A Multi-objective model for a Chemical Industry considering economic risk and environment

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Abstract. The research proposes a multiple objective model considering economic risk and environment in the chemical industry. The economic order quantity (EOQ) model is used for the economic aspect which considers the transportation modes and all unit quantity discount. The objective of this research is to optimize economic, safety and green performance in terms of cost minimization, risk control, and carbon emission reduction. A solution approach to obtain the optimal solution is proposed. A numerical example is performed to demonstrate the applicability and efficacy of the procedures.

Keywords: EOQ model, transportation, quantity discount, multi-objective optimization, chemical industry.

1. INTRODUCTION
According to Cefic chemical data, the annual sale of global chemicals in 2015 increased by €434 billion from 2014 – a substantial difference for the chemical industry. Chinese sales were the main reason for this change, with a value of €1,409 billion earned in 2014 when compared to €1,084 in 2014 (a 30% value increase).

Furthermore, transportation generated 14% of global Green House Gas (GHG) emissions in 2010. The main contributors to these transportation emissions were road vehicles, trains, airplanes, and maritime transport ships, which mostly used diesel and gasoline fuels (EPA, 2016). Road and marine transportation methods were the main avenues of transportation used by chemical logistics, in terms of ton-kilometer usage, and also the main contributors of CO\textsubscript{2} emissions. Meanwhile, freight transportation accounts for 1/3rd of all transportation emissions, out of which heavy long-distance trucking is a main contributor for CO\textsubscript{2} emission (Cefic, 2015). Heavy trucking transportation consists of two categories: the truckload mode (TL) and less-than-truckload mode (LTL).

TL transportation occurs when a firm utilizes capacities that may be less than the full capacity offered by a truck, while paying the cost of a full truck. Thus, a partial fixed cost per load can be calculated by the costs incurred by the truck, the driver, and by other operating expenses. In contrast, LTL transportation is calculated at a constant cost per unit due to standardized rates [1]. Risk management is also an important logistical component due to its ability to prevent interruptions, such as transportation hazards and labor disputes. The transport of dangerous chemicals involves a factor of risk for the driver and passengers, and also to other drivers. In the event of a chemical spill, the materials may be toxic or inflammable, and if spilled on the roadways, may incur cleanup costs and jeopardize traffic. The scale of risk may be anywhere from physical harm to the involved persons to fatalities. Thus, risk
can be calculated as the product of the sum of accident probabilities and their corresponding consequences of failure [2]. Modern economic competition requires members in the chemical industry to enter into cooperative relationships between suppliers, allies, and customers in order to overcome a variety of challenges, such as cost, quality, lead time, flexibility, customer service, and accident prevention. In addition, the participants must counter environmental change by minimizing carbon emissions. However, producers often hold a preference for optimization methods that create financial value over risk management and emissions reduction. Thus, risk reduction and carbon emissions control methods that do not increase economic costs present a challenge for supply chain managers.

A traditional and well-known method of supply chain optimization is the economic order quantity (EOQ) model, which was popularized due to its simple design, adaptability, and straightforward application [3]. Harris (1913) first created the model to calculate optimal order quantity based on manufacturing parameters and several cost considerations. Over time, the model underwent various adaptations as additional considerations were used to extend its formula. Mousavi et al. (2016) created a seasonal multi-product, multi-period control model with an all unit discount policy and inflation costs [4]. Tersine et al. (1995) extended the original model by considering fully back-ordered shortages with all unit discounts, incremental order volume discounts, and transportation discounts offered by the seller [5]. Bai et al. (2011) adapted an inventory model using multiple-supplier dynamic demand considerations for order cost, incremental order volume discounts, multiple setups, and all-unit quantity discount systems [6]. Taleizadeh (2014) developed an EOQ model allowing for partial backorders and all-unit discounts [7].

Mendoza et al. (2008) created a single-echelon EOQ model over a finite planning timeframe using two transportation methods [8]. Later, the authors extended the model to an infinite planning horizon [1]. The models, however, did not consider additional aspects such as risk planning and environmental impact minimization. Attempts were made by researchers to extend the model by considering variables such as transportation methods [1], risk management [2,9], and carbon emissions [10]. However, there is no integrated model considering these factors with EOQ.

Multi-objective considerations have seen widespread use in many research fields [11]. One such optimization solution is the Pareto optimal solution, which was applied by several researchers 94,11,12. Wang et al. (2011) used Pareto optimal solutions to calculate a Pareto frontier distribution which was then presented as a set of optimized solutions [11]. The stated model used only two objective functions. Zhao et al. (2017) adapted a green multi-optimization supply chain model that minimizes hazardous accident risks, carbon emissions, and cost [12]. The model, however, does not consider transportation modes, nor does it consider all unit quantity discounts. This research contributes by developing a multi-objective, two-echelon carbon emissions-minimizing supply chain model for the chemical industry. The model takes into account issues of cost, risk, and environmental concerns by introducing them as decision variables. These modified variables also provide considerations for economic cost decisions.

This paper proposes a multi-objective optimization model which considers economic costs, risk management, and carbon emissions control. In this research, an EOQ model was applied to calculate the system’s total cost, which directly impacts the cost aspect. Next, performance of the proposed model is tested via numerical analysis. The aspects of cost minimization, risk control, and carbon emission reduction can be clarified through this analysis, allowing for an appropriate strategy. The purpose of this research is to analyze and study the two-echelon network while considering economic costs, risk management, and environmental impacts in the chemical industry. The goal is to arrive at an EOQ system which can reduce costs, risks, and carbon emissions, so the research scope matches these aspects accordingly. Lastly, truckload and less than truckload (TL and LTL) transport methods are considered as specific costs along with all-unit quantity discounts as an extension to the model.

2. METHODS
The proposed two-echelon network has two members: the manufacturer and the distribution center. The research scheme description is portrayed below in Figure 1.
Figure 1. The proposed two-echelon network

2.1 Notations and parameters
The corresponding indices, decision variables, and criteria for this EOQ extension are shown below:

Indices
- \( m \): manufacturer
- \( d \): distribution center
- \( k \): the index set for the breakpoints \( \{0, \ldots, B\} \)

Parameters
- \( K \): individual setup cost, $
- \( h \): holding cost per time unit, $/unit/month
- \( d \): demand rate, $/unit/month
- \( Q \): order quantity, units
- \( CT \): fixed cost, $/truck
- \( B \): number of price breakpoints
- \( TQ \): demand time, months/truck
- \( QT \): truck volume for a full load, units/truck
- \( j \): quantity of truckloads, units
- \( s \): LTL cost per unit delivered, $/units
- \( n+1 \): number of breakpoints for changes in purchasing cost per unit
- \( \beta \): the \( i \)-th breakpoint (for the order interval \( T \)), month
- \( c_i \): unit cost for item \( i \), $
- \( l \): constant lead time, month
- \( r \): reorder point, \( r^* = dl \)
- \( demk \): main manufacturer demand for raw materials, kg
- \( demc \): consumer demand \( c \), kg
- \( Q_{ij} \): quantity of transported products
- \( caf \): capacity of facility, \( f \in \{m,d\} \)
- \( cat \): capacity of transportation
- \( Invm \): risk control investment at risk level \( m \)
- \( Invl \): carbon emissions reduction investment at emissions level \( l \)
- \( Rf \): Probability \( f \) that a failure will occur in facility \( i \)
- \( Rt \): goods delivery transportation risk
- \( Probm \): risk probability at the level \( m \)
- \( Probf \): probability of risk in facility \( f \)
- \( Probf'f \): risk for transport from \( f \) to \( f' \)
- \( Nfp \): monetary consequence of a type-\( p \) risk failure in facility \( f \), million dollars
- \( Nfp' \): monetary consequence of an accident resulting from a type-\( p \) risk failure during transportation from \( f \) to
$f', p \in \{1,2,3\}, \text{ million dollars}$

$L_{ij}$ distance between facility $f \in \{m,d\}$ and $f' \in \{m,d\}, \text{ km}$

$A_{rij}$ vehicle transport accident probability

$CE_f$ total carbon emissions in all network facilities, kgCO$_2$/kg

$CE_t$ transportation carbon emissions, calculated from transport distances, kgCO$_2$/kg

$EM_l$ emission factor at emission level $l$, kgCO$_2$/kg

$EM_f$ facility $f$ emission factor, kgCO$_2$/kg

$EM_{ff'}$ emission factor for transport from $f$ to $f'$, kgCO$_2$/kg

$x_{md}$ product quantity traveling from the manufacturer to distribution center $d$

Network decision variables are shown below:

$x_k$ 1, if the item is purchased
     0, otherwise

$y_d$ 1, if distribution center $d$ is chosen
     0, otherwise

$y_m$ 1, if risk level $m$ is chosen during risk control measures
     0, otherwise

$z_l$ 1, if carbon emission level is chosen during emission reduction measures
     0, otherwise

Assumptions for the network are:

• Distribution center demand is deterministic and known.
• The quantity delivered is known.
• Lead time is constant.
• Shortages are not allowed.
• Order quantities are made only when the inventory runs out.
• The truckload and less-than-truckload transport methods are always available.
• Each truckload delivers a quantity matching the time unit demand.
• Filling a truck to full capacity incurs a cost is lower than shipping via LTL, since equal costs would allow LTL transport benefits at no additional expense.
• The order transportation cost depends on the transportation method and the order quantity.
• Short-term risks are considered for the delivery item and in the facility.

Mathematical formulation

The model was made with three functional objectives: the minimization of risk, emission quantities, and total cost. Minimizing risk

Three risk types exist: fatalities, environmental harm and property damage, and are calculated as the product of the risk probability multiplied by the results of their occurrence. Environmental harm can be further expanded as water, air and soil pollution, and property damage can be classified as any accident that incurs losses on supply chain operations. The resulting function is a sum of these probabilities, shown below [12]:

$$\text{Minimizing risk} \quad R_i = \text{Prob}_i \cdot \sum_{p=1}^{3} N_{ip}$$

The sum of transportation risks and their corresponding events is shown below [12]:

$$R_{ij} = \text{Prob}_{ij} \cdot \sum_{p=1}^{3} N_{ip}$$

$$\Pr \text{Prob}_{ij} = A_{rij} \cdot L_{ij} \cdot Q_{ij}$$

Minimizing these inherent risks can be expressed by the following function:
Minimizing carbon emissions
Supply chain carbon emissions for the facility and for transportation can be calculated as follows:
\[
\text{Min } Z = CE_f + CE_t
\]
(7)
\[
CE_f = EM_f \cdot z_i \cdot \text{dem}_k
\]
(8)
\[
CE_t = EM_t \cdot z_i \cdot \text{dem}_k + x_{md} \cdot EM_{md} \cdot L_{md}
\]
(9)

2.2 Minimizing total economic cost
The EOQ model is applied as a part of the total cost. This model considers both truckload and less-than-truckload transportation, in addition to an all-unit quantity discount consideration [1].

The transportation cost \(C(T)\) denotes a cost for the order interval \(T\) which exists during the period \(jTQ \leq T < (j+1)TQ\) as shown below:
\[
C(T) = \begin{cases} 
sd(T - jTQ) + jC_T & \text{for } T \in I_j^1, \\
(j + 1)C_T & \text{for } T \in I_j^2,
\end{cases}
\]
(10)
where \(I_j^1 = \{T : jTQ \leq T < (C_T/sd) + jTQ\}\) and \(I_j^2 = \{T : (C_T/sd) + jTQ \leq T < (j+1)TQ\}\).

The purchasing cost depends on the order interval \(T\):
\[
F(T) = \begin{cases} 
c_0, & \text{if } 0 \leq T < \beta_1, \\
c_1, & \text{if } \beta_1 \leq T < \beta_2, \\
\vdots & \text{if } \beta_n \leq T < \infty.
\end{cases}
\]
(11)
It is then assumed that \(c_0 > c_1 > \ldots > \ldots > c_n > 0\)

Adding the all unit quantity discount creates this extension to the EOQ average total system cost:
\[
W(T) = \frac{K}{T} + \frac{hdT}{2} + \frac{C(T)}{T} + d \cdot F(T),
\]
(12)
\[
W(T) = \begin{cases} 
\frac{K - jsdTQ + jC_T}{T} + \frac{hdT}{2} + sd + d \cdot F(T) & \text{for } T \in I_j^1, \\
\frac{K + (j+1)C_T}{T} + \frac{hdT}{2} + d \cdot F(T) & \text{for } T \in I_j^2.
\end{cases}
\]
(13)
The algorithms used to calculate the optimal order interval values \((T_0\) and \(T^*_0)\) are then applied [1].

The total cost consists of setup, holding, transportation, risk reduction investment costs, and carbon emission reduction investment costs, which are shown with the following expression:
\[
\text{Min } Z = FC + HC + TC + RC + CE
\]
(14)
where \(FC\) is the fixed setup cost based on the operation of the facilities. \(HC\) is the holding cost, \(TC\), the transportation cost. \(RC\) contains all investments made towards risk reduction, and \(CE\) the investments made towards carbon emissions reduction.
3. RESULT AND DISCUSSION
Some constraints are considered in the model, including capacity limit constraints and the decision variables. These constraints are as follows:

3.1. Capacity limit constraints
\[ x_{kd} \leq c_{ak} \] \hspace{0.5cm} (15)
\[ x_{ff}' \leq c_{af}' \] \hspace{0.5cm} (16)

3.2. Constraints of decision variables
\[ x_d \leq x_{dc} \] \hspace{0.5cm} (17)
\[ x_d \in \{0,1\} \hspace{0.5cm} \forall \hspace{0.5cm} d \] \hspace{0.5cm} (18)
\[ x_{df} \geq 0 \] \hspace{0.5cm} (19)
\[ y_m, z_l \in \{0,1\} \hspace{0.5cm} and \hspace{0.5cm} m \in \{1, \ldots,a\}, \hspace{0.5cm} l \in \{1, \ldots,b\}, \hspace{0.5cm} a,b \in \mathbb{Z} \] \hspace{0.5cm} (20)

Solution Approach
The solution approach in this section is meant to determine a Pareto frontier, out of which a set of optimal solutions may be inferred. The decision maker is then able to choose the most beneficial tradeoff for their own purposes. Risk reduction is an additional constraint that must be considered while calculating minimum carbon emissions. The solution values to these goals were added to the total cost function in order to calculate the overall minimal cost. Lingo programming, or ILOG CPLEX, is used to solve the model.

Here, the model is analyzed using numerical analysis. Data was taken from previous studies [1, 12] with several modifications. The intent of these calculations is to find the optimal configurations which minimize all three objective functions.

Table 1. Data of The Parameters

| Parameter | Value     | Unit          |
|-----------|-----------|---------------|
| d         | 7,000     | units/month   |
| K         | 6,000     | $             |
| h         | 0.5       | $/unit/month  |
| C_T       | 2,000     | $/truck      |
| Q_T       | 5,000     | units/truck  |
| s         | 2.5       | $/unit       |
| T_Q       | 0.57      | months/truck |
| c_0       | 7         | $/unit (<10,000 units) |
| c_1       | 6         | $/unit (10,000 ≤ units < 30,000 units) |
| c_2       | 5.5       | $/unit (≥30,000 units) |
| β_1       | 1.43      | months       |
| β_2       | 4.29      | months       |
| dem_k     | 3652.3958 | kg/d         |
| N_kp      | 1,439     | million $    |
| N_kdp     | 215.911   | million $    |
| EM_m      | 247.64    | kg CO₂/ton of product |
| EM_kd     | 0.14      | kg CO₂/ton of product |
| Ar_kd     | 2.4 x 10⁻⁴ | frequent accidents |
|           | 1.61 x 10⁻⁵ | the expected number of accidents |
The optimal results for these three functions, in addition to the order quantity, are shown below in Table 2.

| The optimal reorder interval, $T_0$ | 1.71 months |
|-----------------------------------|-------------|
| The optimal reorder interval, $T^*$ (TL and LTL transportation and all unit quantity discount) | 4.29 months |
| Total cost | $51,135.71 |
| Optimal order quantity | 30,000 units |
| Inherent Risk | $5,892,937.13 |
| Carbon emissions | 3540.01 kg CO$_2$ |
| Total economic cost | $168,410.80 |

4. CONCLUSION
In recent years, due to the rapid development of the logistics industry, the shipping efficiency of goods has significantly improved compared to the past, but the losses in the shipping process will lead to a decline in profit. This study was designed to develop an EOQ cost model that minimizes cost, accident risk, and carbon emissions. The problem was separated into three objective functions, which were then employed to find the optimal Pareto solution. The model's economic relevance results from its use of the EOQ formula. Lastly, numerical analysis was used to test the model's applicability. It is expected that this model can provide users with consideration of cost, risk and other factors as a reference basis for making the best decisions, thereby achieving the goal of improving overall profitability. The factors that affect the development and profitability of the chemical industry are not only the three items mentioned in this article. It is expected that subsequent researchers should consider changes in production and transportation modes and incorporate new considerations in a timely manner to make the model and the results obtained more realistic need.

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