-food industry [101], implementing the model in the cases of pharmaceutical company [87, 93], developing sustainable supply chain for UK construction industry [139], and application of ethanol supply disruption management model and methodology to Brazilian refineries system [140].

5. Conclusions

In this paper, a literature review has been presented in the field of managing risk and disruption in production-inventory and supply chain systems. In this section, we summarize the review and provide future research directions, based on the research gaps in the literature.

5.1 Summary of the literature review

In the literature, most of the previous studies considered only one risk factor such as uncertainty or disruption in a single stage and very little has been done for developing quantitative model to manage other risk and disruption incidents, such as imperfect production process, and disruption in production, supply and demand, and their combination. A very few study considered multiple types of risk and disruption incidents. In addition, the study of multiple disruptions, one after another as a series, on a real-time basis is very rare. However in a supply chain environment, any type of disruption can happen, one after another as a series, at any point in time. Furthermore, a limited number of studies covered multiple disruptions, whether dependent or independent, in a supply chain environment on a real-time basis. By implementing the developed approach in real-world case problems, one can judge the performance of the approach. Also, only a very few models were found to be implemented for real-life supply chain systems. Some papers developed a heuristic to solve their models, but very little has been done to develop a combined heuristic and simulation approaches to operate a model as a real-world process. So, it can be concluded that more research is needed to develop quantitative and real-time disruption management system that covers all the risk and disruption incidents.

In the literature, a reasonable number of works have been found in the area of supply chain disruption and risk management. Still there is a lack of quantitative disruption and risk management models to help the decision maker to make prompt and accurate decision. More researches are needed to fulfil the research gaps found in the literature by developing quantitative disruption and risk management models in production-inventory and supply chain systems.

5.2 Future research direction

From the literature review summarized above, it can be concluded that more research is needed to develop quantitative risk and disruption management model that covers imperfect production processes, and disruptions in production, supply, transportation and demand. Some of the future research directions include:

i. Consideration of multiple types of disruption and risk factors in a single study.
ii. Development of a real-time disruption management model for production-inventory systems.
iii. Extension of the disruption management model for supply chain systems.
iv. Consideration of multiple disruptions, one after another as a series, either dependent or independent, on a real-time basis.
v. Development of both the heuristic and simulation approach: (a) to make the model simple, (b) to improve operational efficiency and performance of the model, and (c) to operate the model as a real-life process.
vi. Development of alternative approaches to compare and validate the results.
vii. Implementation of the developed approach in a real-life case to judge applicability of the model.

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