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## Article

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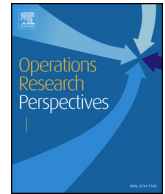
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# Incorporating analytical hierarchy process and goal programming to design responsive and efficient supply chains

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## ABSTRACT

The main aim of this article is to propose a new supply chain (SC) design methodology in order to enable organizations to better utilize their resources and structure their SC drivers to achieve the desired level of responsiveness and efficiency. A great challenge in this endeavor is that the SC drivers, which are categorized as logistical and cross-functional, are interrelated and have different (often conflicting) performance measures. By combining the analytical hierarchy process (AHP) with weighted binary goal programming (GP), this article introduces a two-stage approach to SC design. At the initial stage, the AHP model attempts to develop weights for the efficiency and responsiveness of the overall SC design as well as the individual SC drivers. These weights are subsequently used in the latter stage to construct a GP model to determine the optimal set of SC-driver decisions that would develop the overall satisfactory SC design.

## 1. Introduction

A “one-size-fits-all” approach does not provide a viable solution to contemporary supply chain (SC) design and strategic issues (e.g., see [10,11], and [33]). An optimal SC design for an organization might not necessarily perform optimally for other firms in the same industry. Even within a firm, there may be a need for multiple supply chains [10]. For instance, Zara, the well-known apparel giant, uses a responsive SC for its fashion clothes and an efficient SC for its commodity-type products (e.g., white under-shirts). The effectiveness of a SC design/strategy is greatly determined by how well it fits and is aligned with the organization's competitive strategy. Consequently, it is inevitable that organizational resources and SC capabilities—i.e., the logistical drivers (facility, inventory, and transportation) and cross-functional drivers (information, sourcing, and pricing)—be utilized to enforce the right balance between efficiency and responsiveness to satisfy customer needs [9]. In fact, the higher the fit between the SC and the organizational strategies, the higher the return on assets [51]. However, while the significance of attaining strategic fit is indisputable, the means of achieving such a fit has been a great challenge for the practitioners and an evolving subject for the researchers [29].

SC design issues are complex and comprise a wide range of decisions, both strategic and operational, that are interrelated in nature—e.g., inventory stock levels vs. speed of transportation [44]. SC design deals with various issues at different stages of the supply chain,

starting from the procurement of the raw materials and how those materials are manufactured, transported, stored, and promoted for sales. Furthermore, each of these issues comprises different decisions/alternatives, such as determining the number and type of suppliers, facility locations/capacity, type of distribution network(s), mode of transportation, inventory policy, and pricing strategy, to name a few [9,13]. This interrelated multilateral process of SC design raises two major issues:

- i) How to deal with the inherently conflicting objectives of various stages of the SC (i.e., how to ensure global, rather than local, optimization in SC design).
- ii) How to determine a performance measure that is (1) comprehensive (i.e., all-inclusive of all SC stages) and (2) objective [2,42,54,56].

Although SC objectives encompass various goals, such as cost, service level, resource utilization, quality, product variety, and availability, they are usually recapped into the two primary objectives of SC, namely, providing an appropriate (acceptable) level of responsiveness while maintaining a required level of efficiency. Whereas SC efficiency is concerned with lowering cost and minimizing waste, responsiveness deals with issues related to speed, volume and variety, lead time, innovation, and service level [48]. Traditionally these two primary components of SC are perceived as being negatively correlated, implying that a highly efficient SC will be at the lower end of

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responsiveness and vice versa (e.g., see [14,25]). However, some recent studies suggest a hybrid solution to SC design in which a firm can be highly efficient and, meanwhile, highly responsive (e.g., see [30,46]).

Christopher et al. [12] suggest that a robust SC design should be “holistic” and should consider multiple objectives of the entire chain rather than focusing on a single objective. Initially, most of the studies on SC design focused on individual issues such as inventory policy, facility location, network design, or service level [15,28,31]. However, much research has been conducted focusing on a multi-objective approach to SC design (e.g., [1,6,21,32,34,43]).

This article suggests a unique approach to SC design. The proposed multi-objective methodology is composed of two distinct stages. The initial stage uses the analytical hierarchy process (AHP) for setting priority among the SC objectives. The latter stage uses the results of the AHP to construct a binary goal programming (GP) for resource allocation. To this end, the proposed approach obtains weights for the SC drivers based on the level of the contribution of each driver to the overall SC design objectives. Subsequently, the proposed model develops a set of goals for each SC driver while considering the simultaneous effect of all SC drivers on the SC efficiency and responsiveness. The weights obtained at the initial stage are utilized to prioritize goals in GP and assign weights to them to allow for tradeoff among them. The proposed method in this article uses the technique suggested by Alhusain and Khorramshahgol [1] as the baseline and advances it further by allowing the decision-maker(s) to rank the SC objectives as well as the SC drivers and specify trade-offs among them when designing a supply chain network. A comparison of the suggested method and the baseline model demonstrates a clear improvement in SC design, both in terms of efficiency and responsiveness. Moreover, as indicated in the following literature review, even though various SC design methodologies suggested by researchers have their advantages, they have a partial treatment of SC drivers. The proposed methodology in this article considers all SC drivers and allows tradeoffs among them, which provides a higher level of responsiveness and efficiency simultaneously.

## 2. Literature review

In his pioneering research, Fisher [14] addresses the efficiency and responsiveness tradeoff and relates it to the problem of designing “the right SC.” Fisher [14] categorizes the products into functional or innovative and identifies the SC strategy as being either efficient or responsive and recommends an efficient SC strategy for functional products and a responsive strategy for innovative products. Any other combination of the two dimensions is considered a mismatch that can result in an ineffective SC design and an imminent failure. Although Fisher’s model represented an essential building block for SC design, it raised some controversy since product characteristics were the primary factor influencing the SC design. In their empirical study, Lo and Power [26] investigate the relationship between product nature and SC strategy, using the framework suggested by Fisher [14], and conclude that the relationship between the two is not significant. Based on Lo and Power [26], a hybrid strategy that seeks to synchronize both efficiency and responsiveness is mostly employed by the majority of organizations. Lee [25] expands Fisher’s model to include supply uncertainty and categorizes it as either stable or evolving and proposes four SC strategies to match demand uncertainties with supply uncertainties, namely efficiency, risk-hedging, responsiveness, and agility. Ensuing SC researchers started to perceive the idea that efficiency and responsiveness are not necessarily distinct objectives, and both could be achieved simultaneously. Table 1 summarizes the relevant literature on SC design models that attempt to improve both responsiveness and efficiency, the type of models used, and the related SC drivers considered.

Except for Alhusain and Khorramshahgol [1], most of the related literature on SC design is focused on a few SC drivers, such as facility location, production capacity, inventory, transportation, and supplier

issues. However, in order to determine the right balance between efficiency and responsiveness for a SC design, a holistic approach that considers both logistical and cross-functional drivers is essential. Although each one of the methodologies mentioned thus far has its own merits, they do not allow for the profound manipulation and simultaneous control of the SC drivers that would enable the decision-makers to achieve a desired level of responsiveness while maintaining a certain level of efficiency. The main aim of this article is to address these shortcomings and drill down into components and sub-components of each driver, singly and collectively in conjunction with other drivers, to select an appropriate level for each to achieve the desired efficiency–responsiveness level.

The proposed SC design methodology in this paper builds upon Alhusain and Khorramshahgol’s [1] multi-objective SC design model and extends it by combining AHP with a binary goal programming model to assist in designing a SC that offers the desired level of responsiveness and efficiency as determined by the SC managers. The suggested methodology, using AHP, allows for the consideration of priorities and trade-offs among SC drivers when pursuing the desired efficiency–responsiveness balance in SC design.

## 3. Description of the proposed two-stage approach to SC design

As mentioned earlier, SC design is a sophisticated process that involves the determination of various decision variables related to different drivers at different stages of the SC. Supply chain design presents a huge challenge for organizations to utilize their resources appropriately in order to achieve the desired balance between efficiency and responsiveness. SC design becomes even more complicated when dealing with enormous combinations of various components of the SC drivers. To overcome these challenges, a two-stage approach that uses AHP and binary GP is proposed in this study for effective SC design.

To apply the two-stage model, the decision-maker should first evaluate the product characteristics [26] and then assess the extent of the impact of the decisions within each SC driver toward the desired efficiency and responsiveness levels of the overall SC design. Based on Chopra and Meindl [9], six distinct SC drivers are classified as logistical (facility, inventory, and transportation) and cross-functional (information, sourcing, and pricing). The SC drivers and their related decision variables used in this study are presented in Table 2. This table is reproduced from an earlier study by Alhusain and Khorramshahgol [1]. In Table 2, it should be noted that a facility is either a production or storage facility.

The first stage of the proposed methodology uses AHP to determine the desired level of efficiency and responsiveness for the overall SC design and calculate the relative importance of the SC drivers toward achieving this efficiency–responsiveness balance. The weights of the efficiency and responsiveness indicators of the SC drivers are evaluated using pair-wise comparison (PWC) matrices based on different sets of criteria and sub-criteria. These weights are then used as penalty weights in the binary GP model.

The second stage of the proposed methodology involves the application of binary GP to incorporate the multi-objective nature of the SC design. At this stage, different sets of efficiency and responsiveness goals for the overall SC design and the SC drivers are developed as the desired SC performance targets to be achieved. These goals are developed based on the decision maker’s evaluation of the effect of the SC drivers’ decisions toward the achievement of efficiency and responsiveness. This evaluation process can be estimated using the Likert scale, based on experts’ opinion [1]. This allows for the estimation of a multidimensional construct into a unified measure of performance [8]. The Likert-scale estimation has been used widely in the literature for various SC design issues (e.g., see [1,4,7,18,24,50]). The Likert-scale scores estimated by the decision-maker are then used as parameters of the GP model.

The binary GP model is then solved to find an optimal combination

**Table 1**  
Summary of supply chain design models.

Authors	Method	SC Drivers					
		Facility	Inventory	Transportation	Information	Sourcing	Pricing
Sabri and Beamon [40]	Multi-objective mixed-integer programming model	✓		✓			
Korpela et al. [23]	Analytical hierarchy process and mixed-integer programming	✓				✓	
Koops et al. [22]	Structural equation modeling	✓				✓	
Stratton and Warburton [46]	Case-based theory of concept and The theory of inventive problem-solving—TRIZ	✓	✓				
Holweg [19]	Case-based conceptual model	✓					
Minnich [30]	Simulation	✓					
Baghalian et al. [3]	Mixed integer non-linear model	✓	✓	✓			
Songsong and Papageorgiou [45]	Multi-objective mixed-integer programming model	✓					
Wei et al. [52]	Game theory model	✓					✓
Rahimi et al. [37]	Mixed integer linear programming model	✓		✓		✓	
Zhang et al. [55]	Mixed integer non-linear programming	✓		✓		✓	
Bilir et al. [6]	Multi-objective mixed integer programming model	✓		✓			✓
Alhusain and Khorramshahgol [1]	Multi-objective binary integer programming model	✓	✓	✓	✓	✓	✓
Gholami et al. [16]	Multi-objective mixed-integer programming model	✓		✓		✓	
Sun and Wang [47]	Hybrid evolutionary algorithm	✓		✓			
Yang et al. [53]	Multi-objective optimization model	✓				✓	

of decisions in each of the SC drivers that would minimize the total weighted sum of all the deviations as presented by the objective function. Finally, the resultant SC design is validated by the decision-maker to assure that there is no discrepancy among SC drivers' decisions. For example, an organization might not wish to apply centralized manufacturing facilities with a slow mode of transportation. Therefore, contingency constraints need to be added to the GP model based on the decision maker's recommendations to achieve a final SC design. Fig. 1 depicts the structure of the proposed two-stage model. A detailed discussion of the proposed methodology is presented in subsequent sections.

### 3.1. Stage I: The AHP model

The analytic hierarchy process (AHP) is a multicriteria decision-making model used to rank criteria and alternatives in order to select the best alternative. AHP is a powerful method that enables the decision-maker to decompose a complex problem into its components. AHP implementation involves a well-organized hierarchical structure consisting of objectives, criteria of evaluation, sub-criteria, and lastly, the set of alternatives that should be evaluated to choose the best from among them [38]. The top-level reflects the overall objective. Criteria and sub-criteria are listed at intermediate levels, while the lowest level represents the alternatives. Tamarico et al. [49] report that AHP has

**Table 2**  
Supply chain drivers and related decision variables.  
Source: Alhuhsain and Khorramshahgol [1].

Drivers $D_i$	Components	Explanation of Decision Variables
<b>D<sub>1</sub>: Facility</b>	<b>Role</b>	For a <i>production</i> facility, the role concerns its purpose and how it should be utilized (e.g., flexible or dedicated manufacturing). For a <i>storage</i> facility, the role concerns how it should be utilized (e.g., cross-docking or storage only).
Issues related to the operations strategy of manufacturing and storage facilities	<b>Focus</b>	For a production facility, this concerns the type of production function (e.g., product focus or functional focus).
	<b>Location</b>	This concerns the type of dispersal of a facility whether production or storage (e.g., centralized or decentralized).
	<b>Capacity Utilization</b>	For a production facility, this concerns the fraction of manufacturing capacity that will be used.
	<b>Inventory Function</b>	Inventory function relates to the type of finished goods (e.g., cycle, safety, and seasonal) and raw material inventory held in a facility and their related quantity.
<b>D<sub>2</sub>: Inventory</b>	<b>Location</b>	This concerns the type of dispersal of both finished goods and raw material inventory (e.g., centralized or decentralized).
Issues related to the type of inventory	<b>Ownership</b>	Ownership specifies whether a company should operate its own fleet, or manage it through a third-party logistics provider (3PL).
	<b>Mode</b>	This concerns the type of transportation mode a company wishes to use (e.g., air, truck, rail, or sea).
	<b>Network Design</b>	This relates to the type of network a company wishes to use to deliver its products (e.g., direct shipments or through intermediaries).
<b>D<sub>3</sub>: Transportation</b>	<b>Push vs. Pull</b>	This relates to the type of strategy with which a company wishes to operate its SC (e.g., demand-driven or demand- projection).
Issues related to product delivery	<b>Coordination &amp; Information Sharing</b>	This relates to the visibility and type of coordination of information exchange throughout the SC (e.g., periodic or instantaneous information sharing).
	<b>Task Performance</b>	This relates to whether some tasks such as production, storage, transportation, and information should be performed in-house or outsourced.
<b>D<sub>4</sub>: Information</b>	<b>Supplier Selection</b>	This relates to the number of suppliers a company wishes to deal with and the criteria of evaluation (e.g., efficient or responsive supplier).
Issues related to purchasing goods and services from suppliers	<b>Discounts</b>	This relates to the type of discounts strategy a company wishes to use (e.g., everyday low pricing or high-low pricing).
	<b>Menu</b>	This relates to the menu options a company wishes to adopt when pricing goods or services (e.g., fixed pricing or variable pricing).
<b>D<sub>5</sub>: Sourcing</b>		
<b>D<sub>6</sub>: Pricing</b>		

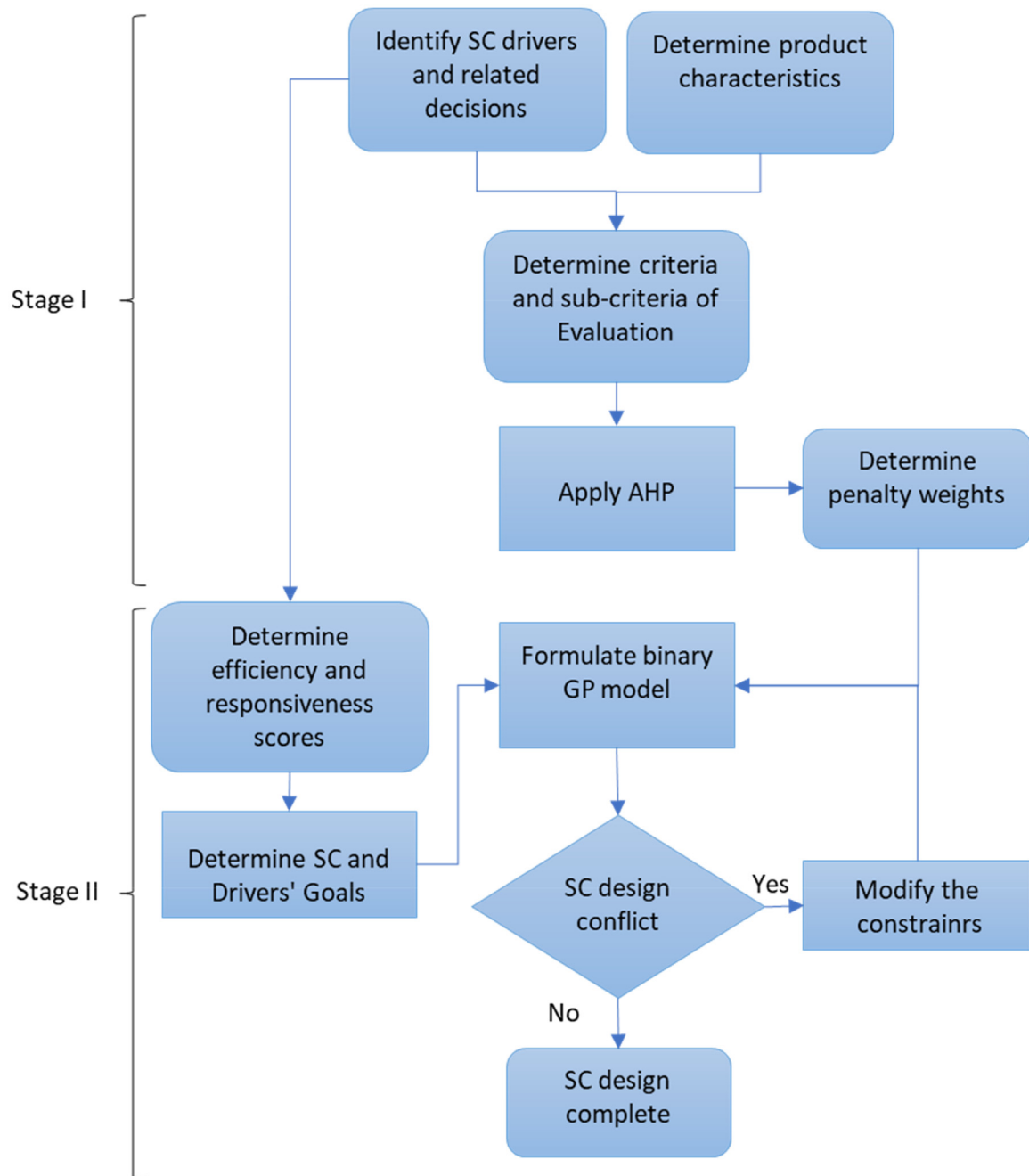


Fig. 1. Structure of the proposed two-stage model.

**Table 3**  
Pair-wise comparison scale.

Intensity of Importance	Definition
1	Equal importance of both elements
3	Weak importance of one element over another
5	Essential or strong importance of one element over another
7	Demonstrated importance of one element over another
9	Absolute importance of one element over another
2,4,6,8	Intermediate values between two adjacent judgments

been the most widely used method applied to supply chain problems. Moreover, Sipahi et al. [41] state that AHP is one of the most widely used MCDM methods as a management tool in several industrial sectors, such as supply chain and logistics.

AHP is used in the suggested model to determine the relative weights for SC efficiency and responsiveness and to evaluate the role and extent of the contribution of each SC driver towards achieving the desired efficiency–responsiveness balance. Rather than treating all SC drivers as equally important when determining the optimal combination of decisions (as is the case in [11]), a ranking of the SC drivers is first determined, using pairwise comparison matrices.

The process of using AHP to determine the relative importance of SC drivers is broken down into three steps: (1) decomposing the problem into a top-down, hierarchical structure, (2) determining the weights for the criteria of evaluation, and (3) calculating the overall weights for the SC drivers. The comparison of any two criteria and sub-criteria is made based on the decision maker's evaluation of which criterion/sub-criterion is more critical concerning the product characteristics and the overall SC objectives. The nine-point scale (Table 3) suggested by Satty

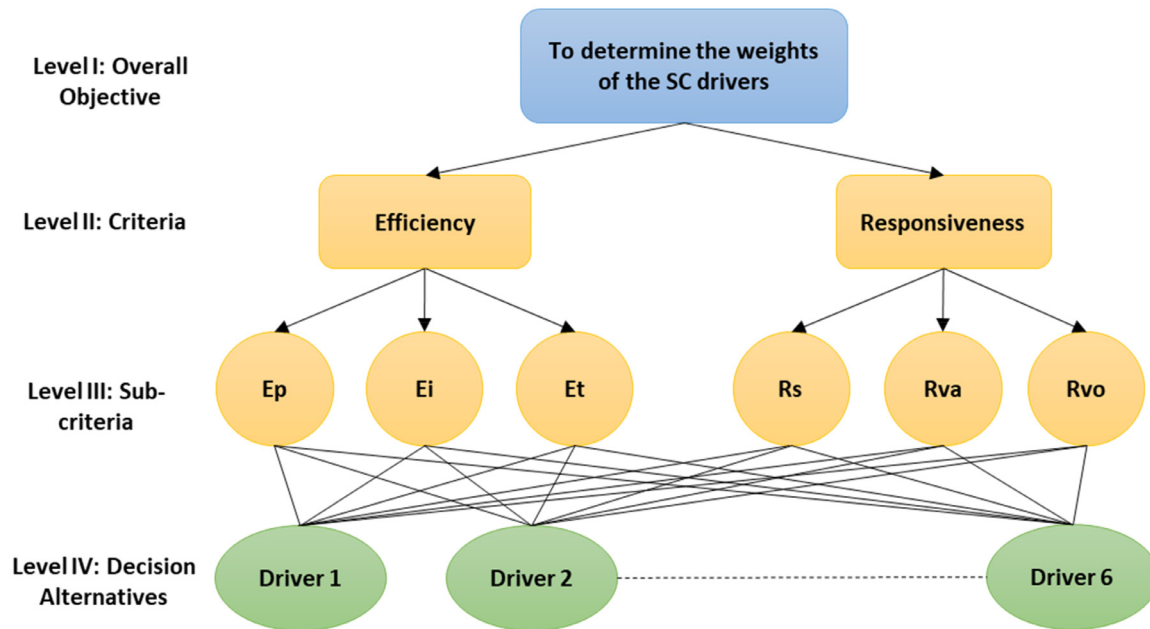


Fig. 2. The Structure of the AHP Model.

[39] is used for this purpose.

Fig. 2 demonstrates the hierarchy structure of the AHP, which is composed of four levels. Level I represents the main objective. Level II shows the major criteria, which are efficiency and responsiveness. Level III depicts the sub-criteria. For the “efficiency” criterion, the sub-criteria are the efficiency of production (Ep), efficiency of inventory (Ei), and efficiency of transportation (Et). For the “responsiveness” criterion, the sub-criteria are service level (Rs), variety (Rva), and volume (Rvo).

It should be noted that the sub-criteria presented in level III are not all-inclusive, and the SC designers can add any other criterion. A powerful feature of AHP is that it can accommodate any number of criteria, sub-criteria, and alternatives. Level IV of the AHP hierarchy (Fig. 2) represents the decision alternatives under consideration, which are the six SC drivers, as elaborated in Table 2. Table 4 defines the criteria and sub-criteria and provides a symbolic code for each.

To ensure the consistency of the decision-makers’ judgments regarding the relative importance of the entries in the pairwise comparison matrix (PWC) in levels II, III, and IV, the consistency ratio (CR) is calculated for each matrix. The CR should be, at most, 10 percent to ensure the consistency of judgments [38].

### 3.2. Stage II: the GP model

This stage constructs a weighted binary GP model to set numeric goals (efficiency and responsiveness levels) for the overall SC design and each SC driver. Goal Programming (GP) is perhaps the most widely used approach among Multiple Criteria Decision Making (MCDM) methods. GP, an extension of linear programming, allows incorporating several goals into the model (C. Romero, 1991). GP has been widely used in SC design (e.g., see Bhattacharya et al. [5], Paydar et al. [36], Khalili et al. [20] and Gupta et al. [17]).

The binary GP seeks a satisfying solution comprising of an optimal combination of components within each SC driver that makes as much contribution as possible towards achieving a specific efficiency–responsiveness balance in the SC design. The objective of the binary GP model is to minimize the total weighted sum of all the deviations from the desired goals, where the penalty weights for under-achievement of the desired goals were already calculated using AHP (Stage I). The identification of decision variables and trade-offs among criteria in each SC driver are made based on the efficiency and responsiveness scores. Moreover, the contingency constraints among decisions within each SC driver are constructed to reflect the interdependencies among SC decisions. The notations of the GP model, including the sets, indices, parameters, and variables are introduced in Table 5.

### 3.3. Problem formulation

#### 3.3.1. The objective function

The objective of the weighted binary GP model is to minimize the total weighted sum of the deviations. These deviations are for both efficiency and responsiveness performances of the overall SC design and the SC drivers under consideration. The penalty weights used in the objective function are determined using the predefined AHP model.

$$\text{Min} \sum_{i \in D} (ew_i ed_i^- + rw_i rd_i^-) + w_{SCE} d_{SCE}^- + w_{SCR} d_{SCR}^- \quad (1)$$

#### 3.3.2. Constraints

The constraints of the GP model are classified into four major categories, namely, the driver efficiency and responsiveness constraints and the overall SC design efficiency and responsiveness constraints. The

**Table 4**  
Performance Definition of Criteria and Sub-criteria.

	Code	Definition
<i>Criteria</i>		
Efficiency	Eff	lowering cost and minimizing waste
Responsiveness	Res	The ability to respond to customer orders and changing business conditions
<i>Sub-criteria</i>		
Production	Ep	Cost of manufacturing
Inventory	Ei	Cost of storing raw material, work in process, and finished goods
Transportation	Et	Cost of shipping raw materials and finished goods
Service Level	Rs	The ability to respond to customer orders on a timely basis
Variety	Rva	The ability to deal with orders of different product variety
Volume	Rvo	The ability to deal with orders of different sizes

**Table 5**  
Notation for the goal programming model.

Notation	Definition
<b>Sets</b>	
D	Set of SC drivers
C	Set of decisions within each SC driver D
<b>Indices</b>	
i	SC driver number $\in D$ , where $i = 1, 2, 3, 4, 5, 6$
j	SC decision number $\in C^i$ , where $j = 1, 2, \dots, n$
<b>Parameters</b>	
$e_{ij}$	Efficiency score of decision j in driver i
$ell_i$	Efficiency lower limit for SC driver i
$r_{ij}$	Responsiveness score of decision j in driver i
$rll_i$	Responsiveness lower limit for SC driver i
$EG_i$	Efficiency goal of driver i
$RG_i$	Responsiveness goal of driver i
$ew_i$	Efficiency penalty weight of driver i
$rw_i$	Responsiveness penalty weight of driver i
$w_{SCE}$	Penalty weight of overall SC design efficiency
$w_{SCR}$	Penalty weight of overall SC design responsiveness
$SCEG$	Goal of overall SC design efficiency
$SCRG$	Goal of overall SC design responsiveness
$SCEll$	Overall SC design efficiency lower limit
$SCRll$	Overall SC design responsiveness lower limit
<b>Variables</b>	
$x_{ij}$	The assignment of decision j in SC driver i, $x_{ij} = \begin{cases} 1 & \text{assign} \\ 0 & \text{not assign} \end{cases}$
$ed_i^-$	Efficiency under-achievement of SC driver i
$ed_i^+$	Efficiency over-achievement of SC driver i
$rd_i^-$	Responsiveness under-achievement of SC driver i
$rd_i^+$	Responsiveness over-achievement of SC driver i
$d_{SCE}^-$	Overall SC design efficiency under-achievement
$d_{SCE}^+$	Overall SC design efficiency over-achievement
$d_{SCR}^-$	Overall SC design responsiveness under-achievement
$d_{SCR}^+$	Overall SC design responsiveness over-achievement

other types include contingency, mutually-exclusive, and non-negativity constraints.

#### I Driver efficiency constraints

$$\sum_{j \in C^i} e_{ij} x_{ij} + ed_i^- - ed_i^+ = EG_i, \text{ for every } i \quad (2)$$

$$EG_i \leq \sum_{j \in C^i} \max(e_{ij}), \text{ for every } i \quad (3)$$

$$\sum_{j \in C^i} e_{ij} x_{ij} \geq ell_i, \text{ for every } i \quad (4)$$

$$ell_i \geq \sum_{j \in C^i} \min(e_{ij}), \text{ for every } i \quad (5)$$

#### II Driver responsiveness constraints

$$\sum_{j \in C^i} r_{ij} x_{ij} + rd_i^- - rd_i^+ = RG_i, \text{ for every } i \quad (6)$$

$$RG_i \leq \sum_{j \in C^i} \max(r_{ij}), \text{ for every } i \quad (7)$$

$$\sum_{j \in C^i} r_{ij} x_{ij} \geq rll_i, \text{ for every } i \quad (8)$$

$$rll_i \geq \sum_{j \in C^i} \min(r_{ij}), \text{ for every } i \quad (9)$$

#### III Overall SC efficiency constraints

$$\sum_{i \in D} \sum_{j \in C^i} e_{ij} x_{ij} + d_{SCE}^- - d_{SCE}^+ = SCEG \quad (10)$$

$$SCEG \leq \sum_{i \in D} \sum_{j \in C^i} \max(e_{ij}) \quad (11)$$

$$\sum_{i \in D} \sum_{j \in C^i} e_{ij} x_{ij} \geq SCEll \quad (12)$$

$$SCEll \geq \sum_{i \in D} \sum_{j \in C^i} \min(e_{ij}) \quad (13)$$

#### IV Overall SC responsiveness constraints

$$\sum_{i \in D} \sum_{j \in C^i} r_{ij} x_{ij} + d_{SCR}^- - d_{SCR}^+ = SCRG \quad (14)$$

$$SCRG \leq \sum_{i \in D} \sum_{j \in C^i} \max(r_{ij}) \quad (15)$$

$$\sum_{i \in D} \sum_{j \in C^i} r_{ij} x_{ij} \geq SCRll \quad (16)$$

$$SCRll \geq \sum_{i \in D} \sum_{j \in C^i} \min(r_{ij}) \quad (17)$$

#### V Mutually exclusive alternatives

$$\sum_{j \in C^i} x_{ij} = 1, \text{ for every driver } i \quad (18)$$

$$\sum_{j \in C^i} x_{ij} \leq 1, \text{ for every driver } i \quad (19)$$

#### VI Non-negativity constraints

$$x_{ij} \geq 0 \text{ for all } i \text{ and } j \quad (20)$$

$$ed_i^- \geq 0 \text{ for all } i \quad (21)$$

$$ed_i^+ \geq 0 \text{ for all } i \quad (22)$$

$$rd_i^- \geq 0 \text{ for all } i \quad (23)$$

$$rd_i^+ \geq 0 \text{ for all } i \quad (24)$$

$$d_{SCE}^- \geq 0 \quad (25)$$

$$d_{SCE}^+ \geq 0 \quad (26)$$

$$d_{SCR}^- \geq 0 \quad (27)$$

$$d_{SCR}^+ \geq 0 \quad (28)$$

### 3.3.3. Description of the constraints

Eq. (2) represent the efficiency goals of every SC driver, which the model attempts to achieve. The efficiency goal for every SC driver is calculated so that it is less than or equal to the sum of the maximum assigned scores of each component in every SC driver, as shown in Eq. (3). In other words, based on the pre-assigned Likert-scale scores by the decision-maker, an efficiency goal for a specific SC driver cannot be more than what the driver can offer. Eq. (4) represent hard constraints imposed by the decision-maker on the model to ensure that the sum of efficiency scores of the assigned decisions in a specific SC driver is greater than the desired level or equal to the lower limit. The lower limit is calculated such that it is set to be greater than or equal to the sum of the minimum assigned scores of each component in every SC driver, as shown in Eq. (5). In other words, based on the pre-assigned Likert-scale scores by the decision-maker, a hard constraint on the minimum efficiency score that should be achieved by a specific driver cannot be less than the total sum of the minimum scores in that driver.

The same argument is used for the constraints on the responsiveness goals of the SC drivers, the goal of the overall SC efficiency, and the goal of the overall SC responsiveness. These constraints are presented in Eqs. (6) through (9), Eqs. (10) through (13), and Eqs. (14) through (17), respectively. Eqs. (18) and (19) represent mutually exclusive requirements within each component of every driver.

Other constraints represent the specific design capability of the SC and contingency among decisions within the same driver or between different drivers. For example, a decision-maker may wish to specifically use a flexible facility role for manufacturing. Likewise, if a centralized production facility decision is selected, then an air transportation mode must also be selected. These contingency constraints among different decisions are determined by the decision-makers and SC designers.

## 4. Illustrative example

Consider a medium-sized company named Getachoo corp. that produces standard commodity-type clothing and sends them to its distribution centers (DC) in Europe and Asia for final sales to retail stores. Due to the nature of its products, Getachoo faces a low demand uncertainty and a long product life cycle. Getachoo's manufacturing facility and the suppliers of its raw materials are located in India. Getachoo SC designers wish to design an efficient SC; however, they would like to maintain a certain level of responsiveness. To achieve the right balance between efficiency and responsiveness, both logistical and cross-functional drivers are used.

### 4.1. Stage I: the analytic hierarchy process (AHP)

Based on the product characteristics under consideration (i.e., commodity-type apparel with low demand uncertainty and a long life-cycle), the decision-maker first evaluates the desired relative importance of the efficiency and responsiveness of the overall SC design. For this purpose, a PWC is constructed (Table 6), using Saaty's scale. Table 6 shows that the subjective evaluation of the decision-maker for the overall SC design is such that efficiency is estimated to be much more critical than responsiveness. Using AHP, the efficiency and responsiveness weights are calculated to be 0.875 and 0.125, respectively, with a CR of 0%. Hence, the intended SC design will lean heavily toward efficiency.

**Table 6**  
Pair-wise comparisons of criteria.

Criteria of Evaluation	Eff	Res	Weight	CR
Eff	1	7	0.875	0%
Res	1/7	1	0.125	

**Table 7**  
Pair-wise comparison for the efficiency sub-criteria.

Efficiency Sub-criteria	Ep	Ei	Et	Weight	CR
Ep	1	1/5	1/3	0.109	0.40%
Ei	5	1	2	0.582	
Et	3	1/2	1	0.309	

The second step of Stage I is to evaluate the relative importance of the sub-criteria for both efficiency and responsiveness and calculate their weights. The SC designer decided to use the same sub-criteria that were presented in Table 4. For the efficiency sub-criteria, the SC designer considers Ei to be strongly more important than Ep and slightly more important than Et, thus entering 5 for  $E_i-E_p$  element and 2 for  $E_i-E_t$  element in the PWC matrix. Likewise, Et is considered to be slightly more important than Ep. The same procedure is applied to the responsiveness sub-criteria. Tables 7 and 8 show the decision maker's judgments of the relative importance of sub-criteria for efficiency and responsiveness, respectively. The numbers in these tables are obtained from the Saaty scale (Table 3). The PWC matrices, containing weights for the sub-criteria, are given in Tables 7 and 8 along with the CR for each. Since CRs are less than 10% for both efficiency and responsiveness sub-criteria, there is no inconsistency in the SC designer's subjective judgments.

The next step is to determine the relative importance of each alternative (i.e., each SC driver) concerning the sub-criteria of efficiency and responsiveness. Table 9 presents the PWC matrix for all the SC drivers, considering only the production efficiency (Ep). Table 9 also shows the weights for each driver and the CR. Since  $CR = 4.4\%$ , there are no inconsistencies in the judgments. Five similar PWC matrices will be constructed for the remaining five sub-criteria (i.e., Ei, Et, Rs, Rva, Rvo). Table 10 shows the overall results for the AHP model, which includes the weights of the criteria and sub-criteria, the relative importance of the six SC drivers along with the efficiency and responsiveness weight for each driver. The efficiency weights of the SC drivers are shown to be greater than the responsiveness weights, which are consistent with the SC design objective.

The AHP results (Table 10) for the efficiency and responsiveness weights of the overall SC design and the weights for the six SC drivers are used in Stage II to construct the binary GP model.

### 4.2. Stage II: goal programming formulation

Based on the weights obtained in the AHP model of stage I (Table 10), the objective function of the GP model translates to the following equation:

**Table 8**  
Pair-wise comparison for the responsiveness sub-criteria.

Responsiveness Sub-criteria	Rs	Rva	Rvo	Weight	CR
Rs	1	5	4	0.687	9.80%
Rva	1/5	1	2	0.186	
Rvo	1/4	1/2	1	0.127	

**Table 9**  
Pair-wise comparison of efficiency of production (Ep).

Efficiency of Production (Ep)	D1	D2	D3	D4	D5	D6	Weight	CR
D1	1	1/8	1/6	1/7	1/8	4	0.041	4.40%
D2	8	1	2	1	1	9	0.258	
D3	6	1/2	1	1/2	1/3	8	0.148	
D4	7	1	2	1	1	9	0.252	
D5	8	1	3	1	1	8	0.278	
D6	1/4	1/9	1/8	1/9	1/8	1	0.023	

#### Min Total Weighted Sum of Deviations

$$= [(0.0414 \cdot ed_1^- + 0.01439 \cdot rd_1^-) + (0.13564 \cdot ed_2^- + 0.01726 \cdot rd_2^-) + (0.25502 \cdot ed_3^- + 0.02395 \cdot rd_3^-) + (0.12905 \cdot ed_4^- + 0.00769 \cdot rd_4^-) + (0.24203 \cdot ed_5^- + 0.05842 \cdot rd_5^-) + (0.07186 \cdot ed_6^- + 0.00331 \cdot rd_6^-)] + 0.875 \cdot d_{SCE}^- + 0.125 \cdot d_{SCR}^-$$

The SC designer then evaluates the effect of every decision component of each one of the six SC drivers on (1) the efficiency and (2) the responsiveness of the overall SC design. To this end, a Likert-scale approach is used as an evaluation methodology. The Likert-scale scores used for this evaluation range from 1 to 5, as shown in Table 11. For example, for the decision variable representing flexible manufacturing in the facility driver, a decision-maker should input a score from 1 to 5 for both its efficiency and responsiveness effect on the overall SC design. The same procedure is carried out for all decision components for all drivers.

It should be noted that the Likert-scale scores are not selected randomly, rather they are experts' opinions in the field and reflect the work in literature as well. For example, an air transportation mode decision in the transportation driver would score more on responsiveness than efficiency. Based on the scores selected for all decisions of the six drivers, the lower and upper limits of efficiency and responsiveness for each SC driver are calculated based on Eqs. (3) and (5) for efficiency, and Eqs. (7) and (9) for responsiveness. This will allow a decision-maker to set numerical goals for efficiency and responsiveness for each SC driver that the GP model will strive to achieve, considering the penalty weights of the drivers and the overall SC design objectives. For instance, Table 12 presents the scores for the facility driver. Similarly, five other tables should be constructed for the remaining SC drivers.

Considering the facility driver (D1), the efficiency and responsiveness constraints for it can be written, as shown below. All the parameters in the following equations/inequalities are obtained from Table 12.

#### 4.3. Facility efficiency constraints

$$2x_{i1} + 5x_{i2} + 4x_{i3} + x_{i4} + 5x_{i5} + x_{i6} + 4x_{i7} + 2x_{i8} + 3x_{i9} + x_{i10} + 4x_{i11} + x_{i12} + ed_1^- - ed_1^+ = EG_1$$

**Table 10**  
Weights of criteria, sub-criteria, and alternatives.

Driver	Efficiency 0.875			Responsiveness 0.125			Eff Weights	Res Weights	Overall Weights
	Ep 0.109	Ei 0.582	Et 0.309	Rs 0.687	Rva 0.186	Rvo 0.127			
1	0.041	0.046	0.052	0.086	0.213	0.129	0.0414	0.01439	0.05578
2	0.258	0.106	0.211	0.166	0.072	0.084	0.13564	0.01726	0.1529
3	0.148	0.369	0.196	0.229	0.073	0.163	0.25502	0.02395	0.27897
4	0.252	0.151	0.104	0.033	0.064	0.212	0.12905	0.00769	0.13674
5	0.278	0.205	0.411	0.46	0.548	0.389	0.24203	0.05842	0.30045
6	0.023	0.123	0.026	0.026	0.03	0.024	0.07186	0.00331	0.07517

**Table 11**  
Efficiency and responsiveness scores of the likert scale.

Score	Interpretation	
	Efficiency	Responsiveness
1	Strongly inefficient	Very poorly responsive
2	Somewhat inefficient	Poorly responsive
3	Moderately efficient	Moderately Responsive
4	Efficient	Responsive
5	Strongly efficient	Strongly responsive

$$EG_1 \leq \max(2, 5) + \max(4, 1) + \max(5, 1) + \max(4, 2) + \max(3, 1) + \max(4, 1)$$

$$EG_1 \leq 25$$

$$2x_{i1} + 5x_{i2} + 4x_{i3} + x_{i4} + 5x_{i5} + x_{i6} + 4x_{i7} + 2x_{i8} + 3x_{i9} + x_{i10} + 4x_{i11} + x_{i12} \geq ell_1$$

$$ell_1 \geq \min(2, 5) + \min(4, 1) + \min(5, 1) + \min(4, 2) + \min(3, 1) + \min(4, 1)$$

$$ell_1 \geq 8$$

#### 4.4. Facility responsiveness constraints

$$5x_{i1} + 3x_{i2} + 2x_{i3} + 4x_{i4} + 2x_{i5} + 5x_{i6} + 2x_{i7} + 4x_{i8} + 5x_{i9} + x_{i10} + x_{i11} + 4x_{i12} + rd_1^- - rd_1^+ = RG_1$$

$$RG_1 \leq \max(5, 3) + \max(2, 4) + \max(2, 5) + \max(2, 4) + \max(5, 1) + \max(1, 4)$$

$$RG_1 \leq 27$$

$$5x_{i1} + 3x_{i2} + 2x_{i3} + 4x_{i4} + 2x_{i5} + 5x_{i6} + 2x_{i7} + 4x_{i8} + 5x_{i9} + x_{i10} + x_{i11} + 4x_{i12} \geq rll_1$$

$$rll_1 \geq \min(5, 3) + \min(2, 4) + \min(2, 5) + \min(2, 4) + \min(5, 1) + \min(1, 4)$$

$$rll_1 \geq 11$$

After using the penalty weights and the Likert-scale scores in the GP model, an optimal combination of decisions for all SC drivers are determined that are best matched with the drivers' efficiency and responsiveness goals. Hence, a SC design that fits with the overall SC objective is achieved. Table 13 shows the solution for the GP model, which includes the max and min of each of the efficiency and responsiveness goals for each driver and the achievement level for each goal. This allows the decision-makers to determine what can or cannot be achieved in the intended SC design based on the design constraints and

**Table 12**

Likert-scale scores for SC decisions for facility\*.  
Source: Alhusain and Khorramshahgol [1].

The Facility Driver (D1)			Supply Chain Scores	
Type	Components	Decision	Efficiency	Responsiveness
Manufacturing	Role	Flexible	2	5
		Dedicated	5	3
	Focus	Product focus	4	2
		Functional focus	1	4
	Location	Centralized	5	2
		Decentralized	1	5
Warehouse and DC	Capacity Utilization	High Utilization	4	2
		Low Utilization	2	4
	Role	Cross-docking	3	5
		Storage	1	1
	Location	Centralized	4	1
		Decentralized	1	4

\* Source: Alhusain and Khorramshahgol [1].

interdependencies among the SC drivers. Also, the decision-makers can identify where exactly the underachievement of the goals are and by how much. This can help generate additional potential alternative SC designs and evaluate them against the base model if the initial SC design is not satisfactory.

In this example, since the efficiency of the overall SC design and SC drivers are weighted more than responsiveness, results (Table 13) show that most of the underachievement of the goals occurred for responsiveness rather than efficiency. For instance, in the facility driver (D1), there is no underachievement of the efficiency goal and a 12-unit underachievement of the responsiveness goal. Also, for the inventory driver (D2), there are only 2 units of underachievement for efficiency, and 11 units of underachievement for responsiveness. The same argument is valid for the remaining four drivers. This indicates that the model is striving to utilize the drivers to design a SC that achieves a higher level of efficiency than responsiveness.

It is important to note that the combination of decisions from each driver determined by the model, which leads to the overall SC design, is based on the Likert-scale scores (chosen by the decision-maker) and the penalty weights obtained from the AHP model. Consequently, the importance of the proposed two-stage approach lies in its ability to tailor organizational resources toward the desired SC design objective. In this case, a combination of drivers' decisions would lead to more efficient SC design, while providing satisfactory responsiveness.

## 5. Sensitivity analysis

To study the robustness of the proposed model, this section explores a few scenarios and examines various combinations along the efficiency—responsiveness spectrum. The main objective is to probe the superiority of the proposed model over the baseline model and to investigate whether the inclusion of weights for the SC drivers and the

allowance of trade-offs among SC objectives (i.e., efficiency and responsiveness) exhibits an improvement over the baseline model. The following are the scenarios considered in the analysis. Scenario-0 is the baseline model, and scenarios 1 to 5 are different cases of the proposed model, distinguished by the relative importance of the efficiency vs. responsiveness, as determined by the SC designers.

<b>Scenario-0</b>	<b>S0:</b>	The baseline model (as studied by AlHusain and Khorramshahgol, 2018).
<b>Scenario-1</b>	<b>S1:</b>	The proposed model, SC designers value efficiency much more important than responsiveness (this is the illustrative example, and the SC is suitable for commodity type products – see Table 13. Commodity type products that have been in the market for some time can fit in this category).
<b>Scenario-2</b>	<b>S2:</b>	The proposed model, SC designers value responsiveness much more important than efficiency (e.g., innovative product in the introduction and growth stages of its life cycle, such as fashion apparel with a short life cycle and high-tech products such as laptops – see Table 14).
<b>Scenario-3</b>	<b>S3:</b>	The proposed model, SC designers value efficiency and responsiveness as equally important (e.g., an innovative product in the later stage of growth, such as some models of mobile phones that have been in the market for some time).
<b>Scenario-4</b>	<b>S4:</b>	The proposed model, SC designers value efficiency slightly more important than responsiveness (e.g., an innovative product in the later stages of its maturity during its life cycle. Mobile phones and fashion apparel can fit in this category).
<b>Scenario-5</b>	<b>S5:</b>	The proposed model, SC designers value responsiveness slightly more important than efficiency (e.g., an innovative product in the later stages of its growth or early stages of its maturity in its life cycle. Mobile phones and fashion apparel can fit in this category).

The illustrative example focused on the scenario where SC designers value efficiency much more than responsiveness (as can be the case for

**Table 13**

Summary of the results for a highly efficient supply chain.

Driver	Facility		Inventory		Transportation		Information		Sourcing		Pricing	
	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.
Penalty weight	0.0414	0.0144	0.1356	0.0173	0.2550	0.0240	0.2420	0.0584	0.1291	0.0077	0.0719	0.0033
Max Possible Score	25	27	22	23	9	9	9	10	22	26	8	10
Min Possible Score	8	11	8	10	2	3	6	5	18	15	4	4
Max Desired Goal	25	27	22	23	9	9	9	10	22	26	8	10
Min Desired Goal	8	11	8	10	2	3	6	5	18	15	4	4
Total Scores Achieved	25	15	22	10	9	3	9	5	22	20	8	4
Deviation from Goals	0	12	0	13	0	6	0	5	0	6	0	6
Weighted Deviation	0	0.1726	0	0.2244	0	0.1437	0	0.2921	0	0.0461	0	0.0199
Weighted Sum of Deviation	0.1726	0.2244	0.1437	0.2921	0.0461	0.0199						

**Table 14**  
Summary of the results for a highly responsive supply chain.

Driver	Facility		Inventory		Transportation		Information		Sourcing		Pricing	
	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.	Eff.	Resp.
Penalty weight	0.0047	0.0275	0.0155	0.2468	0.0291	0.1275	0.0147	0.2649	0.0277	0.1800	0.0082	0.0534
Max Possible Score	25	27	22	23	9	9	9	10	22	26	8	10
Min Possible Score	8	11	8	10	2	3	6	5	18	15	4	4
Max Desired Goal	25	27	22	23	9	9	9	10	22	26	8	10
Min Desired Goal	8	11	8	10	2	3	6	5	18	15	4	4
Total Scores Achieved	10	27	8	23	4	9	6	10	18	26	4	10
Deviation from Goals	15	0	14	0	5	0	3	0	4	0	4	0
Weighted Deviation	0.0710	0	0.2170	0	0.1457	0	0.0442	0	0.1106	0	0.0329	0
Weighted Sum of Deviation	0.0710	0.2170	0.1457	0.0442	0.1106	0.0329						

commodity type products with low demand uncertainty and high economy of scale in production and distribution). Moving along the responsiveness—efficiency spectrum, the scenarios were constructed by allowing a gradual decline of efficiency, meanwhile, a steady rise of responsiveness. The intent was to cover all viable combinations to address various degrees of responsiveness and efficiency. For instance, Table 14 is a counterpart of Table 13 and depicts the results of the proposed model for a highly responsive supply chain.

While Tables 13 and 14 represent scenario 1 (S1) and scenario 2 (S2) respectively, there are similar tables for scenarios 3, 4, and 5 that are not reproduced here due to space limitation. Table 15 presents the summary of results for efficiency and responsiveness for all scenarios.

Using the information about the five scenarios, presented in Table 15, an efficiency—responsiveness frontier (E—R frontier) was sketched, shown as Frontier-A in Fig. 3. Frontier-B (reproduced from [1]) presents the baseline model.

Fig. 3 indicates that the E—R frontier for the proposed model (Frontier-A) demonstrates a significant improvement in both the efficiency and responsiveness of the supply chain over the baseline model (Frontier-B). The E—R frontier for the proposed model (Frontier-A) is an upward shift of the E—R frontier for the baseline model (Frontier-B). Consequently, incorporating the weights for the criteria and the drivers in SC design results in significant gains in both responsiveness and efficiency. For instance, keeping the desired responsiveness at 90, the proposed model provides an improvement for efficiency from about 55 (provided by the baseline model) to over 70. Similarly, keeping the desired efficiency at 80, the proposed model provides an improvement for responsiveness from below 70 (provided by the baseline model) to about 80.

## 6. Advantages and shortcomings of the proposed methodology

The suggested methodology is an integrated SC design process that is backed by two rigorous and widely used mathematical models—namely, GP and AHP, both of which have been successfully applied to supply chain problems. The SC designers, using the suggested model, are required at several instances to construct the PWC matrixes, comparing SC drivers in terms of their relative contribution to the responsiveness and efficiency. Thus, the decision-makers are obliged to evaluate SC resources critically and consider the tradeoff among them when designing the supply chain. Constructing AHP, coupled with the

**Table 15**  
Summary of the results for all scenarios.

Scenario	Efficiency	Responsiveness
S1	95	57
S2	50	105
S3	78	81
S4	83	75
S5	71	89

formulation process for GP, portrays the proposed model as an iterative process in SC design that forces the decision-makers to gain a deeper grasp of SC resources and tradeoffs among them, leading to better utilization of resources to provide desired responsiveness and efficiency.

An essential feature of the proposed methodology is that it provides a hierarchical view of the supply chain and relates the SC objectives (responsiveness vs. efficiency) to its related cost and service level components and ultimately to the SC drivers—including the sub-components of each driver. This pictorial view of the entire SC design's manipulatable variables and their hierarchical relationship links the most important SC objectives to design alternatives. The suggested methodology can have the following managerial implications:

- More efficient risk assessment and risk management.
- It is an interactive and iterative design tool (for instance, consider constructing PWC matrixes for criteria, sub-criteria, and SC drivers).

Nevertheless, one notable shortcoming of the suggested methodology is the tedious task of constructing the PWC matrixes in stage I. However, one may consider this as an advantage since constructing the PWCs would force the decision-makers and SC designers to consider the criteria and sub-criteria and the trade-offs among them more critically and gain a more in-depth insight into the various alternative SC designs.

Another shortcoming of the proposed methodology is its high reliance on the analytic hierarchy process (AHP). The construction of AHP and its pairwise comparison matrix is highly subjective and can be a time consuming and tedious task. A practical approach for reducing the subjectivity would be to use fuzzy AHP (e.g., [27,35]).

## 7. Conclusion

Given the complexity of the SC design problem that comprises a wide range of interrelated decisions at different stages of the chain, the need to develop a design tool that would enable organizations to utilize their resources better and achieve the desired efficiency—responsiveness balance between SC and organizational strategy is evident. Despite the growing interest in this subject, there is a deficiency of methods that use holistic approaches and tackle the idea of finding the right balance between efficiency and responsiveness. This research addresses this gap and proposes an integrated two-stage SC design methodology that considers the six drivers of SCs and develops a SC design that is consistent with the organizational business strategy by achieving the right efficiency—responsiveness balance. In the first stage of the design process, a multi-criteria model based on AHP is used. This stage allows decision-makers to use their expertise and evaluate each SC driver based on some criteria and sub-criteria and rank the importance of each driver toward achieving the desired efficiency—responsiveness balance in SC design. The second stage utilizes a multi-objective binary GP model that uses the weights developed in the first stage and applies them to a set of goals to identify the optimal decisions in each SC driver

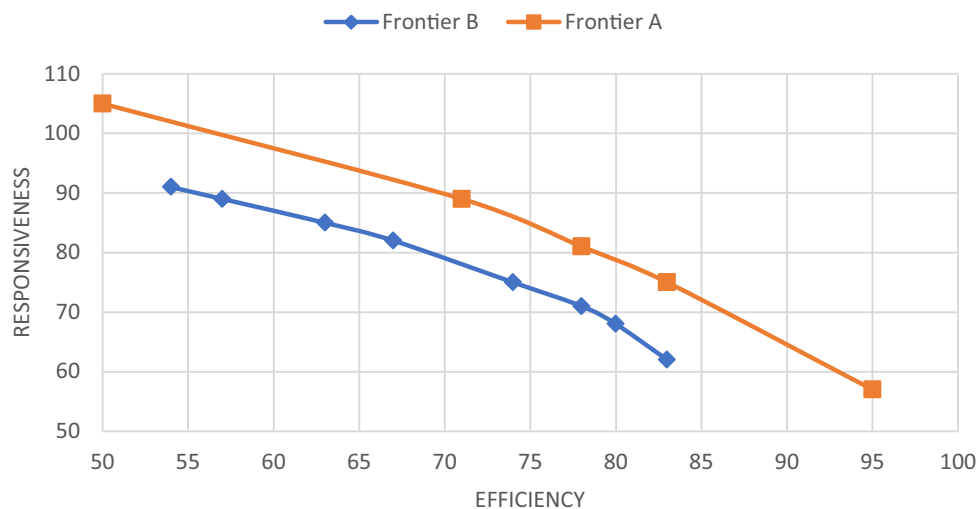


Fig. 3. An Upward shift in responsiveness—efficiency frontier.

that would achieve the desired efficiency–responsiveness balance in SC design. Finally, the applicability of the proposed two-stage hybrid model is illustrated, and the responsiveness and efficiency improvements that it provides are demonstrated by performing a sensitivity analysis.

#### CRedit authorship contribution statement

**Raed Al-Husain:** Conceptualization, Methodology, Validation, Writing - original draft, Project administration. **Reza Khorramshahgol:** Conceptualization, Writing - review & editing, Project administration.

#### Declaration of Competing Interest

None

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