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計 畫 主 持 人：陳誠亮

計畫參與人員：博士班研究生-兼任助理：邱瑩鵑
碩士班研究生-兼任助理：賴佑年、林立峰、湯志偉

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摘　要

本研究提出一個在產品需求與價格不確定下之多產品、多層級、多週期、多目標生產與配送規劃供應鏈網路模式。在面對產品價格不確定時，本文分別從買方與賣方的觀點建立模糊集合和相關隸屬度函數，來衡量雙方對於產品價格的偏好。此外，本文選擇以情境為基礎之方法來描述不確定的產品需求，並注意到：有時雖然目標的期望值符合決策者之期待，但在實際面對某些情境時，目標值卻變得很差，也就是相關決策缺乏韌性。因此，本研究提出一個指標，下方局部平均值，來衡量決策的韌性，並將其納入目標函數中。

將供應鏈模式整合成一個混合整數非線性最適化問題，同時滿足數個互斥的目標，如各成員間的公平收益分配、顧客服務水準、安全存貨水準以及在產品需求不確定下決策的韌性，並提升買賣雙方對於產品價格的滿意度。

為了讓各目標函數在彼此互斥的關係下，能得到相互妥協的最適解，本文提出兩階段模糊多目標規畫法來求解：在第一階段以 min 運算子最大化滿意度最低的目標；接著於第二階段在具備最低滿意度的保證下，以 product 或算數平均運算子盡量提升個別隸屬度函數的值。

最後，提出數個模擬範例，由模擬的結果可得知：兩階段模糊多目標規畫法可以得到較佳的妥協解；而將衡量韌性的指標納入目標函數，則能明顯地降低因產品需求不確定所導致的目標函數數值變動。

Abstract

A multi-product, multi-stage, and multi-period scheduling model is proposed in this paper to deal with multiple incommensurable goals for a multi-echelon supply chain network with uncertain market demands and product prices. We set up fuzzy sets, with monotonic increasing membership functions, to describe the sellers' and buyers' preference on sales prices, respectively. The scenario-based approach will be adopted for modeling the uncertain market demands, however, the realization of objective values might be unacceptably low for certain scenarios.That is, the related decisions lack robustness. Thus, we propose the lower partial mean as the measure of robustness, and include it as part of objectives.

The supply chain scheduling model is constructed as a mixed-integer nonlinear programming problem to satisfy several conflict objectives, such as fair profit distribution among all participants, safe inventory levels, maximum customer service levels, and robustness of decision to uncertain product demands, therein the compromised preference levels on product prices from the sellers and buyers point of view are simultaneously taken into account.

For purpose that a compensatory solution among all participants of the supply chain can be achieved, a two-phase fuzzy decision-making method is presented. In phase one, use the minimum operator to maximize the degree of satisfaction for the worst situation.Then, apply the product operator to maximize the overall satisfactory level with guaranteed minimal fulfillment in phase two. Several numerical examples illustrate that the proposed two-phase method can provide a better compensatory solution. And the inclusion of robustness measures as part of objectives can significantly reduce the variability of objective values to product demand uncertainties.

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1

緒論

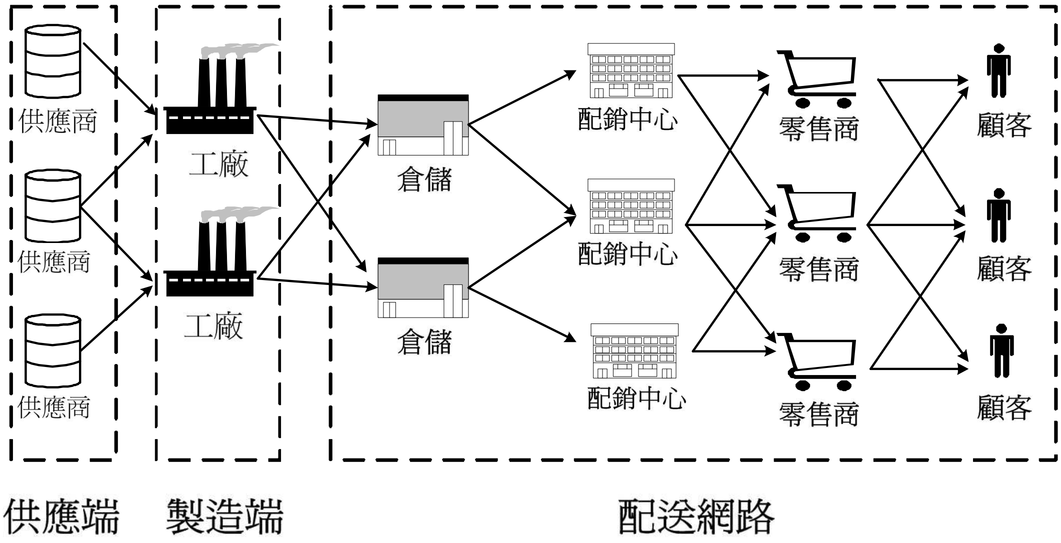
1.1 前言

在今日競爭激烈的商業環境中，由於生產技術進步，使得產品的生命週期被快速壓縮，再加上消費者意識高漲、家庭成員數減少，消費者所重視的是「少量多樣性」的商品與高服務品質的消費模式，迫使各企業必須摒除本位主義，整合彼此的物流與資訊流，以迅速回應消費者多變的需求。因此，企業間必須維持良好的聯盟與合作關係，並透過協調與分工來提升整體的營運績效與競爭力。而這種企業與企業間的新關係，發展成一種『供應鏈』的關係，進而擴大形成了供應鏈管理 (Supply Chain Management, SCM) 的概念[49] [50]。

1.2 供應鏈之定義與架構

美國供應鏈協會 (Supply Chain Council) 對供應鏈提出以下定義：供應鏈乃是包括從供應商到顧客之間，所有對產品的生產與配銷之相關活動流程。所有的相關活動流程可區分為四個基本的功能模組：規劃 (Plan)、採購 (Source)、製造 (Make)、配銷 (Deliver)，定義了基本供給與需求的管理、原物料採購、製造與裝配、倉儲與存貨的追蹤、訂單進入與訂單管理以及整體供應鏈上的配銷等相關活動之基本流程。根據美國供應鏈協會的定

圖 **1.1** 供應鏈架構之示意圖



義，供應鏈管理是涵蓋生產與配送最終產品所作的努力，其對象從供應商到顧客，其目的在透過順暢、及時的資訊流動，以及鏈上所有成員之間密切的協調配合，使顧客獲得滿意的產品與服務，廠商獲得應有的利潤並且健康地成長。

圖 1.1 為供應鏈架構之示意圖，一般而言，供應鏈架構可分為三個主要階層[49] [50]，包括：供應商 (suppliers)、製造商或工廠 (manufacturers/plants)、以及配送網路 (distribution network)，以下將針對各項作一簡單說明：

➤ 供應商：

供應商提供各項產品、原物料或服務給負責生產或組裝的廠商。此處的供應商通常是指直接供應商 (immediate suppliers)，即直接將其原物料提供給廠商者。

➤ 製造商或工廠：

製造商或工廠主要是透過特定的生產程序，將上述供應商所提供的各項元素轉換成最終的產品或者是服務，可包含製造廠商 (fabrication plants)、次組裝場 (subassembly plants) 以及最終組裝場 (final assembly plants) 等等。

➤ 配送網路：

網路配送包含了配送中心 (distribution centers)、零售商 (retailers) 以及終端顧客 (end customers) 等等，其主要工作是將已生產完成的產品或服務轉移到終端顧客的手中，以滿足其需求。

至於供應鏈架構中各階層之間的關係，則必須考慮各個企業所處的競爭位置為何。假使有某個企業之力量大到足以掌控整個供應鏈，則供應鏈中其他個體只能扮演跟隨者的角色，彼此間的關係也相對單純，這種供應鏈體系可視為集中式的供應鏈 (centralized supply chain) 。然而，由於現今的生產環境大多是由甲地供應原料、乙地生產、丙地組裝，甚至最後再交由另一個地方負責產品配銷，因此供應鏈中每個個體其實是以一種相依或互補的關係共存著，彼此之間透過合作或聯盟，進行包括物流、金流、資訊流等生產運籌之整合，此種供應鏈體系可視為分散式的供應鏈 (decentralized supply chain)。

1.3 文獻回顧

在供應鏈管理領域，有許多學者提出看法與研究，相關文獻不勝枚舉，此處只列舉幾個與本文有關的文獻，逐一詳述如下：

Clark 和 Scarf(1960)[14] 提出在多階層架構下，獲得最佳倉儲策略的模式。雖然並非是完整的供應鏈模式，但目前供應鏈中許多階層的概念，實肇始於本模式。

Cohen 與 Moon (1990)[15]將整個供應鏈中的活動發展成一個名為 PILOT 的數學模式，以成本極小化作為其目標式，限制式則包含了原料的需求、供給、產能等。作者指出在不同的情況下有許多因素都會影響到供應鏈的成本，其中運輸成本在整個供應鏈的成本中尤其扮演重要的角色。

Vakharia 等人 (1991)[57]將過去供應鏈模式研究的發展作一詳細整理，包含供應鏈的定義、架構、網路設計以及從操作層級的觀點來整合生產與配送規劃模式的方式；並歸納常見的模式建構方式，討論過去許多學者所提出的供應鏈模式研究之間的差異。最後並指出未來供應鏈研究發展的方向，例如：如何同時整合各個成員的整體最佳決策，而非侷限在各成員各自最佳決策的問題。

由於化工產業也可以透過整合供應鏈網路獲取更多的利益，因此近年來，有許多程

序系統工程方面的學者投入這個領域。舉例如下：

Gupta 與 Maranas(2000)[24]提出一個兩階段隨機規劃 (stochastic programming) 模式來處理供應鏈中產品需求的不確定性。其方式為：將整個供應鏈規劃分成生產與配送規劃兩個階段，在第一階段先處理生產規劃，接著在第二階段同時處理配送規劃與產品需求的不確定性。並假設產品需求為常態分佈 (normal distribution)，用解析的方式找出第二階段的期望成本，然後將隨機規劃問題轉換成相等的定量規劃 (deterministic programming) 問題。最近， Gupta 與 Maranas(2003)[25]又將其擴展至多週期的規劃。

Bose 與 Pekny(2000)[4]使用類似模式預測控制概念來進行生產與配送規劃，其中建立一個預測模式和一個規劃模式，並讓兩個模式在一個包含不確定性的模擬環境中，一前一後地運作。由預測模式計算未來週期的存貨量，再以規劃模式透過最適化使未來的存貨量達到預測之存貨量。

Zhou 等人 (2000)[60]提出一個將永續經營當成目標的供應鏈模式。考量社會、經濟、資源與環境等永續經營目標，形成一個多目標規劃問題，然後使用目標規劃法求得最適解。

Applequist 等人 (2000)[2]提出一個指標來評估在不確定情況下，供應鏈設計與方案規劃的風險。此風險指標可以作為理性地平衡投資獲利期望值與變異量之基礎。

Shah 等人 (2001)[20]提出一個考慮多個層級之間各個供應鏈成員公平利益分配的模式，並參考著名經濟學學者 Nash[38]所提出的賽局理論 (Game Theory) 來建立其目標函數，如式 (1.1) 所示，即在各種限制式之下：例如，存貨限制、生產限制，將目標函數定為供應鏈中各成員的收益函數 π_m 減去最低收益下限 π_m^L 後的乘積並求取其最大化；其中 m 代表供應鏈中成員的編號。

$$\max \Phi = \Pi_m(\pi_m - \pi_m^L) \tag{1.1}$$

Grossmann 等人 (2001)[21]建立了一個動態模擬分析的生產與配銷模式，以傳統工業上使用的比例控制與預測性控制觀念設計存貨管理政策，並討論在不同的存貨管理政策與不同形式的顧客需求變動下對製造成本、運送成本、倉儲成本與服務水準的影響。雖然在這篇文獻中並非以數學規劃方式來求得整個系統的最佳化參數，但是其將顧客服務

水準列入考慮的方式，將可應用在本研究中作為考量目標函數之一。

Pantelides 等人 (2001)[39]提出一個以最小化生產、運輸、存貨等成本總和為單一目標函數之多時期、多產品、確定參數的混合整數線性規劃模式，採用情境為基礎 (scenario-based) 的方法來描述不確定之產品需求。透過模式的運算，決定工廠、倉庫、配送中心的數量與相對位置以及配送方式。

Grossmann 等人 (2003)[22]使用模式預測控制的策略來找出最佳決策變數，以最大化一個包含多產品、多階層配送網路及批次工廠的供應鏈收益。其模式是一個時間不連續的混合整數線性動態規劃問題，並比較集中式與分散式供應鏈的行為，其研究顯示集中式管理能得到較高的收益。

1.4 研究動機與目的

在過去的研究中常以成本最小化或收益最大化為單一考量目標的方式，如文獻[15]、[24]、 [39]及[22]等等。然而今日消費者意識型態提高，唯有不斷提升顧客服務水準才是企業生存的利基。因此，本研究將顧客服務水準列入考慮之中，此外，為降低產品需求不確定性所帶來的影響，亦同時考量安全存貨水準。

現今有許多供應鏈是屬於分散式管理，也就是其中並無任何企業之力量大到足以掌控整個供應鏈，甚至擁有分配收益的決定權。各成員參與供應鏈網路之目的是期望整合彼此的功能，以求取本身最大的利益。因此，若無法平均分配利益，企業參與意願必然下降，甚至退出供應鏈。而能保證各成員間公平收益分配之供應鏈，顯然能吸引更多的企業加入，而使整個供應鏈更具競爭力。 Shah 等人 (2001)[20]採用賽局理論來處理公平收益分配的問題，但其缺點有三：

1. 必須由決策者輸入最低收益下限，而供應鏈中每一成員的合理明確的最低收益下限往往難以計算或須經由協調而得。

2. 直接採用收益差乘積最大化的方式，因數量級的不同，可能無法達到真正平均收益的目的。

3. 無法同時考量其他非金錢項目標。

因此，本研究將採用兩階段模糊最適化法，以改善上述的缺點。

在實際的商業環境中，市場狀況與顧客的期望總是不斷地改變，為此有許多的學者致力於研究在不確定環境下的供應鏈管理。例如， Gupta 與 Maranas(2000)[24]以常態分佈和相關平均值與標準差來描述不確定的產品需求。 Pantelides 等人 (2001)[39]則以數個情境和相關發生機率來描述不確定的產品需求，但是卻沒有考量到在產品需求不確定下決策的韌性 (robustness)。

有時雖然目標的期望值符合決策者之期待，然而實際面對某些情境時，目標值卻變得很差，而令人無法接受。所以，如何降低目標值在不同情境中的變動，也就是增加決策的韌性，便成為不容忽視的問題。因此，本研究將選擇以情境為基礎之方法來描述不確定的產品需求，並同時考量在產品需求不確定下決策的韌性。

由於模糊集合具有處理口語表達及不確定問題之潛力，所以 Petrovic(1998)[42] 使用模糊集合來處理產品需求與外部原料之不確定性，並在之後的研究[43]中進一步考慮不確定供應配送之問題。 Giannoccaro(2003)[18]亦應用模糊集合理論來描述市場需求與存貨成本不確定之問題。

產品的價格雖具有明顯的可協商性與不確定性，但在過去的研究中似乎很少考慮其不確定性，相反地，產品價格通常都被視為固定參數。因此，本研究將以模糊集合理論來處理產品價格之不確定性。

總結以上所述，本研究之目的是希望建構一個在產品需求與價格不確定下之多目標供應鏈生產排程與配送規劃模式，並考慮到多個供應鏈績效指標如：確保各成員間的公平收益分配、顧客服務水準、安全存貨水準、在產品需求不確定下決策的韌性以及各成員對於產品價格的滿意度。最後，採用兩階段模糊多目標規畫法求取相互妥協之最適解。

1.5 組織章節

本文共分為七個章節，包含：

第一章 緒論：

介紹供應鏈管理，並回顧相關的文獻，從中歸納出研究動機與研究的方法。

第二章 多目標生產與配送規劃之供應鏈模式建構：

詳細說明建構模式的背景、假設條件、所使用的符號、參數與變數以及目標函式與限制式。

第三章 模糊多目標最適化：

介紹模糊多目標最適化方法，並回顧過去多種處理模糊多目標規劃的方法，在從中探討適合本研究的方法。

第四章 模式情境模擬分析與討論：

在設計的情境下對所建構的模式進行模擬，並以第三章中討論的兩階段模糊多目標法求解並討論相關結果。

第五章 在產品價格不確定下之供應鏈網路最適化：

以模糊理論描述價格不確定，並進行模擬與討論相關結果。

第六章 在產品需求與價格不確定下之供應鏈網路最適化：

以情境為基礎之方法來描述不確定的產品需求，並進行模擬及討論相關結果。

第七章 結論與未來展望。

2

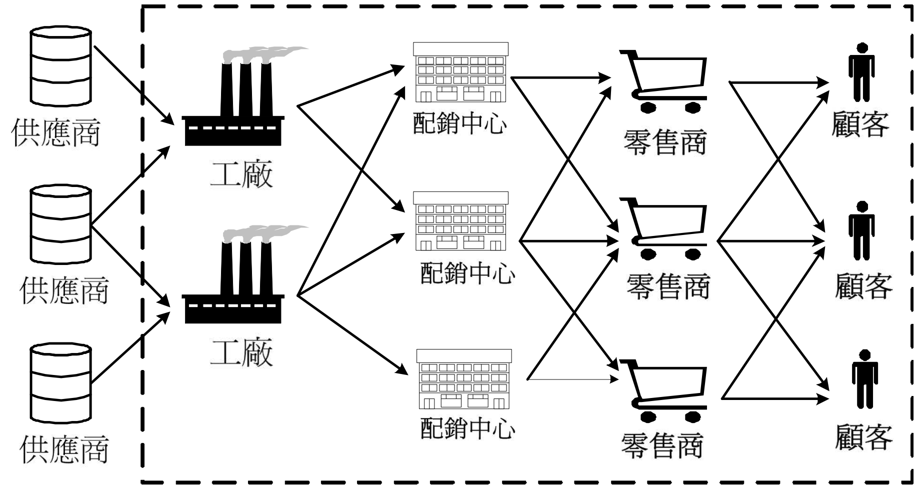
多目標生產與配送規劃之供應鏈模式建構

2.1　模式建立之背景說明

在傳統的供應鏈管理中，處理生產排程與配送規劃問題時，常以成本最小化或收益最大化為單一考量目標，雖然可以得到整個系統的最佳規劃結果，但是可能會造成供應鏈中某些成員成本提高或收益下降；也就是說，有可能必須要犧牲其中部分成員的利益，來達成整個供應鏈的最佳化；例如，配銷商在經濟批量運送模式的考量下，會儘量採取整批運送的方式將產品運往下游廠商，以降低運送成本、維護自身的利益。但是在處理整個供應鏈規劃生產排程與配送規劃問題時，為了達到整個供應鏈的成本最小化或收益最大化，可能迫使配銷商無法以經濟批量模式整批運送的方式來配送，而增加了零星少量的配送次數，卻造成配銷商本身運送成本提高，降低收益。因此，如果不能提出一套有效的決策系統，能同時整合供應鏈中各個成員的資源與達到合理公平的成本或收益分配，可能會造成供應鏈中各成員相互合作的意願降低，使得整合整個供應鏈系統資源的目標趨於困難。

此外，今日消費者意識型態提高，不論製造業或服務業皆漸漸以顧客服務之導向為重心，唯有不斷提升顧客服務水準才是企業生存的利基。所以在整合整個供應鏈規劃的

圖 **2.1** 研究範圍之示意圖



過程中，也應該將顧客服務水準列入考慮之中。但是在傳統的供應鏈管理中，以成本最小化或收益最大化為單一考量目標的方式，無法包含像是顧客服務水準這一類難以金錢精確量化衡量的目標函數。此外，許多供應鏈模式研究都是以預測的顧客需求進行規劃，本模式為降低顧客需求不確定所帶來的影響，加入了安全存貨水準作為考量的績效指標之一。使得即便是在預測的需求量有偏差時，系統仍能具有彈性來克服這些偏差所帶來的影響。因此，本模式將採用多目標規劃法來整合供應鏈生產排程與配送規劃問題，除了考量整體收益最佳化以外，一併考慮供應鏈中各個參與成員公平收益分配的問題，以及顧客滿意度與安全存貨度等其他評量供應鏈績效的指標。此外，在建構本模式時，也考慮到現實工業界中常見的經濟批量銷售與經濟批量運送方式，以及工廠批次量產的特性。

2.2 模式建立之基本假設條件

為了簡化問題，本研究不將原物料的供應商列入考慮；同時假設倉儲與工廠的距離很近，屬於同一個企業，所以倉儲也不列入考量。討論範圍是從製造端到顧客端，如圖 2.1 中虛線部分所示。

在建構模式前，必須作下列的假設：

1. 各產品的銷售與售價都是獨立的，不會互相影響。
2. 每一層級皆訂有安全存貨量以降低產品需求不確定的影響。
3. 工廠以批次生產方式製造產品，每一期只能生產一種產品。
4. 每一期生產的產品項目改變時，有固定換線製造成本；若工廠生產線閒置，則有固定閒置成本。
5. 容許加班工時生產該期正常工時所設定生產的產品，並有最多加班總次數與連續加班次數限制。
6. 不考慮原物料的採購儲存問題，並將原物料的採購成本併入製造成本中。
7. 每一期生產之產品經過一期的生產製造，在下一期期初完成。
8. 產品的需求量為預測。
9. 有最低顧客服務水準限制。
10. 考慮各層級間運送所需的前置時間。
11. 工廠與配銷中心間、配銷中心與零售商間是採用經濟批量銷售與經濟批量運送。
12. 產品售價與銷售量的關係為不連續線性 (piecewise linear) 模式。
13. 運送成本與運送量的關係為不連續線性模式。
14. 每一期只能選擇一種經濟批量銷售方式。
15. 每一期最多只能選擇一種經濟批量運送方式。

因此整個模式可以描述如下：

1. 決策者提供：
   (a) 生產製造資料，例如正常工時與加班工時的批次生產量、加班生產總期數的限制等等。
   (b) 運送資料，例如運送所需的前置時間、運送量限制等等。
   (c) 存貨資料，例如存貨量限制、安全存貨量等等。
   (d) 各項成本參數，例如製造、存貨、產品處理等等。
   (e) 產品的預測需求量。
   (f) 產品售價。
2. 以模式計算出：
   (a) 各工廠的生產排程規劃。
   (b) 各工廠與配銷中心的運送規劃。
   (c) 各零售商的銷售量。
   (d) 各層級的存貨量。
   (e) 各層級的各項成本。
3. 模式的目標是同時整合供應鏈中多個層級成員生產與配送規劃的決策，以達成：
   (a) 確保各成員間的公平收益分配。
   (b) 盡量提升顧客服務水準以及安全存貨水準。

2.3 模式之符號、系統參數與系統變數 (Index, Parameters, and Variables)

建立模式的首要步驟就是決定系統中的符號、參數以及變數，本文將分別列於2.3.1 ～ 2.3.3節。

2.3.1 符號說明 (Index)

符號	集合	總數	物理意義
$c \in$	$\mathcal{C}$	$[\mathcal{C}] = C$	c 為顧客編號；$\mathcal{C}$ 為顧客集合；C 為顧客總數。
$d \in$	$\mathcal{D}$	$[\mathcal{D}] = D$	d 為配銷中心編號；$\mathcal{D}$ 為配銷中心集合；D 為配銷中心總數。
$i \in$	$\mathcal{I}$	$[\mathcal{I}] = I$	i 為產品編號；$\mathcal{I}$ 為產品集合；I 為產品總數。
$k \in$	$\mathcal{K}$	$[\mathcal{K}] = K$	產品從配銷中心運送至零售商時，可選擇的經濟批量運送方式，其中 k 為經濟批量運送方式編號；$\mathcal{K}$ 為經濟批量運送方式集合；K 為經濟批量運送方式總數。
$k' \in$	$\mathcal{K}'$	$[\mathcal{K}'] = K'$	產品從工廠運送至配銷中心時，可選擇的經濟批量運送方式，其中 k' 為經濟批量運送方式編號；$\mathcal{K}'$ 為經濟批量運送方式集合；K' 為經濟批量運送方式總數。
$\ell \in$	$\mathcal{L}$	$[\mathcal{L}] = L$	配銷中心售予零售商產品時，可選擇的經濟批量銷售方式，其中 ℓ 為經濟批量銷售方式編號；$\mathcal{L}$ 為經濟批量銷售方式集合；L 為經濟批量銷售方式總數。
$\ell' \in$	$\mathcal{L}'$	$[\mathcal{L}'] = L'$	工廠售予配銷中心產品時，可選擇的經濟批量銷售方式，其中 ℓ' 為經濟批量銷售方式編號；$\mathcal{L}'$ 為經濟批量銷售方式集合；L' 為經濟批量銷售方式總數。
$m \in$	$\mathcal{M}$	$[\mathcal{M}] = M$	m 為目標編號；$\mathcal{M}$ 為目標集合；M 為目標總數。
$p \in$	$\mathcal{P}$	$[\mathcal{P}] = P$	p 為工廠編號；$\mathcal{P}$ 為工廠集合；P 為工廠總數。
$r \in$	$\mathcal{R}$	$[\mathcal{R}] = R$	r 為零售商編號；$\mathcal{R}$ 為零售商集合；R 為零售商總數。
$t \in$	$\mathcal{T}$	$[\mathcal{T}] = T$	t 為規劃週期編號；$\mathcal{T}$ 為規劃週期集合；T 為規劃週期總數。

2.3.2 系統參數 (Parameters)

本節將介紹模式中所需的資訊，即需要決策者所輸入的參數。本文取每一個英文字的第一個字母，來為參數命名，例如：預測的顧客需求 (Forecast Customer Demand)，其命名為 FCD。

參數	$* \in$	物理意義
FCD^{i}_{*t}	$\{rc\}$	預測零售商 r 在第 t 期時，面臨顧客 c 對於產品 i 的需求量。
FIC^{i}_{*}	$\{p\}$	工廠 p 在第 t 期時，生產線被設定於製造產品 i 卻閒置時的固定閒置成本。
FMC^{i}_{*}	$\{p\}$	工廠 p 在第 t 期時，換線製造產品 i 的固定製造成本。
FMQ^{i}_{*}	$\{p\}$	工廠 p 於正常工時批次製造產品 i 的量。
FTC^{k}_{*}	$\{dr\}$	配銷中心 d 將產品運往零售商 r，使用第 k 種經濟批量運送方式時的固定運送成本。
$\mathrm{FTC}^{k'}_{*}$	$\{pd\}$	工廠 p 將產品運往配銷中心 d，使用第 k' 種經濟批量運送方式時的固定運送成本。
MIC_{*}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 的最大存貨量。
MITC_{*}	$\{d\}$	配銷中心 d 將產品運往所有零售商的總運量上限。
MOTC_{*}	$\{d\}$	配銷中心 d 將產品從所有工廠進貨的總運量上限。
MTO_{*}	$\{p\}$	工廠 p 加班生產總期數的上限。
N		工廠最多可連續加班的期數。
OMC^{i}_{*}	$\{p\}$	工廠 p 在第 t 期時，加班工時製造產品 i 的單位製造成本。
OMQ^{i}_{*}	$\{p\}$	工廠 p 於加班工時批次製造產品 i 的量。
SIQ^{i}_{*}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 產品 i 的安全存貨量。
$\mathrm{SQL}^{i\vee}_{*}$	$\{p,d\}$	產品 i 使用第 ℓ' (ℓ) 種經濟批量銷售方式的數量上限，$(*,\vee) \in \{(p,\ell'),(d,\ell)\}$。
UHC^{i}_{*}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 的產品 i 單位處理成本。
UIC^{i}_{*}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 的產品 i 單位存貨成本。
UMC^{i}_{*}	$\{p\}$	工廠 p 在第 t 期時，正常工時製造產品 i 的單位製造成本。
$\mathrm{USP}^{i\vee}_{*}$	$\{pd,dr\}$	在第 t 期時，使用第 ℓ' (ℓ) 種經濟批量銷售方式，產品 i 的單位售價，$(*,\vee) \in \{(pd,\ell'),(dr,\ell)\}$。
USP^{i}_{*}	$\{rc\}$	零售商 r 售予顧客 c 產品 i 的單位售價。
UTC^{k}_{*}	$\{dr\}$	配銷中心 d 將產品運往零售商 r，使用第 k 種經濟批量運送方式時的單位運送成本。
$\mathrm{UTC}^{k'}_{*}$	$\{pd\}$	工廠 p 將產品運往配銷中心 d，使用第 k' 種經濟批量運送方式時的單位運送成本。
TCL^{k}_{*}	$\{dr\}$	配銷中心 d 將產品運往零售商 r，使用第 k 種經濟批量運送方式時的最大運量。
$\mathrm{TCL}^{k'}_{*}$	$\{pd\}$	工廠 p 將產品運往配銷中心 d，使用第 k' 種經濟批量運送方式時的最大運量。
TLT_{*}	$\{pd,dr\}$	從工廠 p 到配銷中心 d、從配銷中心 d 到零售商 r 運送產品的前置時間。

2.3.3 系統變數 (Variables)

0,1 變數是表示一個事件存在或不存在的邏輯變數，例如：當 $\alpha_{pt}^{i}=1$ 表示工廠 p 於正常工時有製造產品 i，$\alpha_{pt}^{i}=0$ 則表示沒有製造產品 i。

0,1 變數	$*\in$	值等於 1 時的物理意義
$\mathrm{V}_{*t}^{i\ell}$	$\{dr\}$	配銷中心 d 在第 t 期時，決定使用第 ℓ 種經濟批量銷售方式將產品售予零售商 r。
$\mathrm{V}_{*t}^{i\ell'}$	$\{pd\}$	工廠 p 在第 t 期時，決定使用第 ℓ' 種經濟批量銷售方式將產品售予配銷中心 d。
Y_{*t}^{k}	$\{dr\}$	配銷中心 d 在第 t 期時，決定使用第 k 種經濟批量運送方式將產品運往零售商 r。
$\mathrm{Y}_{*t}^{k'}$	$\{pd\}$	工廠 p 在第 t 期時，決定使用第 k' 種經濟批量運送方式將產品運往配銷中心 d。
α_{*t}^{i}	$\{p\}$	工廠 p 決定在第 t 期於正常工時批次製造產品 i。
β_{*t}^{i}	$\{p\}$	工廠 p 的生產線於第 t 期時設定為製造產品 i。
γ_{*t}^{i}	$\{p\}$	工廠 p 決定於第 t 期時更換生產線設定為製造產品 i。
o_{*t}^{i}	$\{p\}$	工廠 p 決定在第 t 期於加班工時批次製造產品 i。

實數變數	$* \in$	物理意義
B_{*t}^{i}	$\{r\}$	零售商 r 於第 t 期末的產品 i 缺貨量。
D_{*t}^{i}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期末的產品 i 安全存貨短缺量。
I_{*t}^{i}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期末的產品 i 存貨量。
J_*	$\{m\}$	目標
PSP_{*t}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的總銷售收益。
SQ_{*t}^{i}	$\{pd, dr, rc\}$	工廠 p 售予配銷中心 d、配銷中心 d 售予零售商 r、零售商 r 售予顧客 c 產品 i 於第 t 期的銷售量。
TIC_{*t}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的總存貨成本。
THC_{*t}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的總處理成本。
TMC_{*t}	$\{p\}$	工廠 p 於第 t 期的總製造成本。
TPC_{*t}	$\{d, r\}$	配銷中心 d、零售商 r 於第 t 期的總購買成本。
TQ_{*t}^{k}	$\{dr\}$	配銷中心 d 將產品運往零售商 r，使用第 k 種經濟批量運送方式的實際運送量。
$\mathrm{TQ}_{*t}^{k'}$	$\{pd\}$	工廠 p 將產品運往配銷中心 d，使用第 k' 種經濟批量運送方式的實際運送量。
TQ_{*t}	$\{pd, dr\}$	工廠 p 將產品運往配銷中心 d、配銷中心 d 將產品運往零售商 r 的總運送量。
TTC_{*t}	$\{p, d\}$	工廠 p、配銷中心 d 於第 t 期的總運送成本。
USP_{*t}^{i}	$\{pd, dr\}$	工廠 p 售予配銷中心 d、配銷中心 d 售予零售商 r 產品 i 的單位售價。
SIL_{*t}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的安全存貨水準。
CSL_{*t}	$\{d\}$	零售商 r 於第 t 期的顧客服務水準。
Z_{*t}	$\{p, d, r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的淨收益。

2.4 目標函數與限制式 (Objective Functions and Constraints)

在這部分將根據2.2節中提到的假設與供應鏈網路各成員的特性，建立相關的限制式與目標函數。

2.4.1 工廠的生產製造限制 (Manufacture Constraints for Plants)

在生產製造方面，2.2節中的第三個假設限制工廠每一期只能設定製造一種產品，而 $\beta_{pt}^{i} = 1$ 時表示工廠 p 於第 t 期設定製造產品 i， $\beta_{pt}^{i} = 0$ 則表示沒有製造。因此，在每一期，一個工廠內所有產品的 β_{pt}^{i} 總和必須要等於 1，如式 (2.1) 所示。 式 (2.2) 限制工廠 p 的生產線必須設定為製造特定單一產品 i 之後才能決定是否於正常工時生產，而且必須於正常工時產量不足，才可以於加班工時生產。在式 (2.3) 中，當 $\beta_{pt}^{i} - \beta_{p,t-1}^{i}$ 為 1 時，即表示工廠於上一期並沒有設定製造產品 i ，而這一期改為設定製造產品 i，也就是工廠有換線生產，所以 γ_{pt}^{i} 等於 1。在2.2節中的第五個假設提到最多加班總次數與連續加班次數限制，其相關的限制式如式 (2.4) 和式 (2.5) 所示。

$$\sum_{\forall i \in \mathcal{I}} \beta_{pt}^{i} = 1 \tag{2.1}$$

$$o_{pt}^{i} \leq \alpha_{pt}^{i} \leq \beta_{pt}^{i} \tag{2.2}$$

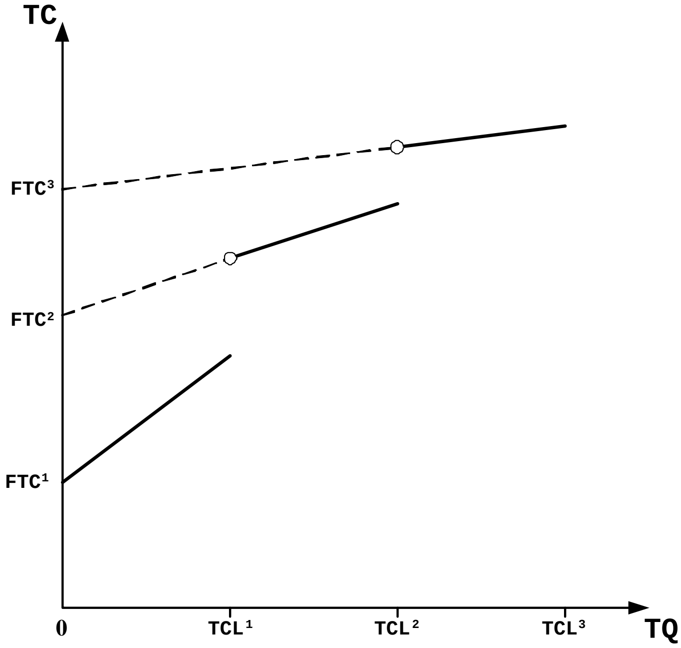
$$\gamma_{pt}^{i} \geq \beta_{pt}^{i} - \beta_{p,t-1}^{i} \tag{2.3}$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{\forall t \in \mathcal{T}} o_{pt}^{i} \leq \mathrm{MTO}_p \tag{2.4}$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{n=0}^{N} o_{p,t-n}^{i} \leq N \tag{2.5}$$

$$\forall p \in \mathcal{P}, i \in \mathcal{I}, t \in \mathcal{T}$$

圖 **2.2** 運送成本 (TC) 與運送量 (TQ) 之關係示意圖



2.4.2 產品運送限制 (Transportation Constraints)

在2.2節中的第 11 個假設中提到：本文考慮數種經濟批量運送方式，運送的量愈多，單位運送成本就愈低，每一種運送方式都有運送量的上限與下限，其限制式如式 (2.6) 與式 (2.7) 所示。第 15 個假設限制每一期最多只能選擇一種運送方式，而當 $\mathrm{Y}_{pdt}^{k'} = 1$ 時，表示選擇第 k' 種運送方式，因此，每一期所有運送方式的 $\mathrm{Y}_{pdt}^{k'}$ 總和必須小於或等於 1 ，如式 (2.8) 所示。第 13 個假設中提到：運送成本與運送量的關係為不連續線性模式。其概念如圖 2.2 所示，這個圖描述的例子總共有三種經濟批量運送方式可以選擇。 式 (2.9) 為配銷中心 d 從工廠 p 進貨總運送量等於工廠 p 售予配銷中心 d 所有產品的總量； 式 (2.10) 為配銷中心 d 運往零售商 r 總運送量等於配銷中心 d 售予零售商 r 所有產品的總量； 式 (2.11) 為配銷中心 d 從所有工廠進貨總運送量不能超過其進貨量上限； 式 (2.12) 為配銷中心 d 運往所有零售商總運送量不能超過其出貨量上限。

$$\mathrm{TCL}_{pd}^{k'-1}\mathrm{Y}_{pdt}^{k'} \; < \; \mathrm{TQ}_{pdt}^{k'} \; \leq \; \mathrm{TCL}_{pd}^{k'}\mathrm{Y}_{pdt}^{k'} \tag{2.6}$$

$$\mathrm{TCL}_{dr}^{k-1}\mathrm{Y}_{drt}^{k} \; < \; \mathrm{TQ}_{drt}^{k} \; \leq \; \mathrm{TCL}_{dr}^{k}\mathrm{Y}_{drt}^{k} \tag{2.7}$$

$$\sum_{\forall k' \in \mathcal{K}'} \mathrm{Y}_{pdt}^{k'} \; \leq \; 1 \qquad \sum_{\forall k \in \mathcal{K}} \mathrm{Y}_{drt}^{k} \; \leq \; 1 \tag{2.8}$$

$$\mathrm{TQ}_{pdt} \; = \; \sum_{\forall k' \in \mathcal{K}'} \mathrm{TQ}_{pdt}^{k'} \; = \; \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}_{pdt}^{i} \tag{2.9}$$

$$\mathrm{TQ}_{drt} \; = \; \sum_{\forall k \in \mathcal{K}} \mathrm{TQ}_{drt}^{k} \; = \; \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}_{drt}^{i} \tag{2.10}$$

$$\sum_{\forall p \in \mathcal{P}} \mathrm{TQ}_{pdt} \; \leq \; \mathrm{MITC}_{d} \tag{2.11}$$

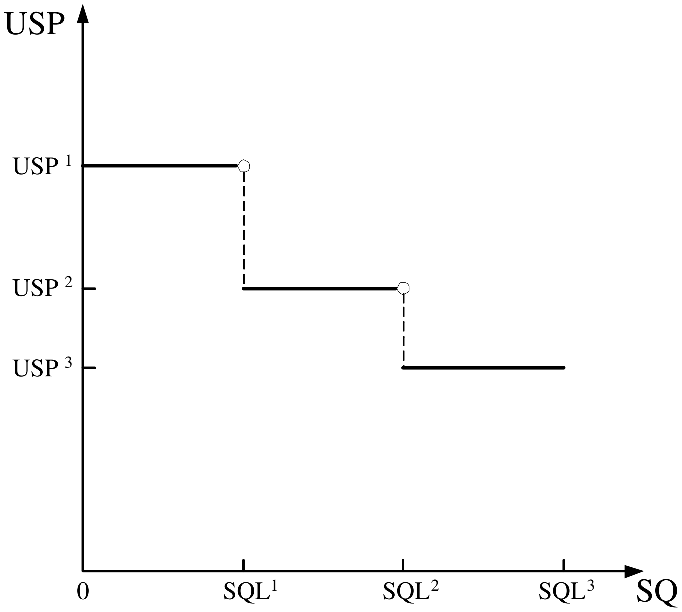
$$\sum_{\forall r \in \mathcal{R}} \mathrm{TQ}_{drt} \; \leq \; \mathrm{MOTC}_{d} \tag{2.12}$$

$$\forall p \in \mathcal{P},\; d \in \mathcal{D},\; r \in \mathcal{R},\; k' \in \mathcal{K}',\; k \in \mathcal{K},\; t \in \mathcal{T}$$

2.4.3 產品售價限制

在2.2節中的第 11 個假設中提到：本文考慮數種經濟批量銷售方式，購買的量愈多，產品單位售價就愈低，每一種銷售方式都有銷售量的上限與下限，其限制式如式 (2.13) ～ 式 (2.16) 所示。第 14 個假設限制每一期只能選擇一種運送方式，而當 $\mathrm{V}_{pdt}^{i\ell'} = 1$ 時，表示選擇第 k' 種銷售方式，因此，每一期所有銷售方式的 $\mathrm{Y}_{pdt}^{k'}$ 總和必須等於 1 ，如式 (2.17) 所示。第 12 個假設中提到：產品單位售價與銷售量的關係為不連續線性模式。其概念如圖 2.3 所示，這個圖描述的例子總共有三種經濟批量銷售方式可以選擇。 式 (2.18) 決定每一期產品 i 從工廠 p 售予配銷中心 d 時，產品 i 的單位售價； 式 (2.19) 決定每一期產品 i 從配銷中心 d 售予零售商 r 時，產品 i 的單位售價；

圖 **2.3** 產品單位售價 (USP) 與銷售量 (SQ) 之關係示意圖



$$\mathrm{SQL}_{pd}^{i,\ell'-1}\mathrm{V}_{pdt}^{i\ell'} \leq \mathrm{SQ}_{pdt}^{i} < \mathrm{SQL}_{pd}^{i,\ell'}\mathrm{V}_{pdt}^{i\ell'} \quad \forall \ell' \in \{1,2,\ldots,L'-1\} \tag{2.13}$$

$$\mathrm{SQL}_{dr}^{i,\ell-1}\mathrm{V}_{drt}^{i\ell} \leq \mathrm{SQ}_{drt}^{i} < \mathrm{SQL}_{dr}^{i,\ell}\mathrm{V}_{drt}^{i\ell} \quad \forall \ell \in \{1,2,\ldots,L-1\} \tag{2.14}$$

$$\mathrm{SQL}_{pd}^{i,L'-1}\mathrm{V}_{pdt}^{iL'} \leq \mathrm{SQ}_{pdt}^{i} \leq \mathrm{SQL}_{pd}^{i,L'}\mathrm{V}_{pdt}^{iL'} \tag{2.15}$$

$$\mathrm{SQL}_{dr}^{i,L-1}\mathrm{V}_{drt}^{iL} \leq \mathrm{SQ}_{drt}^{i} \leq \mathrm{SQL}_{dr}^{i,L}\mathrm{V}_{drt}^{iL} \tag{2.16}$$

$$\sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}_{pdt}^{i\ell'} = 1 \qquad \sum_{\forall \ell \in \mathcal{L}} \mathrm{V}_{drt}^{i\ell} = 1 \tag{2.17}$$

$$\mathrm{USP}_{pdt}^{i} = \sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}_{pdt}^{i\ell'}\mathrm{USP}_{pd}^{i\ell'} \tag{2.18}$$

$$\mathrm{USP}_{drt}^{i} = \sum_{\forall \ell \in \mathcal{L}} \mathrm{V}_{drt}^{i\ell}\mathrm{USP}_{dr}^{i\ell} \tag{2.19}$$

$$\forall p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ \ell' \in \mathcal{L}',\ \ell \in \mathcal{L},\ t \in \mathcal{T}$$

2.4.4 存貨限制 (Inventory Constraints)

所有與工廠、配銷中心和零售商有關的存貨限制式可以整理如下： 式 (2.20) 為零售商 r 每一期期末的存貨量會等於上一期期末的存貨量加上該期期初由所有配銷中心的進貨量減去該期售予所有顧客的量，其中 TLT_{dr} 即為2.2節第 10 個假設中提到的運送前置時間；配銷中心與工廠也有相似的限制式，如式 (2.21) 和式 (2.22) 所示； 式 (2.20) ～式 (2.21) 也考慮由於運送前置時間而延遲的運送量； 式 (2.23) 為零售商 r 每一期期末的缺貨量會等於上一期期末的缺貨量加上該期的顧客需求量減去該期的出貨量；而且限制在規劃時程的最後一期，第 T 期的缺貨量要為 0； 式 (2.24) 為最大存貨量限制； 式 (2.25) 為限制當存貨大於安全存貨時，安全存貨短缺量為 0；而當存貨小於安全存貨時，安全存貨短缺量為安全存貨與存貨的差； 式 (2.26) 為物理意義限制式。

$$
\begin{aligned}
\mathrm{I}^i_{rt} &= \mathrm{I}^i_{r,t-1} + \sum_{\forall d\in\mathcal{D}} \mathrm{SQ}^i_{dr,t-\mathrm{TLT}_{dr}} - \sum_{\forall c\in\mathcal{C}} \mathrm{SQ}^i_{rct} && (2.20)\\
\mathrm{I}^i_{dt} &= \mathrm{I}^i_{d,t-1} + \sum_{\forall p\in\mathcal{P}} \mathrm{SQ}^i_{pd,t-\mathrm{TLT}_{pd}} - \sum_{\forall r\in\mathcal{R}} \mathrm{SQ}^i_{drt} && (2.21)\\
\mathrm{I}^i_{pt} &= \mathrm{I}^i_{p,t-1} + \mathrm{FMQ}^i_p \alpha^i_{p,t-1} + \mathrm{OMQ}^i_p o^i_{p,t-1} - \sum_{\forall d\in\mathcal{D}} \mathrm{SQ}^i_{pdt} && (2.22)\\
\mathrm{B}^i_{rt} &= \mathrm{B}^i_{r,t-1} + \sum_{\forall c\in\mathcal{C}} \mathrm{FCD}^i_{rct} - \sum_{\forall c\in\mathcal{C}} \mathrm{SQ}^i_{rct}, \quad \mathrm{B}^i_{rT} = 0 && (2.23)\\
\sum_{\forall i\in\mathcal{I}} \mathrm{I}^i_{*t} &\le \mathrm{MIC}_* && (2.24)\\
\mathrm{D}^i_{*t} &\ge \mathrm{SIQ}^i_* - \mathrm{I}^i_{*t} && (2.25)\\
& \mathrm{I}^i_{*t}, \mathrm{SQ}^i_{*t}, \mathrm{B}^i_{*t}, \mathrm{D}^i_{*t} \ \ge\ 0 && (2.26)\\
* &\in \{p, d, r\}\\
& \forall p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R},\ i\in\mathcal{I},\ t\in\mathcal{T}
\end{aligned}
$$

2.4.5 成本與收益 (Costs and Revenues)

工廠的製造成本、配銷中心與零售商的購買成本、所有的存貨與產品處理成本、和產品運送成本列出如下：在式 (2.27) 中，總製造成本為固定換線製造成本、固定閒置成本以及正常工時與加班工時製造成本的總和； 式 (2.28) 為配銷中心與零售商的購買成本 ； 式 (2.29) 為存貨成本，而式 (2.30) ～式 (2.32) 分別為工廠、配銷中心和零售商的產品處理成本； 式 (2.33) 為工廠出貨的運送成本，其中總運送成本是由第 k' 種經濟批量運送方式的固定運送成本與第 k' 種經濟批量運送方式的單位運送成本乘以運送量的總和；而式 (2.34) 為配銷中心出貨的運送成本； 式 (2.35) 為工廠、配銷中心和零售商的總銷售收益；

$$\mathrm{TMC}_{pt}=\sum_{\forall i\in\mathcal{I}}\left[\mathrm{FMC}_p^i\gamma_{pt}^i+\mathrm{FIC}_p^i(\beta_{pt}^i-\alpha_{pt}^i)+\mathrm{UMC}_p^i\mathrm{FMQ}_p^i\alpha_{pt}^i+\mathrm{OMC}_p^i\mathrm{OMQ}_p^i o_{pt}^i\right] \tag{2.27}$$

$$\mathrm{TPC}_{dt} = \sum_{\forall p\in\mathcal{P}}\sum_{\forall i\in\mathcal{I}}\mathrm{USP}_{pdt}^i\mathrm{SQ}_{pdt}^i, \qquad \mathrm{TPC}_{rt} = \sum_{\forall d\in\mathcal{D}}\sum_{\forall i\in\mathcal{I}}\mathrm{USP}_{drt}^i\mathrm{SQ}_{drt}^i \tag{2.28}$$

$$\mathrm{TIC}_{*t} = \sum_{\forall i\in\mathcal{I}}\mathrm{UIC}_*^i\mathrm{I}_{*t}^i \qquad *\in\{p,d,r\} \tag{2.29}$$

$$\mathrm{THC}_{pt} = \sum_{\forall i\in\mathcal{I}}\mathrm{UHC}_p^i\left(\mathrm{FMQ}_p^i\alpha_{p,t-1}^i+\mathrm{OMQ}_p^i o_{p,t-1}^i+\sum_{\forall d\in\mathcal{D}}\mathrm{SQ}_{pdt}^i\right) \tag{2.30}$$

$$\mathrm{THC}_{dt} = \sum_{\forall i\in\mathcal{I}}\mathrm{UHC}_d^i\left(\sum_{\forall p\in\mathcal{P}}\mathrm{SQ}_{pd,t-\mathrm{TLT}_{pd}}^i+\sum_{\forall r\in\mathcal{R}}\mathrm{SQ}_{drt}^i\right) \tag{2.31}$$

$$\mathrm{THC}_{rt} = \sum_{\forall i\in\mathcal{I}}\mathrm{UHC}_r^i\left(\sum_{\forall d\in\mathcal{D}}\mathrm{SQ}_{dr,t-\mathrm{TLT}_{dr}}^i+\sum_{\forall c\in\mathcal{C}}\mathrm{SQ}_{rct}^i\right) \tag{2.32}$$

$$\mathrm{TTC}_{pt} = \sum_{\forall k'\in\mathcal{K}'}\sum_{\forall p\in\mathcal{P}}\left(\mathrm{FTC}_{pd}^{k'}\mathrm{Y}_{pdt}^{k'}+\mathrm{UTC}_{pd}^{k'}\mathrm{TQ}_{pdt}^{k'}\right) \tag{2.33}$$

$$\mathrm{TTC}_{dt} = \sum_{\forall k\in\mathcal{K}}\sum_{\forall r\in\mathcal{R}}\left(\mathrm{FTC}_{dr}^{k}\mathrm{Y}_{drt}^{k}+\mathrm{UTC}_{dr}^{k}\mathrm{TQ}_{drt}^{k}\right) \tag{2.34}$$

$$\begin{aligned}\mathrm{PSP}_{pt} &= \sum_{\forall d\in\mathcal{D}}\sum_{\forall i\in\mathcal{I}}\mathrm{USP}_{pdt}^i\mathrm{SQ}_{pdt}^i,\ \mathrm{PSP}_{dt}=\sum_{\forall r\in\mathcal{R}}\sum_{\forall i\in\mathcal{I}}\mathrm{USP}_{drt}^i\mathrm{SQ}_{drt}^i,\\ \mathrm{PSP}_{rt} &= \sum_{\forall c\in\mathcal{C}}\sum_{\forall i\in\mathcal{I}}\mathrm{USP}_{rc}^i\mathrm{SQ}_{rct}^i\end{aligned} \tag{2.35}$$

$$\forall p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R},\ t\in\mathcal{T}$$

2.4.6 目標函數 (Objective Fuctions)

本研究同時考量三個目標：各成員的淨收益、平均安全存貨水準與平均顧客服務水準，並逐一說明如下：

目標一：同時最大化各成員的淨收益

相較於最大化整個供應鏈網路的淨收益，本研究傾向於將收益公平地分配給供應鏈網路的各個成員。淨收益為總銷售收益減去各種成本。

$$\begin{aligned}
\mathrm{Z}_p &= \sum_{\forall t\in\mathcal{T}} (\mathrm{PSP}_{pt} - \mathrm{TMC}_{pt} - \mathrm{TTC}_{pt} - \mathrm{TIC}_{pt} - \mathrm{THC}_{pt}) \quad \forall\, p\in\mathcal{P} \\
\mathrm{Z}_d &= \sum_{\forall t\in\mathcal{T}} (\mathrm{PSP}_{dt} - \mathrm{TPC}_{dt} - \mathrm{TTC}_{dt} - \mathrm{TIC}_{dt} - \mathrm{THC}_{dt}) \quad \forall\, d\in\mathcal{D} \\
\mathrm{Z}_r &= \sum_{\forall t\in\mathcal{T}} (\mathrm{PSP}_{rt} - \mathrm{TPC}_{rt} - \mathrm{THC}_{rt} - \mathrm{TIC}_{rt}) \quad \forall\, r\in\mathcal{R}
\end{aligned} \tag{2.36}$$

目標二：最大化平均安全存貨水準

安全存貨水準可以降低顧客需求不確定所帶來的影響，避免因需求量突然增高而缺貨，因此，本文將其納入考量的目標。零售商 r 在第 t 期的安全存貨水準，其定義為該期所有產品安全存貨率的平均值；安全存貨率為 1 減去安全存貨短缺量 D^i_{rt} 除以安全存貨量 SIQ^i_r 的比率。相似的定義也可適用於工廠和配銷中心。

$$\begin{aligned}
\mathrm{SIL}_* &= \frac{100}{I\,T} \sum_{\forall t\in\mathcal{T}} \sum_{\forall i\in\mathcal{I}} \left(1 - \frac{\mathrm{D}^i_{*t}}{\mathrm{SIQ}^i_*}\right) \%, \qquad * \in \{p,d,r\} \\
& \forall p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R}
\end{aligned} \tag{2.37}$$

目標三：最大化平均顧客服務水準

今日消費者對於顧客服務水準的要求已經提高很多，因此唯有不斷提升服務水準才是企業生存的利基，所以本文將其納入考量的目標。零售商 r 在第 t 期的顧客服務水準，其定義為該期所有產品出貨率的平均值；產品出貨率為總銷售量 $\sum_{\forall c\in\mathcal{C}} \mathrm{SQ}^i_{rct}$

除以顧客總需求量 $\sum_{\forall c\in\mathcal{C}} \mathrm{FCD}^i_{rct}$ 與上一期的缺貨量 $\mathrm{B}^i_{r,t-1}$ 的總和。

$$\mathrm{CSL}_r \;=\; \frac{100}{I\,T}\sum_{\forall t\in\mathcal{T}}\sum_{\forall i\in\mathcal{I}}\left(\frac{\displaystyle\sum_{\forall c\in\mathcal{C}}\mathrm{SQ}^i_{rct}}{\mathrm{B}^i_{r,t-1}+\displaystyle\sum_{\forall c\in\mathcal{C}}\mathrm{FCD}^i_{rct}}\right)\% \quad \forall\, r\in\mathcal{R} \tag{2.38}$$

2.4.7 生產與配送規劃之供應鏈模式整合

將前面2.4.1、2.4.2、2.4.3 、2.4.4、2.4.5、2.4.6節所討論的限制式與目標函數整合成一個「多目標混合整數非線性規劃問題」 (Multi-Objective Mixed-Integer Nonlinear Programming, MO-MINLP)，如式 (2.39) 所示。在式 (2.28) 和式 (2.35) 中的 $\mathrm{USP}^i_{pdt}\mathrm{SQ}^i_{pdt}$ 與 $\mathrm{USP}^i_{drt}\mathrm{SQ}^i_{drt}$ ，以及式 (2.38) 是模式中非線性項的主要來源。

其中 $\mathbf{x}$ 為決策變數，$\boldsymbol{\Omega}$ 為整個模式中所有限制式集合形成的可行解區域。

$$\max_{\mathbf{x}\in\boldsymbol{\Omega}} \quad (J_1(\mathbf{x}),\ldots,J_M(\mathbf{x})) = \begin{pmatrix} \mathrm{Z}_p,\ \mathrm{Z}_d,\ \mathrm{Z}_r;\ \mathrm{SIL}_p,\ \mathrm{SIL}_d,\ \mathrm{SIL}_r;\ \mathrm{CSL}_r; \\ \forall p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R} \end{pmatrix}$$

$$\mathbf{x} = \left\{\begin{array}{r} \alpha^i_{pt},\beta^i_{pt},\gamma^i_{pt},o^i_{pt};\mathrm{SQ}^i_{pdt},\mathrm{SQ}^i_{drt},\mathrm{SQ}^i_{rct};\mathrm{USP}^i_{pdt},\mathrm{USP}^i_{drt}; \\ \mathrm{TQ}^{k'}_{pdt},\mathrm{TQ}^{k}_{drt},\mathrm{Y}^{k'}_{pdt},\mathrm{Y}^{k}_{drt};\mathrm{V}^{i\ell'}_{pdt},\mathrm{V}^{i\ell}_{drt};\mathrm{I}^i_{*t};\mathrm{B}^i_{rt};\mathrm{D}^i_{*t}; \\ *\in\{p,d,r\};i\in\mathcal{I},\ p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R}, \\ \ell'\in\mathcal{L}',\ \ell\in\mathcal{L},\ c\in\mathcal{C},\ k'\in\mathcal{K}',\ k\in\mathcal{K},\ t\in\mathcal{T} \end{array}\right\} \tag{2.39}$$

$$
\Omega = \left\{ \mathbf{x} \;\middle|\; \begin{array}{c}
\sum_{\forall i \in \mathcal{I}} \beta^i_{pt} = 1 \\
o^i_{pt} \le \alpha^i_{pt} \le \beta^i_{pt} \\
\gamma^i_{pt} \ge \beta^i_{pt} - \beta^i_{p,t-1} \\
\sum_{\forall i \in \mathcal{I}} \sum_{\forall t \in \mathcal{T}} o^i_{pt} \le \mathrm{MTO}_p \\
\sum_{\forall i \in \mathcal{I}} \sum_{n=0}^{N} o^i_{p,t-n} \le N \\
\mathrm{TCL}^{k'-1}_{pd} \mathrm{Y}^{k'}_{pdt} \;<\; \mathrm{TQ}^{k'}_{pdt} \;\le\; \mathrm{TCL}^{k'}_{pd} \mathrm{Y}^{k'}_{pdt} \\
\mathrm{TCL}^{k-1}_{dr} \mathrm{Y}^{k}_{drt} \;<\; \mathrm{TQ}^{k}_{drt} \;\le\; \mathrm{TCL}^{k}_{dr} \mathrm{Y}^{k}_{drt} \\
\sum_{\forall k' \in \mathcal{K}'} \mathrm{Y}^{k'}_{pdt} \;\le\; 1 \qquad \sum_{\forall k \in \mathcal{K}} \mathrm{Y}^{k}_{drt} \;\le\; 1 \\
\mathrm{TQ}_{pdt} \;=\; \sum_{\forall k' \in \mathcal{K}'} \mathrm{TQ}^{k'}_{pdt} \;=\; \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}^i_{pdt} \\
\mathrm{TQ}_{drt} \;=\; \sum_{\forall k \in \mathcal{K}} \mathrm{TQ}^{k}_{drt} \;=\; \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}^i_{drt} \\
\sum_{\forall p \in \mathcal{P}} \mathrm{TQ}_{pdt} \;\le\; \mathrm{MITC}_d \qquad \sum_{\forall r \in \mathcal{R}} \mathrm{TQ}_{drt} \;\le\; \mathrm{MOTC}_d \\
\mathrm{SQL}^{i,\ell'-1}_{pd} \mathrm{V}^{i\ell'}_{pdt} \le \mathrm{SQ}^i_{pdt} \;<\; \mathrm{SQL}^{i,\ell'}_{pd} \mathrm{V}^{i\ell'}_{pdt} \quad \forall \ell' \in \{1, 2, \dots, L'-1\} \\
\mathrm{SQL}^{i,\ell-1}_{dr} \mathrm{V}^{i\ell}_{drt} \le \mathrm{SQ}^i_{drt} \;<\; \mathrm{SQL}^{i,\ell}_{dr} \mathrm{V}^{i\ell}_{drt} \quad \forall \ell \in \{1, 2, \dots, L-1\} \\
\mathrm{SQL}^{i,L'-1}_{pd} \mathrm{V}^{iL'}_{pdt} \le \mathrm{SQ}^i_{pdt} \;\le\; \mathrm{SQL}^{i,L'}_{pd} \mathrm{V}^{iL'}_{pdt} \\
\mathrm{SQL}^{i,L-1}_{dr} \mathrm{V}^{iL}_{drt} \le \mathrm{SQ}^i_{drt} \;\le\; \mathrm{SQL}^{i,L}_{dr} \mathrm{V}^{iL}_{drt} \\
\sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}^{i\ell'}_{pdt} = 1 \qquad \sum_{\forall \ell \in \mathcal{L}} \mathrm{V}^{i\ell}_{drt} \;=\; 1 \\
\mathrm{USP}^i_{pdt} = \sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}^{i\ell'}_{pdt} \mathrm{USP}^{i\ell'}_{pd} \\
\mathrm{USP}^i_{drt} = \sum_{\forall \ell \in \mathcal{L}} \mathrm{V}^{i\ell}_{drt} \mathrm{USP}^{i\ell}_{dr} \\
\mathrm{I}^i_{rt} = \mathrm{I}^i_{r,t-1} + \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}^i_{dr,t-\mathrm{TLT}_{dr}} - \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}^i_{rct} \\
\mathrm{I}^i_{dt} = \mathrm{I}^i_{d,t-1} + \sum_{\forall p \in \mathcal{P}} \mathrm{SQ}^i_{pd,t-\mathrm{TLT}_{pd}} - \sum_{\forall r \in \mathcal{R}} \mathrm{SQ}^i_{drt} \\
\mathrm{I}^i_{pt} = \mathrm{I}^i_{p,t-1} + \mathrm{FMQ}^i_p \alpha^i_{p,t-1} + \mathrm{OMQ}^i_p o^i_{p,t-1} - \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}^i_{pdt} \\
\mathrm{B}^i_{rt} = \mathrm{B}^i_{r,t-1} + \sum_{\forall c \in \mathcal{C}} \mathrm{FCD}^i_{rct} - \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}^i_{rct}, \quad \mathrm{B}^i_{rT} = 0 \\
\sum_{\forall i \in \mathcal{I}} \mathrm{I}^i_{*t} \le \mathrm{MIC}_* \\
\mathrm{D}^i_{*t} \ge \mathrm{SIQ}^i_* - \mathrm{I}^i_{*t} \quad \mathrm{I}^i_{*t}, \mathrm{SQ}^i_{*t}, \mathrm{B}^i_{*t}, \mathrm{D}^i_{*t} \;\ge\; 0 \\
* \in \{p, d, r\}; \forall i \in \mathcal{I},\ p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ c \in \mathcal{C},\ k' \in \mathcal{K}',\ k \in \mathcal{K},\ t \in \mathcal{T}
\end{array} \right\} \tag{2.40}
$$

3 模糊多目標最適化

前一章的生產與配送規劃供應鏈模式為一個多目標問題，有三個目標：各成員間的公平收益分配、顧客服務水準以及安全存貨水準。這些目標之間通常存在著彼此「互斥」的關係，如何在這些目標間尋求一個相互妥協的最佳解，便形成了一個多目標最適化問題。而本章的主旨便是探討多目標最適化問題的求解方法。在本章中，3.1節將說明多目標最適化的意義與回顧三十多年來多目標規畫問題常見的傳統求解方法。 3.2節中將以模糊多目標規畫法的討論為主，分別說明其基本原理、解的性質、隸屬度函數的形式與兩階段模糊多目標規畫法求解步驟等； 3.3節則為模糊多目標規畫法的演算實例。

3.1 多目標規畫法之回顧

一般對靜態系統的多目標最適化問題可以表示為

$$\max_{\mathbf{x}\in\boldsymbol{\Omega}}[J_1, ..., J_M] = [f_1(\mathbf{x}), ..., f_M(\mathbf{x})] \tag{3.1}$$

$$\boldsymbol{\Omega} = \left\{ \mathbf{x} \;\middle|\; \begin{array}{rcl} \mathbf{h}(\mathbf{x}) & = & \mathbf{0} \\ \boldsymbol{g}(\mathbf{x}) & \le & \mathbf{0} \\ \mathbf{x}^L \le & \mathbf{x} & \le \mathbf{x}^U \end{array} \right\} \tag{3.2}$$

在上述多目標函數的最適化問題中，各目標 $J_1,...,J_M$ 的極大值通常存在著彼此互斥的關係而無法重疊在一起，也就是通常不能同時達到最適解。這就需要在各個目標的最佳解之間進行妥協，分別作出適當讓步，以便取得滿意的整體方案。這也是單目標與多目標最適化最主要的不同，前者有單一最適解，而後者則通常沒有單一最適解。多目標最適解亦稱為 Pareto 最適解，定義如下：

⟨**定義 3.1**⟩ 若有一組解 $\mathbf{x}^* \in \mathbf{\Omega}$ 稱為式 *(3.1)* 之 *Pareto* 解，若且唯若不存在另一解 $\tilde{\mathbf{x}}$, 使得

$$\begin{array}{ll} J_m(\tilde{\mathbf{x}}) & \geq J_m(\mathbf{x}^*), \quad \forall\, m \in \{1,2,\ldots,M\} \\ J_j(\tilde{\mathbf{x}}) & > J_j(\mathbf{x}^*), \quad j \in \{1,2,\ldots,M\} \end{array}$$

舉例來說，考慮如圖 3.1 之兩個目標的最適化情形。在可行解區間內，兩個目標的最適解並不能重疊。根據定義3.1，於兩個目標最適解所涵蓋的區間皆屬於此最適化問題的 Pareto 解。因 Pareto 解將有無限多個，所有的 Pareto 解所構成的解空間稱為 Pareto 解集合。

由於非線性問題最適化只能保證得到局部解，故另行定義局部 Pareto 解如下：

⟨**定義 3.2**⟩ 若有一組最適解 $\mathbf{x}^* \in \mathbf{\Omega}$ 稱為式 *(3.1)* 之局部 *Pareto* 解，則若且唯若不存在一實數 $\delta > 0$ 使得 $\tilde{\mathbf{x}}$ 在 $\mathbf{\Omega} \cap N(\mathbf{x}^*, \delta)$ 中為 *Pareto* 解，其中 $N(\tilde{\mathbf{x}}, \delta\}$ 表示 $\tilde{\mathbf{x}}$ 之鄰近 δ 範圍內之解集合，定義為 $\{\tilde{\mathbf{x}} \in \mathbf{\Omega} \mid ||\tilde{\mathbf{x}} - \mathbf{x}^*|| < \delta\}$

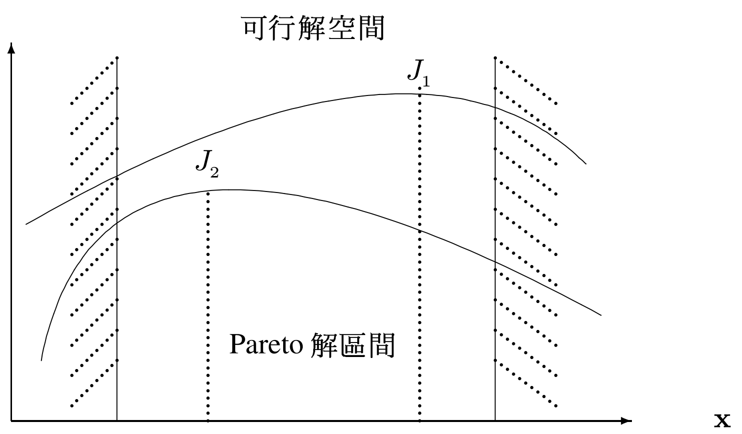
由於多目標最適化的解在數學上不具有互相比較的特性，而需要決策者的認定，由此可見求解多目標最適化問題將會比單目標最適化問題有較多的考量，求解時的難度也較高，而多目標最適化的方法雖然不少，但某些方法對特定問題的求解效果並不理想，下面將介紹幾種常見的多目標最適化問題的求解方法。

權重法 (Weighting method)

此由 Zadeh(1963) 所提出，為最早發展出來的多目標規畫法之一，也是最基本的一種分析法，此方法為將各目標函數乘上一個權重因子，並將加權後的各目標相加，使多目標問題轉化成單目標規畫問題。

$$\max \sum_{m=1}^{M} w_m J_m \tag{3.3}$$

圖 **3.1** 兩個目標函數的 Pareto 解集合示意圖



其中 w_m 為第 m 個目標函數 J_m 的加權係數，藉由加權係數的變動，求出 Pareto 解集合，以供決策者選擇。

權重法最大的優點是觀念簡單，故廣為使用，但缺點主要有二，第一是只適用於解集合為凸集合 (convex) 的問題，否則將無法得到某些 Pareto 解。第二是決策者必須探究為數甚多的加權係數，因為直接決定加權係數並不是一件容易的事，尤其轉換後目標函數，不再具備任何的物理意義，當遇上難以相互比較的目標時，不論如何調配加權係數，皆會失去某些最適值。

ϵ- 限制法 (ϵ-constraint method)

此法為限制其他目標之上下限在某特定值而僅最適化某單一目標。藉由限制其他目標在不同目標值以上，而求得一系列的單一目標最適解，以組成 Pareto 解集合。這個觀念最早由 Marglin(1967) 提出，並應用於公共投資問題。

$$\max J_r \tag{3.4}$$

$$\text{s.t.} \quad J_m \geq \epsilon_m \quad m = 1, 2, \ldots, M \text{ 且 } m \neq r$$

其中式3.4的目標函數可任意指定。

其優點是可處理解集合為凸集合 (convex) 或凹集合 (concave) 的問題，但在某一些限制下，可能會無法求得其解，且整體效率不佳。

效用函數法 (utility function method)

這個方法是利用決策者提供的效用函數來代替決策偏好，使得多目標規畫成為單目標規畫的方法，其目標是最大化總效用函數 U 。

$$\max U(J_1, J_2, \ldots, J_M) \tag{3.5}$$

一般而言，整體的效用函數是不容易求得的，所以通常都以各目標效用之總和來表示。

$$U(J_1, J_2, \ldots, J_M) = \sum_{m=1}^{M} U_m(J_m) \tag{3.6}$$

但如此一來就無法將各目標函數間的關係一併考慮。

主要目標法 (lexicographic method)

若考慮各目標的重要程度不同，在最適化過程中顯然應先考慮主要目標，再同時兼顧次要目標，主要目標法即是以此為精神的處理方式。首先分別求出在不考慮其他目標存在的情形下，各目標函數之最適值，再由決策者依其偏好將各個目標函數按其重要性排列，將最重要的目標取出，然後依次求出各單目標函數的限制最適值，這時將其他目標函數根據之前最佳結果的考慮給予適當的最適值估計值，作為輔助限制條件的處理。

目標規畫法 (Goal programming method)

這個方法由 Charnes 和 Cooper(1961) 提出，是多目標規畫法中應用最廣的方法。原是用來求解多目標線性規畫問題，隨後被各方廣泛使用。其基本觀念是針對每個目標建立一目標值，尋求一滿意解使得每個目標與目標值偏差總和為最小。也就是設定目標值 $\hat{J}_m$，並將目標函數 J_m 加上一個大於零的負偏差變數 d_m^- 及減去一個大於零的正偏差變數 d_m^+，使得 $J_m + d_m^- - d_m^+ = \hat{J}_m$。根據目標函數的形式，，共有三種標準形式，如表 3.1 所示。

表 **3.1** 目標規畫之三種標準形式

目標函數	目標規畫形式	偏差變數
$J_m \geq \hat{J}_m$	$J_m + d_m^- - d_m^+ = \hat{J}_m$	d_m^+
$J_m \leq \hat{J}_m$	$J_m + d_m^- - d_m^+ = \hat{J}_m$	d_m^-
$J_m = \hat{J}_m$	$J_m + d_m^- - d_m^+ = \hat{J}_m$	$d_m^- + d_m^+$

妥協規畫法 (compromised programming)

妥協規畫法是由 Yu 與 Leitmann(1973,1974) 提出的妥協決策觀念而成，其精神是決策者會選擇距離理想解最近的點作為妥協的根據。也就是說決策者面對所有的目標不能同時達到最適值的限制下，會傾向於對每個目標都降低要求，直到成為可行的方案為止，而關鍵是距離理想最近的定義為何？一種廣被接受的數學式可寫成

$$\min \sum_{m=1}^{M} \{\frac{J_m^* - J_m}{J_m^*}\}^p, \quad p = 1, 2, ... \tag{3.7}$$

或

$$\min \left[\sum_{m=1}^{M} \{\frac{J_m^* - J_m}{J_m^*}\}^p\right]^{1/p}, \quad p = 1, 2, ... \tag{3.8}$$

其中 J_m^* 為目標 m 之理想解 (ideal solution)。若考慮不同目標的重要性，則可類似權重法，在每個目標前加入加權係數

$$\min \sum_{m=1}^{M} \{w_m \frac{J_m^* - J_m}{J_m^*}\}^p, \quad p = 1, 2, ... \tag{3.9}$$

其中 w_m 為第 m 個目標函數 (J_m) 的加權係數若 $M = 2$ 且 $p = 1$，則距離為街矩的距離而非直線，$p = 2$ 則為直線距離，$p = \infty$ 也就是 $\max - \min$ 原則。故除了 w_m 代表了決策者的偏好外，p 的決定其實也是一種偏好的設定。

妥協規畫法與目標規畫法有許多相似之處，如決策解必須盡量接近理想點或目標值，不過也有不同之處。目標規畫法的理想點是由決策者依其喜好所提供，而由模式來決定距離的衡量方式；妥協規畫法的理想點則是由模式得到，而決策者提供的只是對距離的衡量方式。此外，兩者對距離的衡量方式亦有所不同，目標規畫採用線性加權方式，而妥協規畫則非。在下一節，將討論的模糊多目標規畫法中的聚集 (aggregation) 運算子其實也是一種距離的衡量。以此觀之，這三種解法實有異曲同工之處。

3.2 模糊多目標規畫法

雖然決策者通常能從眾多的 Pareto 解中選出滿意的解，但是要找出所有的 Pareto 解卻相當費時。若使用其他方式試圖直接得到滿意解，例如目標規畫法、妥協規畫法等等，在種種不確定的因素下，例如目標的重要性往往很難明確的以數值表達，加權因子等決策參數的不易選擇等等，往往使得決策者無法非常明確地決定最適化過程所選用的參數。

自從 1965 年 Zadeh[59]提出模糊集合理論後，將以往決策者只能用「滿意」與「不滿意」描述系統的方式變成可以使用「很不滿意」、「還算滿意」、「滿意」、「非常滿意」等等的口語化敘述來進行描述。這樣的方式相當適合描述決策時的不確定特質。不久之後 Zadeh 與 Bellman[3]更協力將模糊集合理論拓展至決策的用途，此亦為模糊集合理論最早的應用。 Tanaka(1974)[54]首先提出模糊數學規畫的架構。而第一位應用模糊決策法於多目標規畫問題的人則是 Zimmermann(1978)[61] ，他將模糊多目標規畫應用於解多目標線性規畫的問題。 Slowinski(1986)[51]也應用模糊多目標線性規畫處理供水系統的最適化問題。在線性動態系統的最適化方面， Sakawa(1996)[48] 將問題轉換為傳統線性規畫問題，並使用 Simplex 法求解。而非線性系統方面， Chiampi(1996)[12] 利用非線性規畫配合模糊多目標決策解電磁學的設計問題。

一般來說，在下列兩種情況下，使用模糊多目標決策明顯優於傳統的多目標決策：

1. 決策者所擁有的資訊通常不夠完整，以致於不易將問題描述清楚，而使用模糊多目標決策不論決策者所掌握的資訊多寡，皆能得到解；
2. 對於較困難的問題（例如動態最適化或大規模的系統），一些傳統規畫法須耗用的計算成本遠高於模糊規畫法。

3.2.1 模糊多目標規畫的性質

模糊多目標規畫法的特徵，就是決策者以模糊目標 $\mathcal{J}_m$ 與一個可接受的範圍 $[J_m^0, J_m^1]$，來描述每個目標函數 J_m。當目標值大於 J_m^1 時，決策者會非常滿意；而當目標值小於 J_m^0 時，則無法接受。再以一個隸屬度函數 $\mu_{\mathcal{J}_m}(J_m(\mathbf{x})) \in [0,1]$ 描述如何將目標值 $J_m(\mathbf{x})$ 轉

換成對模糊目標 $\mathcal{J}_m$ 的滿意度，成為新的多目標最適化問題。

$$\max_{\mathbf{x}\in\mathbf{\Omega}} [\mu_{\mathcal{J}_1}(J_1(\mathbf{x})), ..., \mu_{\mathcal{J}_M}(J_M(\mathbf{x}))] \tag{3.10}$$

雖然有許多可選擇的隸屬度函數，但是本研究將採用線性隸屬度函數，因為它已經在很多應用上被證明可得到良好的解 (Liu and Sahinidis, 1997)[35]。原來的多目標最適化問題現在已經變成尋找一組決策變數 $\mathbf{x}$ 使得所有模糊目標的模糊交集 $\mathcal{J}_1 \cap \ldots \cap \mathcal{J}_M$ 能有最大的滿意度。模糊決策集合 $\mathcal{FD}$ 可以用來表示所有模糊目標的模糊交集。

$$\mathcal{FD} = \mathcal{J}_1 \cap \mathcal{J}_2 \cap \ \cdots \ \cap \mathcal{J}_M \tag{3.11}$$

Bellman 與 Zadeh[3]認為可利用模糊交集運算子 t-norm 來聚集所有模糊目標的滿意度 $\mu_{\mathcal{J}_m}(J_m(\mathbf{x}))$，以求出整體的滿意度 $\mu_{\mathcal{FD}}(\mathbf{x})$。

$$\mu_{\mathcal{FD}} = \mathbb{T}(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) \tag{3.12}$$

其中 $\mathbb{T}$ 為任意的 t-norm 運算子。

有最大激發值 (firing level) $\mu_{\mathcal{FD}}(\mathbf{x}^*)$ 的解，即為原多目標最適化問題的最適解。

$$\mu_{\mathcal{FD}}(\mathbf{x}^*) = \max_{\mathbf{x}\in\mathbf{\Omega}} \mu_{\mathcal{FD}}(\mathbf{x}) \tag{3.13}$$

一般兩種最常使用的 t-norm 為 minimum 與 product ，其定義如下

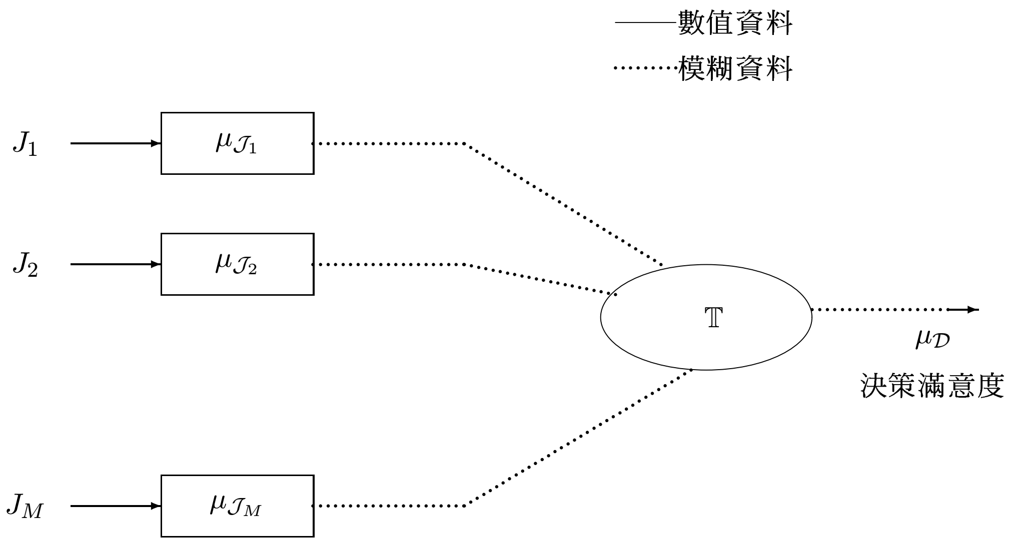
$$\mathbb{T}(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) = \begin{cases} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) & \mathbb{T} = \text{minimum} \\ \mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times \ldots \times \mu_{\mathcal{J}_M} & \mathbb{T} = \text{product} \end{cases}$$

多目標最適化問題經轉換成為單目標最適化問題後，性質上已經與原來不同，為了方便起見， Sakawa [46] 曾仿照 Pareto 解的定義為式 (3.10) 重新定義 M-Pareto(或 Fuzzy-Pareto) 解與*局部 M-Pareto(或局部 Fuzzy-Pareto)* 解如下：

⟨**定義 3.3**⟩ 若有一組解 $\mathbf{x}^* \in \mathbf{\Omega}$ 稱為式 *(3.1)* 之 *M-Pareto* 解，若且唯若不存在另一解 $\tilde{\mathbf{x}}$，使得

$$\begin{array}{lll} \mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) & \geq \mu_{\mathcal{J}_m}(\mathbf{x}^*), & \forall m \in \{1, 2, \ldots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) & > \mu_{\mathcal{J}_j}(\mathbf{x}^*), & j \in \{1, 2, \ldots, M\} \end{array}$$

圖 **3.2** 模糊決策流程圖



〈**定義 3.4**〉 若有一組解 $\mathbf{x}^*(t) \in \mathbf{\Omega}$ 稱為式 *(3.1)* 之局部 *M-Pareto* 解，則若且唯若不存在一實數 $\delta > 0$ 使得 $\tilde{\mathbf{x}}$ 在 $\mathbf{\Omega} \cap N(\mathbf{x}^*, \delta)$ 中為 *M-Pareto* 解，其中 $N(\tilde{\mathbf{x}}, \delta)$ 表示 $\tilde{\mathbf{x}}$ 之鄰近 δ 範圍內之解集合，定義為 $\{\tilde{\mathbf{x}} \in \mathbf{\Omega} \mid ||\tilde{\mathbf{x}} - \mathbf{x}^*|| < \delta\}$

以下兩個性質將說明在任意 t-norm 之決策環境下，得到 M-Pareto 解的條件

〈**性質 3.1**〉 令 $\mathbb{T}$ 為任意 *t-norm*，若 $\mathbf{x}^*$ 為式 *(3.13)* 之唯一最適解，則 $\mathbf{x}^*$ 為 *M-Pareto* 解。

證明：

若 $\mathbf{x}^*$ 為式 (3.13) 之最適解但非 M-Pareto 解，則必定存在一 $\tilde{\mathbf{x}}$，使得

$$\begin{array}{lll} \mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) & \geq \mu_{\mathcal{J}_m}(\mathbf{x}^*), & \forall\, m \in \{1, 2, \ldots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) & > \mu_{\mathcal{J}_j}(\mathbf{x}^*), & j \in \{1, 2, \ldots, M\} \end{array}$$

所以 $\mu_{\mathcal{FD}}(\tilde{\mathbf{x}}) \geq \mu_{\mathcal{FD}}(\mathbf{x}^*)$。

但此敘述與 $\mathbf{x}^*$ 必須是唯一解相矛盾，即 $\tilde{\mathbf{x}}$ 不存在，故 $\mathbf{x}^*$ 必定為 M-Pareto 解

。

〈**性質 3.2**〉 令 $\mathbb{T}$ 為嚴格單調 *t-norm*[*]，若 $\mathbf{x}^*$ 為式 *(3.13)* 之最適解，且 $\mu_{\mathcal{J}_m}(\mathbf{x}^*) \neq 0\, \forall m$，則 $\mathbf{x}^*$ 為 *M-Pareto* 解。

證明：

若 $\mathbf{x}^*$ 為式 (3.13) 之最適解但非 M-Pareto 解，則必定存在一 $\tilde{\mathbf{x}}$，使得

$$\begin{aligned} \mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) &\geq \mu_{\mathcal{J}_m}(\mathbf{x}^*), \quad \forall\, m \in \{1, 2, \ldots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) &> \mu_{\mathcal{J}_j}(\mathbf{x}^*), \quad j \in \{1, 2, \ldots, M\} \end{aligned}$$

又 $\mathbb{T}$ 為嚴格單調 t-norm，所以 $\mu_{\mathcal{FD}}(\tilde{\mathbf{x}}) > \mu_{\mathcal{FD}}(\mathbf{x}^*)$。

但此敘述與 $\mathbf{x}^*$ 必須為式 (3.13) 之最適解相矛盾，即 $\tilde{\mathbf{x}}$ 不存在，故 $\mathbf{x}^*$ 必定為 M-Pareto 解。

min 運算子由於不具備嚴格單調特性，由性質3.2可知除非能證明其解屬於唯一解，否則並不能保證其解為局部 M-Pareto 解； 相對的， product 運算子則具備嚴格單調的性質，一旦得解我們將可保證其為局部 M-Pareto 解。 然而，我們對多目標最適化求解之目的為求得 Pareto 解而非 M-Pareto 解，畢竟 Pareto 解集合只是 M-Pareo 解集合的子集而已，由以下性質，我們可以再對隸屬度函數作規範，如此 M-Pareto 解即為 Pareto 解。

〈**性質 3.3**〉 若 $\mathbf{x}^*$ 為式 *(3.1)* 中符合 $\mu_{\mathcal{J}_m}(\mathbf{x}^*) \in (0,1)\ \forall m$ 之 *M-Pareto* 解，且所有之 $\mu_{\mathcal{J}_m}$ 皆為嚴格遞增函數，則 $\mathbf{x}^*$ 為 *Pareto* 解。

證明：

若 $\mu_{\mathcal{J}_m}$ 皆為嚴格遞增函數，且 $\mathbf{x}^*$ 不為 Pareto 解，則必定存在一 $\tilde{\mathbf{x}}$, 使得

$$\begin{aligned} J_m(\tilde{\mathbf{x}}) &\geq J_m(\mathbf{x}^*), \quad \forall\, m \in \{1, 2, \ldots, M\} \\ J_j(\tilde{\mathbf{x}}) &> J_j(\mathbf{x}^*), \quad j \in \{1, 2, \ldots, M\} \end{aligned}$$

即

$$\begin{aligned} \mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) &\geq \mu_{\mathcal{J}_m}(\mathbf{x}^*), \quad \forall\, m \in \{1, 2, \ldots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) &> \mu_{\mathcal{J}_j}(\mathbf{x}^*), \quad j \in \{1, 2, \ldots, M\} \end{aligned}$$

[*] 嚴格單調 t-norm : *if* $a_1 < a_2$ *and* $b_1 < b_2 \rightarrow \mathbb{T}(a_1, b_1) < \mathbb{T}(a_2, b_2)$

但上面述與 $\mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) < \mu_{\mathcal{J}_m}(\mathbf{x}^*)\ \forall m$ 不合，故得證。

如性質3.2中所述，若採用 min 這種運算子，由於其不具備嚴格單調特性，可能有非唯一局部最適解存在。故對於此解必須再加以確認其唯一性，使得 min 運算子所得到的解為 M-Pareto 解。針對這個問題 Lee 與 Li(1993)[33]提出一個兩階段法 (Two Phase Method) 來求得 M-Pareto 解。

- 階段一 (Phase 1)

  採用 min 運算子計算出 $\mu_{\min}$。所求得的解，如性質3.2所述，由於 min 不具備嚴格單調特性，可能有非唯一局部最適解存在，故無法確認其解為 M-Pareto 解。

$$\begin{aligned}\max_{\mathbf{x}\in\mathbf{\Omega}} \mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\mathbf{\Omega}} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) \\ &= \mu_{\min}\end{aligned} \tag{3.14}$$

- 階段二 (Phase 2)

  將階段一所求得的 $\mu_{\min}$，作為各個隸屬度函數 $\mu_{\mathcal{J}_m}$ 的下限。再最大化所有隸屬度函數的算數平均數 $\sum_{m=1}^{M} \mu_{\mathcal{J}_m}/M$，如式 (3.15) 所示。由於算數平均數運算子具備嚴格單調特性，所以求得的解必為 M-Pareto 解。

$$\max_{\mathbf{x}\in\mathbf{\Omega}^+} \mu_{\mathcal{FD}} = \max_{\mathbf{x}\in\mathbf{\Omega}^+} \frac{1}{M}\sum_{m=1}^{M} \mu_{\mathcal{J}_m} \tag{3.15}$$

$$\mathbf{\Omega}^+ = \mathbf{\Omega} \cap \{\mu_{\mathcal{J}_m} \geq \mu_{\min} | \forall m\} \tag{3.16}$$

〈**性質 3.4**〉 若 $\mathbf{x}^*$ 為兩階段法之最適解，則 $\mathbf{x}^*$ 為 *M-Pareto* 解。

證明：

假設 $\mathbf{x}^*$ 為兩階段法之最適解但非 M-Pareto 解，則必定存在一 $\tilde{\mathbf{x}}$，使得

$$\begin{aligned}\mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) &\geq \mu_{\mathcal{J}_m}(\mathbf{x}^*) &\geq \mu_{\min}, &\quad \forall\, m \in \{1, 2, \ldots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) &> \mu_{\mathcal{J}_j}(\mathbf{x}^*) &\geq \mu_{\min}, &\quad j \in \{1, 2, \ldots, M\}\end{aligned}$$

故

$$\frac{1}{M}\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) > \frac{1}{M}\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\mathbf{x}^*)$$

此與 $\mathbf{x}^*$ 為兩階段法最適解之假設相矛盾，即 $\tilde{\mathbf{x}}$ 不存在，故 $\mathbf{x}^*$ 必為 M-Pareto 解。

Sakawa與Yano(1985)[47]則建議使用如式 (3.17) 的「擴展型 $\max-\min$」以取代 $\max-\min$，且證明了藉由解擴展型 $\max-\min$ 亦可得到 M-Pareto 解。

$$\mu_{\mathcal{FD}} = \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \dots, \mu_{\mathcal{J}_M}) + \rho\sum_{m=1}^{M}\mu_{\mathcal{J}_m} \tag{3.17}$$

其中 ρ 為懲罰因子， Sakawa 建議值為 10^{-3} 至 10^{-5} 之間。

⟨**性質 3.5**⟩ 若 $\mathbf{x}^*$ 為擴展型 $\max-\min$ 問題之最適解，則 $\mathbf{x}^*$ 為 *M-Pareto* 解。

證明：

假設 $\mathbf{x}^*$ 為擴展型 $\max-\min$ 問題之最適解但非 M-Pareto 解，則必定存在一 $\tilde{\mathbf{x}}$，使得

$$\begin{array}{ll} \mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) & \geq \mu_{\mathcal{J}_m}(\mathbf{x}^*), \quad \forall\, m \in \{1, 2, \dots, M\} \\ \mu_{\mathcal{J}_j}(\tilde{\mathbf{x}}) & > \mu_{\mathcal{J}_j}(\mathbf{x}^*), \quad j \in \{1, 2, \dots, M\} \end{array}$$

故

$$\min\{\mu_{\mathcal{J}_1}(\tilde{\mathbf{x}}), \mu_{\mathcal{J}_2}(\tilde{\mathbf{x}}), \dots, \mu_{\mathcal{J}_M}(\tilde{\mathbf{x}})\} \geq \min\{\mu_{\mathcal{J}_1}(\mathbf{x}^*), \mu_{\mathcal{J}_2}(\mathbf{x}^*), \dots, \mu_{\mathcal{J}_M}(\mathbf{x}^*)\}$$

且

$$\rho\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) > \rho\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\mathbf{x}^*)$$

即

$$\begin{aligned} & \min\left\{\mu_{\mathcal{J}_1}(\tilde{\mathbf{x}}), \mu_{\mathcal{J}_2}(\tilde{\mathbf{x}}), \dots, \mu_{\mathcal{J}_M}(\tilde{\mathbf{x}})\right\} + \rho\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\tilde{\mathbf{x}}) \\ > \ & \min\{\mu_{\mathcal{J}_1}(\mathbf{x}^*), \mu_{\mathcal{J}_2}(\mathbf{x}^*), \dots, \mu_{\mathcal{J}_M}(\mathbf{x}^*)\} + \rho\sum_{m=1}^{M}\mu_{\mathcal{J}_m}(\mathbf{x}^*) \end{aligned}$$

此與 $\mathbf{x}^*$ 為擴展型 $\max - \min$ 問題最適解之假設相矛盾，即 $\tilde{\mathbf{x}}$ 不存在，故 $\mathbf{x}^*$ 必為 M-Pareto 解。

此外，類似於擴展型 $\max - \min$ 的概念， Werners(1988)[58]提出一個具補償性的模糊運算子 (Compensatory fuzzy operator) ，如式 (3.18) 所示，亦可得到 M-Pareto 解，其性質與證明類似擴展型 $\max - \min$ ，故在此略過。

$$\mu_{\mathcal{FD}} = (1-\gamma)\min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \dots, \mu_{\mathcal{J}_M}) + \gamma \frac{1}{M} \sum_{m=1}^{M} \mu_{\mathcal{J}_m} \tag{3.18}$$

其中 γ 為補償度，其值介於 0 至 1 之間。

由以上的討論可以發現，為了解決使用 min 運算子求解時，無法保證所得之解為唯一局部最適解的問題，許多學者提出的修正方法中最大的共同點就是將隸屬度函數值的算數平均數加入目標函數中。這些方法有幾個值得注意的地方：

➤ Sakawa 與 Yano 所提出的擴展型 $\max - \min$ 方法，其中甚小的懲罰因子 ($\rho = 10^{-3} \sim 10^{-5}$) 可視為 Werners 所提出的具補償性模糊運算子方法中補償度 γ 極小的一個特例。這兩個方法在選擇補償度或是懲罰因子的值時相當倚賴決策者的決定，因此必須先瞭解決策者的喜好。

➤ Lee 與 Li 提出的兩階段法，則是以 min 運算子計算出的隸屬度函數值為基礎，再最大化整體隸屬度函數值的算數平均數。雖然需要多計算一次，但是仍然保有模糊多目標規劃法不必事先瞭解決策者喜好的優點。

上述的方法都與隸屬度函數值的算數平均數有關，而算數平均數的特點就是具有嚴格單調的性質但是容易造成隸屬度函數值分佈不均。 t-norm 運算子 product 亦有類似的特點。但是相較於最大化隸屬度函數的算數平均數，在最大化隸屬度函數的 product 時，其對個別的隸屬度函數變化更敏感，所以在提升個別的隸屬度函數方面，有比較好的效果。因此 Chen 等人 (2003)[10]提出一個結合最常用的兩種 t-norm， min 與 product 的修正型兩階段法：

➤ 階段一

同樣採取以 min 運算子求解的方式來計算出的階段二中隸屬度函數的下限，如式

(3.19) 所示。此階段主要的目的是最大化滿意度最低的目標。

$$\begin{aligned}\max_{\mathbf{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\boldsymbol{\Omega}} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) \\ &= \mu_{\min}\end{aligned} \tag{3.19}$$

➤ 階段二

在加入隸屬度函數下限的限制下，如式 (3.20) ，最大化隸屬度函數的 product，如式 (3.20) 。因 product 具有嚴格單調的性質，所以我們可以確認所得到的解為 M-Pareto 解[†]。此階段主要的目的是在有最小滿意度的保證下，盡量提升個別隸屬度函數的值。

$$\max_{\mathbf{x}\in\boldsymbol{\Omega}^+} \mu_{\mathcal{FD}} = \max_{\mathbf{x}\in\boldsymbol{\Omega}^+} (\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times \ldots \times \mu_{\mathcal{J}_M}) \tag{3.20}$$

$$\boldsymbol{\Omega}^+ = \boldsymbol{\Omega} \cap \{\mu_{\mathcal{J}_m} \geq \mu_{\min} | \forall m\} \tag{3.21}$$

3.2.2 兩階段模糊多目標規畫法

min 運算子，雖可獲得分佈較為平均的隸屬度函數值，但是由於 min 運算子不具嚴格單調的特性，只關注滿意度最低的目標，所以會有非唯一局部最適解的情形發生。而 product 運算子雖具有嚴格單調的性質，可保證得到 M-Pareto 解，但其追求整體隸屬度函數乘積最大的特性，卻容易造成隸屬度函數值分佈不均。所以 Chen 等人 (2003)[10]結合這兩個運算子，提出一個兩階段模糊多目標規畫法，步驟如下。

步驟 1: 分別對單一目標求取最樂觀的解 $\overline{J_m^1}$ 與最悲觀的解 $\underline{J_m^0}$

$$\begin{aligned}\max_{\mathbf{x}\in\boldsymbol{\Omega}} J_m &= \overline{J_m^1} \\ \min_{\mathbf{x}\in\boldsymbol{\Omega}} J_m &= \underline{J_m^0}\end{aligned}$$

$\overline{J_m^1}$ 與 $\underline{J_m^0}$ 即為目標函數 J_m 之的上、下限。再依據 $\underline{J_m^0} \leq J_m^0 < J_m^1 \leq \overline{J_m^1}$ 的限制來主觀地決定目標函數的可接受範圍 $[J_m^0, J_m^1]$。

[†]其證明類似兩階段法，故略

表 **3.2** 理想解償付表

	$J_1(x_i^*)$	$J_2(x_i^*)$	$\dots$	$J_M(x_i^*)$
$J_i(x_1^*)$	$\overline{J_1^1}(x_1^*)$	$J_2(x_1^*)$	$\dots$	$J_M(x_1^*)$
$J_i(x_2^*)$	$J_2(x_2^*)$	$\overline{J_2^1}(x_2^*)$	$\dots$	$J_M(x_2^*)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$J_i(x_M^*)$	$J_M(x_M^*)$	$J_2(x_M^*)$	$\dots$	$\overline{J_M^1}(x_M^*)$

一般而言，可選擇 $J_m^0 = \underline{J_m^0}$ 和 $J_m^1 = \underline{J_m^1}$ 。或者可由每個單一目標最樂觀的解，建構理想解償付表 (Pay-Off Table of Ideal Solution) ，如表 3.2 所示。再主觀地挑選適當的值作為可接受範圍 $[J_m^0, J_m^1]$。

步驟 2: 訂定各模糊目標的隸屬函數

$$\mu_{\mathcal{J}_m}(J_m(\mathbf{x})) = \begin{cases} 1; & \text{for} \quad J_m(\mathbf{x}) \geq J_m^1 \\ \frac{J_m(\mathbf{x}) - J_m^0}{J_m^1 - J_m^0}; & \text{for} \quad J_m^0 \leq J_m(\mathbf{x}) \leq J_m^1 \\ 0; & \text{for} \quad J_m^0 \geq J_m(\mathbf{x}) \end{cases} \qquad \forall m \in \mathcal{M} \tag{3.22}$$

步驟 3: （階段一）以 min 運算子最大化滿意度最低的目標。

$$\begin{aligned} \max_{\mathbf{x}\in\mathbf{\Omega}} \mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\mathbf{\Omega}} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \dots, \mu_{\mathcal{J}_M}) \\ &= \mu_{\min} \end{aligned} \tag{3.23}$$

步驟 4: （階段二）在具備最低滿意度的保證下，以 product 運算子盡量提升個別隸屬度函數的值。

$$\max_{\mathbf{x}\in\mathbf{\Omega}^+} \mu_{\mathcal{FD}} = \max_{\mathbf{x}\in\mathbf{\Omega}^+} (\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times \dots \times \mu_{\mathcal{J}_M}) \tag{3.24}$$

$$\mathbf{\Omega}^+ = \mathbf{\Omega} \cap \{\mu_{\mathcal{J}_m} \geq \mu_{\min} | \forall m\} \tag{3.25}$$

3.3 演算實例

本節將以兩個簡單的例子實際說明模糊多目標規劃法的運算過程。

3.3.1節: 多目標線性規劃 (Multi-objective linear programming)

3.3.2節: 多目標線性混合整數規劃 (Multi-objective mix-integer linear programming)

3.3.1 例一. 多目標線性規劃問題

考慮如下多目標線性規劃問題：

$$\begin{array}{llcrcrcrcr} \max\limits_{\mathbf{x}\in\boldsymbol{\Omega}} & J_1 & = & 2x_1 & + & 5x_2 & + & 7x_3 & + & 1x_4 \\ & J_2 & = & 4x_1 & + & 1x_2 & + & 3x_3 & + & 11x_4 \\ & J_3 & = & 9x_1 & + & 3x_2 & + & 1x_3 & + & 2x_4 \\ \min\limits_{\mathbf{x}\in\boldsymbol{\Omega}} & J_4 & = & 1.5x_1 & + & 2x_2 & + & 0.3x_3 & + & 3x_4 \\ & J_5 & = & 0.5x_1 & + & 1x_2 & + & 0.7x_3 & + & 2x_4 \end{array} \tag{3.26}$$

$$\boldsymbol{\Omega} = \left\{ \mathbf{x} \left| \begin{array}{l} h_1 : 3x_1 + 4.5x_2 + 1.5x_3 + 7.5x_4 = 150 \\ x_1 \text{ , } x_2 \text{ , } x_3 \text{ , } x_4 \ \geq 0 \end{array} \right. \right\} \tag{3.27}$$

步驟 1： 分別對 $J_1 \sim J_5$ 求得最樂觀的解與最悲觀的解

J_1^1	J_2^1	J_3^1	J_4^1	J_5^1
700	300	450	30	25

J_1^0	J_2^0	J_3^0	J_4^0	J_5^0
20	33.3	40	75	70

選擇 $J_m^0 = \underline{J_m^0}$ 和 $J_m^1 = \underline{J_m^1}$

步驟 2: 訂定各模糊目標的隸屬函數

$$\mu_{\mathcal{J}_m}(J_m(\mathbf{x})) = \begin{cases} 1; & \text{for} \quad J_m(\mathbf{x}) \geq J_m^1 \\ \frac{J_m(\mathbf{x})-J_m^0}{J_m^1-J_m^0}; & \text{for} \quad J_m^0 \leq J_m(\mathbf{x}) \leq J_m^1 \\ 0; & \text{for} \quad J_m^0 \geq J_m(\mathbf{x}) \end{cases} \qquad \forall m \in \mathcal{M} \tag{3.28}$$

步驟 3: 階段一

$$\begin{aligned} \max_{\mathbf{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\boldsymbol{\Omega}} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \mu_{\mathcal{J}_3}, \mu_{\mathcal{J}_4}, \mu_{\mathcal{J}_5}) \\ &= \mu_{\min} \end{aligned} \tag{3.29}$$

$$\boldsymbol{\Omega} = \left\{ \mathbf{x} \left| \begin{array}{l} \mu_{\mathcal{J}_1} = (J_1 - J_1^0)/(J_1^1 - J_1^0) \\ \vdots \qquad\qquad\qquad \vdots \\ \mu_{\mathcal{J}_5} = (J_5 - J_5^0)/(J_5^1 - J_5^0) \\ h_1 : 3x_1 + 4.5x_2 + 1.5x_3 + 7.5x_4 = 150 \\ x_1 \text{ , } x_2 \text{ , } x_3 \text{ , } x_4 \ \geq 0 \end{array} \right. \right\} \tag{3.30}$$

由於 min 運算子不具備唯一解的特性，我們可以得到多組解，其中：

Solution I

J_1	J_2	J_3	J_4	J_5
395.52	230.52	245	52.5	47.5

$\mu_{\mathcal{J}_1}$	$\mu_{\mathcal{J}_2}$	$\mu_{\mathcal{J}_3}$	$\mu_{\mathcal{J}_4}$	$\mu_{\mathcal{J}_5}$
0.552	0.739	0.5	0.5	0.5

x_1	x_2	x_3	x_4	
20.71	3.51	48.05	0	

其中可以看出 $\mu_{\min} = 0.5$，而 $\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times ... \times \mu_{\mathcal{J}_5} = 0.0510$

Solution II

J_1	J_2	J_3	J_4	J_5
371.36	248.64	245	52.5	47.5

$\mu_{\mathcal{J}_1}$	$\mu_{\mathcal{J}_2}$	$\mu_{\mathcal{J}_3}$	$\mu_{\mathcal{J}_4}$	$\mu_{\mathcal{J}_5}$
0.517	0.807	0.5	0.5	0.5

x_1	x_2	x_3	x_4	
21.59	0	46.59	2.05	

其中可以看出 $\mu_{\min} = 0.5$，而 $\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times ... \times \mu_{\mathcal{J}_5} = 0.0522$

因此，必須再由階段二確認所求得的解為唯一最適解。

步驟 4: 階段二

$$\max_{\mathbf{x}\in\mathbf{\Omega}^+} \mu_{\mathcal{FD}} = \max_{\mathbf{x}\in\mathbf{\Omega}^+} (\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times ... \times \mu_{\mathcal{J}_M}) \tag{3.31}$$

$$\mathbf{\Omega}^+ = \left\{ \mathbf{x} \;\middle|\; \begin{array}{l} \mu_{\mathcal{J}_1} \geq \mu_{\min} \\ \vdots \qquad \vdots \\ \mu_{\mathcal{J}_5} \geq \mu_{\min} \\ \mu_{\mathcal{J}_1} = (J_1 - J_1^-)/(J_1^* - J_1^-) \\ \vdots \qquad\qquad\qquad \vdots \\ \mu_{\mathcal{J}_5} = (J_5 - J_5^-)/(J_5^* - J_5^-) \\ h_1 : 3x_1 + 4.5x_2 + 1.5x_3 + 7.5x_4 = 150 \\ x_1\ ,\ x_2\ ,\ x_3\ ,\ x_4\ \geq 0 \end{array} \right\} \tag{3.32}$$

J_1	J_2	J_3	J_4	J_5
400	250	275	52.5	47.5

$\mu_{\mathcal{J}_1}$	$\mu_{\mathcal{J}_2}$	$\mu_{\mathcal{J}_3}$	$\mu_{\mathcal{J}_4}$	$\mu_{\mathcal{J}_5}$
0.599	0.813	0.573	0.5	0.5

x_1	x_2	x_3	x_4	
25	0	50	0	

其中可以看出每一個隸屬度滿意度 μ 皆大於 $\mu_{\text{min}} = 0.5$，並且由於第二階段最大化product 運算子的補償效果使得 $\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times ... \times \mu_{\mathcal{J}_5} = 0.0651$。而相較於階段一中單獨使用 min 運算子所得之解，階段二中的目標函數 J_1, J_2, J_3 的隸屬度函數 $\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \mu_{\mathcal{J}_3}$ 皆有所提升。

3.3.2 例二. 多目標線性混合整數規劃問題

考慮如下多目標整數線性規劃問題：

$$\begin{aligned} \max_{\mathbf{x}\in\mathbf{\Omega}} J_1 &= 0.4x_1 + 0.3x_2 - 100x_3 + 50x_4 \\ \max_{\mathbf{x}\in\mathbf{\Omega}} J_2 &= 0.3x_1 + 0.5x_2 + 150x_3 - 100x_4 \end{aligned}$$

$$\mathbf{\Omega} = \left\{ \mathbf{x} \;\middle|\; \begin{array}{l} g_1 : 2x_1 + x_2 + 100x_3 - 100x_4 \leq 500 \\ g_2 : x_1 + x_2 - 200x_3 + 50x_4 \leq 400 \\ x_1\ ,\ x_2\ \geq 0 \\ x_3\ ,\ x_4 = 0 \text{ or } 1 \end{array} \right\} \tag{3.33}$$

步驟 1： 分別對 J_1，J_2 求得最樂觀的解與最悲觀的解

J_1^1	J_2^1
180	350

J_1^0	J_2^0
-100	-100

選擇 $J_m^0 = \underline{J_m^0}$ 和 $J_m^1 = \underline{J_m^1}$

步驟 2: 訂定各模糊目標的隸屬函數

$$\mu_{\mathcal{J}_m}(J_m(\mathbf{x})) = \begin{cases} 1; & \text{for} \quad J_m(\mathbf{x}) \geq J_m^1 \\ \frac{J_m(\mathbf{x}) - J_m^0}{J_m^1 - J_m^0}; & \text{for} \quad J_m^0 \leq J_m(\mathbf{x}) \leq J_m^1 \\ 0; & \text{for} \quad J_m^0 \geq J_m(\mathbf{x}) \end{cases} \qquad \forall m \in \mathcal{M} \tag{3.34}$$

步驟 3: 階段一

$$\begin{aligned}\max_{\mathbf{x}\in\mathbf{\Omega}} \mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\mathbf{\Omega}} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}) \\ &= \mu_{\min}\end{aligned} \tag{3.35}$$

$$\mathbf{\Omega} = \left\{ \mathbf{x} \;\middle|\; \begin{array}{l} \mu_{\mathcal{J}_1} = (J_1 - J_1^0)/(J_1^1 - J_1^0) \\ \mu_{\mathcal{J}_2} = (J_2 - J_2^0)/(J_2^1 - J_2^0) \\ g_1 : 2x_1 + x_2 + 100x_3 - 100x_4 \leq 500 \\ g_2 : x_1 + x_2 - 200x_3 + 50x_4 \leq 400 \\ x_1\ ,\ x_2\ \geq 0 \\ x_3\ ,\ x_4 = 0 \text{ or } 1 \end{array} \right\} \tag{3.36}$$

我們可以得到一組解：

J_1	J_2
100	300

$\mu_{\mathcal{J}_1}$	$\mu_{\mathcal{J}_2}$
0.714	0.889

x_1	x_2	x_3	x_4
0	500	1	1

其中可以看出 $\mu_{\min} = 0.714$，而 $\mu_{\mathcal{J}_1}$ 與 $\mu_{\mathcal{J}_2}$ 不相等是因為在目標函數中有 0,1 變數存在以致於目標函數不連續，所以無法使 $\mu_{\mathcal{J}_1}$ 與 $\mu_{\mathcal{J}_2}$ 相等。

步驟 4: 階段二

$$\max_{\mathbf{x}\in\mathbf{\Omega}^+} \mu_{\mathcal{FD}} = \max_{\mathbf{x}\in\mathbf{\Omega}^+} (\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times ... \times \mu_{\mathcal{J}_M}) \tag{3.37}$$

$$\mathbf{\Omega}^+ = \left\{ \mathbf{x} \;\middle|\; \begin{array}{l} \mu_{\mathcal{J}_1} \geq \mu_{\min} \\ \mu_{\mathcal{J}_2} \geq \mu_{\min} \\ \mu_{\mathcal{J}_1} = (J_1 - J_1^-)/(J_1^* - J_1^-) \\ \mu_{\mathcal{J}_2} = (J_2 - J_2^-)/(J_2^* - J_2^-) \\ g_1 : 2x_1 + x_2 + 100x_3 - 100x_4 \leq 500 \\ g_2 : x_1 + x_2 - 200x_3 + 50x_4 \leq 400 \\ x_1\ ,\ x_2\ \geq 0 \\ x_3\ ,\ x_4 = 0 \text{ or } 1 \end{array} \right\} \tag{3.38}$$

J_1	J_2
100	300

$\mu_{\mathcal{J}_1}$	$\mu_{\mathcal{J}_2}$
0.714	0.889

x_1	x_2	x_3	x_4
0	500	1	1

所得的答案與階段一相同，故階段一的解已經為唯一解。

4

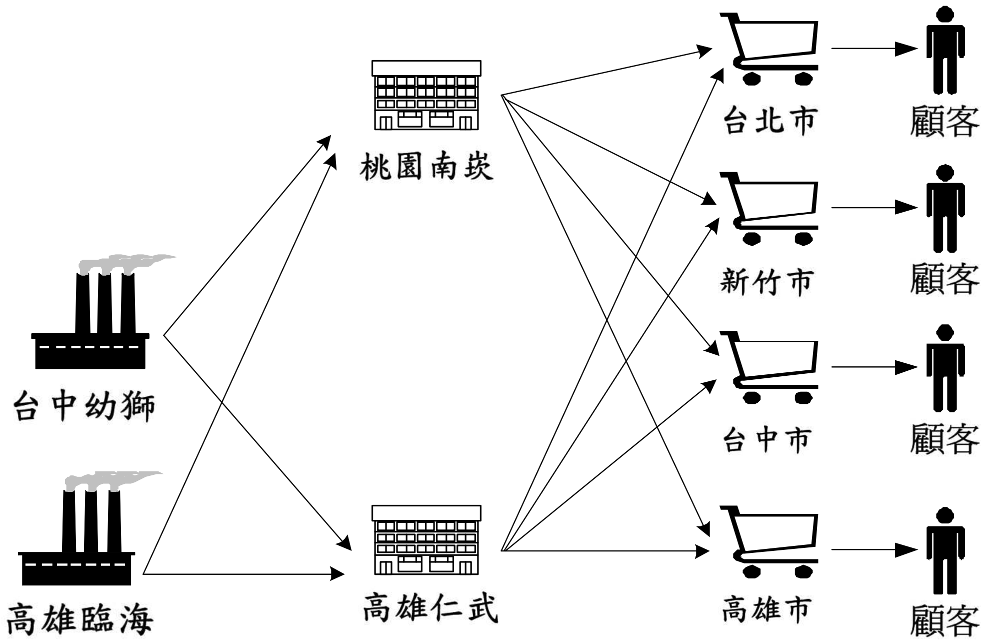
模式情境模擬分析與討論

4.1 模式之情境模擬

4.1.1 模擬例子

由於生產製造資料、各項成本參數等資訊皆為企業的重要資料，外人不易取得，因此要尋找一個實際的例子作模擬，甚為困難。本研究自行設計一個典型的供應鏈網路，其中包含了兩座工廠、兩個配銷中心、四個零售商和三種產品。此供應鏈以台灣為假想地，工廠分別設在台中幼獅工業區 ($p = 1$) 與高雄臨海工業區 ($p = 2$)，並且和桃園南崁 ($d = 1$) 與高雄仁武 ($d = 2$) 的配銷中心合作，由他們將貨物運送到位於台北市 ($r = 1$)、新竹市 ($r = 2$)、台中市 ($r = 3$) 與高雄市 ($r = 3$) 的經銷商。兩座工廠的設備都可以生產每一種產品。為了簡化問題，本研究將各地區的顧客群視為單一顧客。整個生產排程與配送規劃共有 4 週期；每週期的最低顧客服務水準限制為 0.7；可選擇的經濟批量運送方式有三種 ($[\mathcal{K}] = [\mathcal{K}'] = 3$) ；可選擇的經濟批量銷售方式也有三種 ($[\mathcal{L}] = [\mathcal{L}'] = 3$) ；連續加班的期數不能超過兩次 ($N = 2$)。產品的預測需求量如表 4.1 所示，其中零售商 $r = 1$ 所面對的顧客對於第 1 種產品的需求量：第 1 期是 1106 個；第 2 期是 1298 個；第 3 期是 1339 個；第 4 期是 651 個。 表 4.2 列出所有的成本參數，其中包含了三種不同運送方式的單位運送成本與固定運送成本。配送中心 $d = 1$ 運送貨物到零售商 $r = 1$，選擇第 1 種

圖 **4.1** 模擬例子的供應鏈架構示意圖



運送方式，單位運送成本為 6，固定運送成本為 3600；選擇第 2 種運送方式，單位運送成本為 5，固定運送成本為 6000；選擇第 3 種運送方式，單位運送成本為 4，固定運送成本為 7200。產品單位售價如表 4.3 所示，其中包含了三種不同銷售方式的價格，其他參數則列於表 4.4 ，其中配送中心 $d = 1$ 運送貨物到零售商 $r = 3$ 所需的前置時間為 0 週期，也就是當期就能將貨物送到零售商；配送中心 $d = 1$ 運送貨物到零售商 $r = 4$ 所需的前置時間為 1 週期，也就是必須等到下一期才能將貨物送到。

此多目標生產與配送規劃模式包含 2198 個方程式、 1081 個連續變數和 672 個 0-1 變數。

4.1.2 最適化軟體

本研究使用一套著名的高階模式系統軟體， Generalized Algebraic Modeling System (GAMS, Brooke et al., 1988 [5])，來求解最適化問題。由於 GAMS 提供的 MINLP solver 中， DICOPT 比較適合處理 0-1 變數較多的問題，因此，本文選擇它作為主要的 MINLP solver，同時選擇 SNOPT 作為 NLP solver 。

表 **4.1** 產品的預測需求量

	FCD^i_{rct}											
$r =$	1			2			3			4		
$c =$	1											
$i =$	1	2	3	1	2	3	1	2	3	1	2	3
$t =$ 1	1106	518	483	735	462	411	810	400	410	918	906	455
2	1298	507	423	681	685	372	1000	501	305	966	1051	307
3	1339	745	491	811	722	599	773	401	395	1618	1154	536
4	651	866	479	1110	513	512	1086	409	422	902	700	444

4.2 結果與討論

多目標生產與配送規劃模式求解的過程，可整理如下：

步驟 1: 分別對單一目標求取最樂觀的解 $\overline{J^1_m}$ 與最悲觀的解 $\underline{J^0_m}$，並建立理想解償付表，如表 4.5 和表 4.6 所示。然後，選擇目標函數的可接受範圍 $[J^0_m, J^1_m]$，如表 4.7 所示。本研究決定直接以 $\overline{J^1_m}$ 作為所有目標的上限 J^1_m。由於收益的 $\underline{J^0_m}$ 有一些是負值，並不適合作為下限，因此選擇理想解償付表中，最低的正值作為 J^0_m。同時也選擇理想解償付表中的最低值作為，安全存貨水準和顧客服務水準的下限 J^0_m。

步驟 2: （階段一）以 min 運算子最大化滿意度最低的目標， $\mu_{\min} = 0.52$。

步驟 3: （階段二）在具備最低滿意度的保證下，以 product 運算子盡量提升個別隸屬度函數的值。

表 **4.2** 成本參數

單位運送成本 / 固定運送成本

k	p	d	r	UTC^{k}_{dr} \$	FTC^{k}_{dr} \$
1		1	1	6	3600
2		1	1	5	6000
3		1	1	4	7200
1		1	2	10	4800
2		1	2	8	7680
3		1	2	6	8640
1		1	3	15	5400
2		1	3	12	8640
3		1	3	9	9720
1		1	4	26	7800
2		1	4	22	13200
3		1	4	18	16200
1		2	1	28	10080
2		2	1	24	17280
3		2	1	20	21600
1		2	2	21	8400
2		2	2	18	14400
3		2	2	15	18000
1		2	3	18	7920
2		2	3	15	13200
3		2	3	12	15840
1		2	4	7	4480
2		2	4	6	7680
3		2	4	5	9600

k'	p	d	$\mathrm{UTC}^{k'}_{pd}$ \$	$\mathrm{FTC}^{k'}_{pd}$ \$
1	1	1	15	6600
2	1	1	12	10560
3	1	1	9	11880
1	1	2	18	7200
2	1	2	15	12000
3	1	2	12	14400
1	2	1	26	11700
2	2	1	22	19800
3	2	1	18	24300
1	2	2	5	4000
2	2	2	4	6400
3	2	2	3	7200

單位存貨成本 / 單位處理成本

i	r	UIC^{i}_{r} \$	UHC^{i}_{r} \$
1	1	14	8
1	2	11	5
1	3	12	6
1	4	13	7
2	1	24	12
2	2	18	9
2	3	20	10
2	4	22	11
3	1	36	18
3	2	30	15
3	3	32	16
3	4	34	17

i	d	UIC^{i}_{d} \$	UHC^{i}_{d} \$
1	1	10	6
1	2	9	5
2	1	17	9
2	2	15	8
3	1	26	14
3	2	24	13

i	p	UIC^{i}_{p} \$	UHC^{i}_{p} \$
1	1	6	3
1	2	5	2
2	1	10	5
2	2	9	4
3	1	16	10
3	2	14	9

單位製造成本 / 固定換線 / 閒置成本

i	p	UMC^{i}_{p} \$	FMC^{i}_{p} \$	OMC^{i}_{p} \$	FIC^{i}_{p} \$
1	1	30	180000	45	18000
1	2	26	208000	39	20800
2	1	50	200000	75	20000
2	2	42	210000	63	21000
3	1	70	175000	98	17500
3	2	80	240000	112	24000

表 **4.3** 產品單位售價

	i p d r ℓ	\$		i p d r ℓ	\$		i p d r ℓ'	\$		i p d r c	\$
	1 1 1 1	267		2 2 1 1	473		1 1 1 1	211		1 1 1	340
	1 1 1 2	260		2 2 1 2	461		1 1 1 2	203		1 2 1	325
	1 1 1 3	253		2 2 1 3	449		1 1 1 3	194		1 3 1	330
	1 1 2 1	272		2 2 2 1	464		1 1 2 1	215		1 4 1	335
	1 1 2 2	265		2 2 2 2	451		1 1 2 2	207		2 1 1	570
	1 1 2 3	258		2 2 2 3	439		1 1 2 3	200	USP_{rc}^{i}	2 2 1	540
	1 1 3 1	276		2 2 3 1	460		1 2 1 1	211		2 3 1	550
	1 1 3 2	270		2 2 3 2	447		1 2 1 2	202		2 4 1	560
	1 1 3 3	264		2 2 3 3	433		1 2 1 3	192		3 1 1	885
	1 1 4 1	285		2 2 4 1	477		1 2 2 1	207		3 2 1	855
	1 1 4 2	279		2 2 4 2	466		1 2 2 2	197		3 3 1	865
	1 1 4 3	274		2 2 4 3	454		1 2 2 3	186		3 4 1	875
	1 2 1 1	280		3 1 1 1	749		2 1 1 1	364			
	1 2 1 2	272		3 1 1 2	732		2 1 1 2	350			
	1 2 1 3	265		3 1 1 3	715		2 1 1 3	336			
	1 2 2 1	271		3 1 2 1	753		2 1 2 1	375			
	1 2 2 2	263		3 1 2 2	737		2 1 2 2	361			
$USP_{dr}^{i\ell}$	1 2 2 3	254	$USP_{dr}^{i\ell}$	3 1 2 3	720	$USP_{pd}^{i\ell'}$	2 1 2 3	346			
	1 2 3 1	267		3 1 3 1	757		2 2 1 1	369			
	1 2 3 2	258		3 1 3 2	741		2 2 1 2	352			
	1 2 3 3	249		3 1 3 3	725		2 2 1 3	335			
	1 2 4 1	284		3 1 4 1	765		2 2 2 1	360			
	1 2 4 2	277		3 1 4 2	751		2 2 2 2	342			
	1 2 4 3	270		3 1 4 3	736		2 2 2 3	325			
	2 1 1 1	461		3 2 1 1	757		3 1 1 1	606			
	2 1 1 2	449		3 2 1 2	740		3 1 1 2	574			
	2 1 1 3	438		3 2 1 3	723		3 1 1 3	542			
	2 1 2 1	465		3 2 2 1	749		3 1 2 1	615			
	2 1 2 2	454		3 2 2 2	731		3 1 2 2	586			
	2 1 2 3	443		3 2 2 3	713		3 1 2 3	557			
	2 1 3 1	470		3 2 3 1	745		3 2 1 1	606			
	2 1 3 2	459		3 2 3 2	726		3 2 1 2	574			
	2 1 3 3	448		3 2 3 3	707		3 2 1 3	542			
	2 1 4 1	478		3 2 4 1	762		3 2 2 1	596			
	2 1 4 2	468		3 2 4 2	745		3 2 2 2	562			
	2 1 4 3	459		3 2 4 3	728		3 2 2 3	528			

表 **4.4** 其他參數

最大銷售量

	i	p	d	ℓ	
$SQL_d^{i\ell}$	1		1	1	600
	1		1	2	1200
	1		1	3	1800
	2		1	1	600
	2		1	2	1200
	2		1	3	1800
	3		1	1	600
	3		1	2	1200
	3		1	3	1800
	1		2	1	800
	1		2	2	1600
	1		2	3	2400
	2		2	1	800
	2		2	2	1600
	2		2	3	2400
	3		2	1	800
	3		2	2	1600
	3		2	3	2400
$SQL_p^{i\ell'}$	1	1		1	800
	1	1		2	1600
	1	1		3	2400
	2	1		1	800
	2	1		2	1600
	2	1		3	2400
	3	1		1	800
	3	1		2	1600
	3	1		3	2400
	1	2		1	1000
	1	2		2	2000
	1	2		3	3000
	2	2		1	1000
	2	2		2	2000
	2	2		3	3000
	3	2		1	1000
	3	2		2	2000
	3	2		3	3000

安全存貨量

	i	p	d	r	
SIQ_r^i	1			1	600
	1			2	450
	1			3	500
	1			4	550
	2			1	350
	2			2	300
	2			3	250
	2			4	400
	3			1	250
	3			2	225
	3			3	175
	3			4	200
SIQ_d^i	1		1		1600
	1		2		1800
	2		1		1200
	2		2		1400
	3		1		800
	3		2		900
SIQ_p^i	2	1			800
	1	1			1200
	1	2			1500
	2	2			1000
	3	1			600
	3	2			800

最大總加班期數

	p	
MTO_p	1	3
	2	3

最大運量

	k	p	d	r	
TCL_{dr}^k	1		1		600
	2		1		1200
	3		1		1800
	1		2		800
	2		2		1600
	3		2		2400
$TCL_{pd}^{k'}$	1	1			800
	2	1			1600
	3	1			2400
	1	2			1000
	2	2			2000
	3	2			3000

運送前置時間

	p	d	r	
TLT_{dr}		1	1	0
		1	2	0
		1	3	0
		1	4	1
		2	1	1
		2	2	1
		2	3	1
		2	4	0
TLT_{pd}	1	1		0
	1	2		1
	2	1		1
	2	2		0

批次製造量

	i	p	
FMQ_p^i	1	1	6000
	1	2	8000
	2	1	4000
	2	2	5000
	3	1	2500
	3	2	3000
OMQ_p^i	1	1	1200
	1	2	1600
	2	1	800
	2	2	1000
	3	1	500
	3	2	600

最大存貨量

	p	d	r	
MIC_r			1	1800
			2	1500
			3	1400
			4	1700
MIC_d		1		6000
		2		7000
MIC_p	1			2000
	2			3000

最大進出貨量

	d	
$MITC_d$	1	5000
	2	7000
$MOTC_d$	1	5000
	2	7000

表 **4.5** 理想解償付表

		$J_m(x^*)$							
		$Z_{p=1}$	$Z_{p=2}$	$Z_{d=1}$	$Z_{d=2}$	$Z_{r=1}$	$Z_{r=2}$	$Z_{r=3}$	$Z_{r=4}$
	$Z_{p=1}$	4,611,859	1,936,800	803,827	−405,805	1,058,620	860,384	754,485	983,195
	$Z_{p=2}$	1,473,326	5,227,369	673,014	525,249	1,182,755	514,859	55,342	940,917
	$Z_{d=1}$	1,621,561	592,141	3,339,963	2,013,973	479,515	−180,097	−114,513	231,431
	$Z_{d=2}$	1,757,580	2,662,021	1,574,273	3,796,692	−105,796	−181,526	−103,504	−387,264
	$Z_{r=1}$	2,291,202	1,945,335	1,494,116	1,890,276	1,275,169	−535,381	−15,891	886,840
	$Z_{r=2}$	1,385,548	499,773	1,742,297	1,846,492	1,200,284	951,075	330,679	543,949
	$Z_{r=3}$	1,208,118	1,681,443	715,671	1,055,400	507,426	858,521	882,529	1,044,036
	$Z_{r=4}$	1,915,605	2,206,688	450,924	1,015,853	922,160	708,391	489,683	1,165,653
	$SIL_{p=1}$	2,496,919	2,162,608	1,405,657	387,090	1,092,530	627,232	511,748	1,076,951
$J(x_m^*)$	$SIL_{p=2}$	935,082	1,664,066	525,110	1,696,667	977,000	819,403	794,030	798,571
	$SIL_{d=1}$	942,752	1,181,656	363,044	1,972,677	1,104,858	825,559	684,191	922,872
	$SIL_{d=2}$	1,492,147	2,202,045	1,701,155	665,230	1,132,351	629,033	772,483	526,118
	$SIL_{r=1}$	1,939,132	2,118,274	844,713	1,811,389	276,450	550,027	540,225	1,055,294
	$SIL_{r=2}$	866,827	2,502,754	1,353,158	2,317,544	636,077	260,365	595,639	1,015,822
	$SIL_{r=3}$	1,283,845	1,756,533	835,454	834,171	1,040,910	745,600	345,702	1,051,313
	$SIL_{r=4}$	1,562,466	2,620,876	1,566,301	1,578,320	1,163,608	853,688	−40,942	455,164
	$CSL_{r=1}$	1,969,925	2,420,132	1,162,189	2,335,341	1,090,717	−85,178	−200,923	608,680
	$CSL_{r=2}$	1,920,973	2,138,831	1,254,425	2,009,819	957,617	243,683	566,218	438,707
	$CSL_{r=3}$	1,708,211	2,402,481	799,331	1,985,398	454,634	836,654	655,559	944,759
	$CSL_{r=4}$	2,401,197	2,199,182	774,977	1,006,927	1,163,909	325,197	762,646	1,047,542

表 **4.6** 理想解償付表

		$J_m(x^*)$											
		$SIL_{p=1}$	$SIL_{p=2}$	$SIL_{d=1}$	$SIL_{d=2}$	$SIL_{r=1}$	$SIL_{r=2}$	$SIL_{r=3}$	$SIL_{r=4}$	$CSL_{r=1}$	$CSL_{r=2}$	$CSL_{r=3}$	$CSL_{r=4}$
	$Z_{p=1}$	0.03	0.00	0.22	0.46	0.19	0.08	0.33	0.23	0.78	0.80	0.82	0.85
	$Z_{p=2}$	0.10	0.11	0.16	0.52	0.04	0.21	0.27	0.17	0.88	0.81	0.84	0.78
	$Z_{d=1}$	0.25	0.03	0.00	0.17	0.26	0.58	0.54	0.46	0.78	0.80	0.78	0.84
	$Z_{d=2}$	0.01	0.07	0.27	0.09	0.46	0.47	0.22	0.62	0.81	0.82	0.78	0.82
	$Z_{r=1}$	0.13	0.00	0.17	0.54	0.01	0.38	0.35	0.51	0.83	0.78	0.78	0.82
	$Z_{r=2}$	0.25	0.21	0.39	0.22	0.09	0.08	0.33	0.15	0.88	0.78	0.81	0.78
	$Z_{r=3}$	0.00	0.02	0.22	0.43	0.28	0.37	0.00	0.13	0.78	0.81	0.79	0.78
	$Z_{r=4}$	0.04	0.00	0.51	0.47	0.08	0.27	0.19	0.01	0.78	0.88	0.81	0.80
	$SIL_{p=1}$	0.83	0.00	0.14	0.42	0.17	0.25	0.40	0.10	0.88	0.85	0.83	0.82
$J(x_m^*)$	$SIL_{p=2}$	0.17	0.85	0.34	0.28	0.11	0.17	0.00	0.08	0.80	0.81	0.83	0.79
	$SIL_{d=1}$	0.27	0.00	0.99	0.27	0.09	0.49	0.01	0.15	0.86	0.86	0.82	0.82
	$SIL_{d=2}$	0.00	0.10	0.12	0.93	0.08	0.42	0.28	0.17	0.78	0.79	0.78	0.78
	$SIL_{r=1}$	0.00	0.08	0.29	0.18	1.00	0.37	0.23	0.33	0.78	0.84	0.84	0.79
	$SIL_{r=2}$	0.17	0.05	0.38	0.29	0.32	1.00	0.10	0.09	0.78	0.86	0.79	0.79
	$SIL_{r=3}$	0.00	0.06	0.36	0.54	0.33	0.42	1.00	0.24	0.78	0.78	0.80	0.80
	$SIL_{r=4}$	0.14	0.17	0.03	0.39	0.17	0.14	0.54	1.00	0.80	0.78	0.85	0.78
	$CSL_{r=1}$	0.28	0.00	0.23	0.17	0.26	0.38	0.40	0.10	1.00	0.80	0.80	0.78
	$CSL_{r=2}$	0.00	0.14	0.39	0.16	0.06	0.62	0.57	0.11	0.81	1.00	0.85	0.81
	$CSL_{r=3}$	0.17	0.00	0.31	0.31	0.18	0.21	0.46	0.11	0.83	0.83	1.00	0.78
	$CSL_{r=4}$	0.00	0.00	0.44	0.22	0.00	0.38	0.26	0.22	0.79	0.89	0.84	1.00

表 **4.7** 訂定模糊目標隸屬度函數所需的參數

m	J_m	$\underline{J_m^0}$	J_m^0	J_m^1	$\overline{J_m^1}$
1	$\mathrm{Z}_{p=1}$	$-1,541,375$	$866,827$	$4,611,859$	$4,611,859$
2	$\mathrm{Z}_{p=2}$	$-1,162,174$	$499,773$	$5,227,369$	$5,227,369$
3	$\mathrm{Z}_{d=1}$	$-3,672,758$	$363,044$	$3,339,963$	$3,339,963$
4	$\mathrm{Z}_{d=2}$	$-3,495,402$	$387,090$	$3,796,692$	$3,796,692$
5	$\mathrm{Z}_{r=1}$	$-2,218,241$	$276,450$	$1,275,169$	$1,275,169$
6	$\mathrm{Z}_{r=2}$	$-2,162,659$	$243,683$	$951,075$	$951,075$
7	$\mathrm{Z}_{r=3}$	$-2,163,569$	$55,342$	$882,529$	$882,529$
8	$\mathrm{Z}_{r=4}$	$-1,759,862$	$231,431$	$1,165,653$	$1,165,653$
9	$\mathrm{SIL}_{p=1}$	0.00	0.00	0.83	0.83
10	$\mathrm{SIL}_{p=2}$	0.00	0.00	0.85	0.85
11	$\mathrm{SIL}_{d=1}$	0.00	0.00	0.99	0.99
12	$\mathrm{SIL}_{d=2}$	0.00	0.09	0.93	0.93
13	$\mathrm{SIL}_{r=1}$	0.00	0.00	1.00	1.00
14	$\mathrm{SIL}_{r=2}$	0.00	0.08	1.00	1.00
15	$\mathrm{SIL}_{r=3}$	0.00	0.00	1.00	1.00
16	$\mathrm{SIL}_{r=4}$	0.00	0.01	1.00	1.00
17	$\mathrm{CSL}_{r=1}$	0.78	0.78	1.00	1.00
18	$\mathrm{CSL}_{r=2}$	0.78	0.78	1.00	1.00
19	$\mathrm{CSL}_{r=3}$	0.78	0.78	1.00	1.00
20	$\mathrm{CSL}_{r=4}$	0.78	0.78	1.00	1.00

將使用單一階段與兩階段運算法求解的結果整理如表 4.8 所示，其中列出了各成員收益、安全存貨水準、以及顧客服務水準等目標函數值與其隸屬度函數值。此外，為了方便比較，可以對照圖 4.2 。從結果可以看出選擇 min 運算子時，可以讓滿意度較低的隸屬度函數盡量獲得提升，進而得到較為平均的隸屬度函數分佈。整體而言，各目標的隸屬度函數值都約略在 0.52 附近。但是， min 運算子不具嚴格單調的特性，會有非唯一局部最適解的情形發生。選擇 product 運算子時，雖其具有嚴格單調的性質，可以求得唯一最適解，但容易造成隸屬度函數值分佈不均的情形。如工廠 $p = 2$ 與配銷中心 $d = 1$ 和 $d = 2$ 的收益，以及配銷中心 $d = 1$ 和 $d = 2$ 的安全存貨水準，都偏低，而零售商的收益則偏高。這樣的結果，與想要求得目標間相互妥協解的本意有所衝突。而使用兩階段模糊最適化法，則可以在具備最低滿意度 0.52 的保證下，得到令人滿意的妥協解。

表 4.9 列出工廠的製造排程。工廠 $p = 1$ 在第一週期生產產品 $i = 1$，接著於第二週期換線生產生產產品 $i = 3$ ；而第三週期依然生產產品 $i = 3$，第四週期則閒置。此外，工廠 $p = 2$ 在第一週期有加班生產。

圖 4.3 和圖 4.4 為零售商的存貨與缺貨量，以及顧客需求量。 圖 4.5 為工廠與配銷中心的存貨量，而圖 4.6 則為零售商的存貨量。 圖 4.7 至圖 4.9 呈現產品單位售價與銷售量的關係。由圖中可以觀察到，為了節省購買成本，買方會盡量選擇較大的經濟批量採購方式，以壓低產品的單位售價。 圖 4.10 為工廠對配銷中心的產品運送規劃，而 圖 4.11 和圖 4.12 則為配銷中心對零售商的產品運送規劃。為了節省運送成本，出貨端會盡量選擇較大的經濟批量運送方式。此外，由於配銷中心 $d = 1$（桃園）與零售商 $r = 4$（高雄）的距離較遠，運送成本較高，所以配銷中心 $d = 1$ 並沒有供貨給零售商 $r = 4$。

表 **4.8** 模式求解的結果

目標		min		Product		兩階段法	
		目標值	滿意度	目標值	滿意度	目標值	滿意度
收益	$p=1$	2,819,679	0.52	2,881,564	0.54	2,862,855	0.53
	$p=2$	2,964,984	0.52	2,472,184	0.42	2,965,214	0.52
	$d=1$	1,915,362	0.52	1,700,828	0.45	1,915,507	0.52
	$d=2$	2,165,031	0.52	1,794,977	0.41	2,165,197	0.52
	$r=1$	840,971	0.57	1,114,879	0.84	822,201	0.55
	$r=2$	624,760	0.54	839,690	0.84	649,280	0.57
	$r=3$	504,635	0.54	760,117	0.85	495,793	0.53
	$r=4$	773,109	0.58	1,041,992	0.87	819,165	0.63
安全存貨水準	$p=1$	0.43	0.52	0.40	0.48	0.43	0.52
	$p=2$	0.44	0.52	0.49	0.58	0.44	0.52
	$d=1$	0.52	0.52	0.34	0.34	0.52	0.52
	$d=2$	0.53	0.52	0.43	0.41	0.53	0.52
	$r=1$	0.52	0.52	0.58	0.58	0.52	0.52
	$r=2$	0.56	0.52	0.72	0.69	0.56	0.52
	$r=3$	0.52	0.52	0.71	0.71	0.52	0.52
	$r=4$	0.53	0.52	0.58	0.58	0.58	0.58
顧客服務水準	$r=1$	0.89	0.52	1	1	0.9	0.54
	$r=2$	0.89	0.52	1	1	0.9	0.53
	$r=3$	0.89	0.52	1	1	0.99	0.96
	$r=4$	0.89	0.52	0.97	0.85	0.98	0.93

表 **4.9** 工廠製造排程

$p=$		1				2			
$t=$		1	2	3	4	1	2	3	4
	i								
α_{pt}^i	1	1	0	0	0	0	1	0	0
	2	0	0	0	0	1	0	0	0
	3	0	1	1	0	0	0	0	0
β_{pt}^i	1	1	0	0	0	0	1	1	1
	2	0	0	0	0	1	0	0	0
	3	0	1	1	1	0	0	0	0
γ_{pt}^i	1	0	0	0	0	0	1	0	0
	2	0	0	0	0	0	0	0	0
	3	0	1	0	0	0	0	0	0
o_{pt}^i	1	0	0	0	0	0	0	0	0
	2	0	0	0	0	1	0	0	0
	3	0	0	0	0	0	0	0	0

圖 **4.2** 單一階段與兩階段運算法之比較

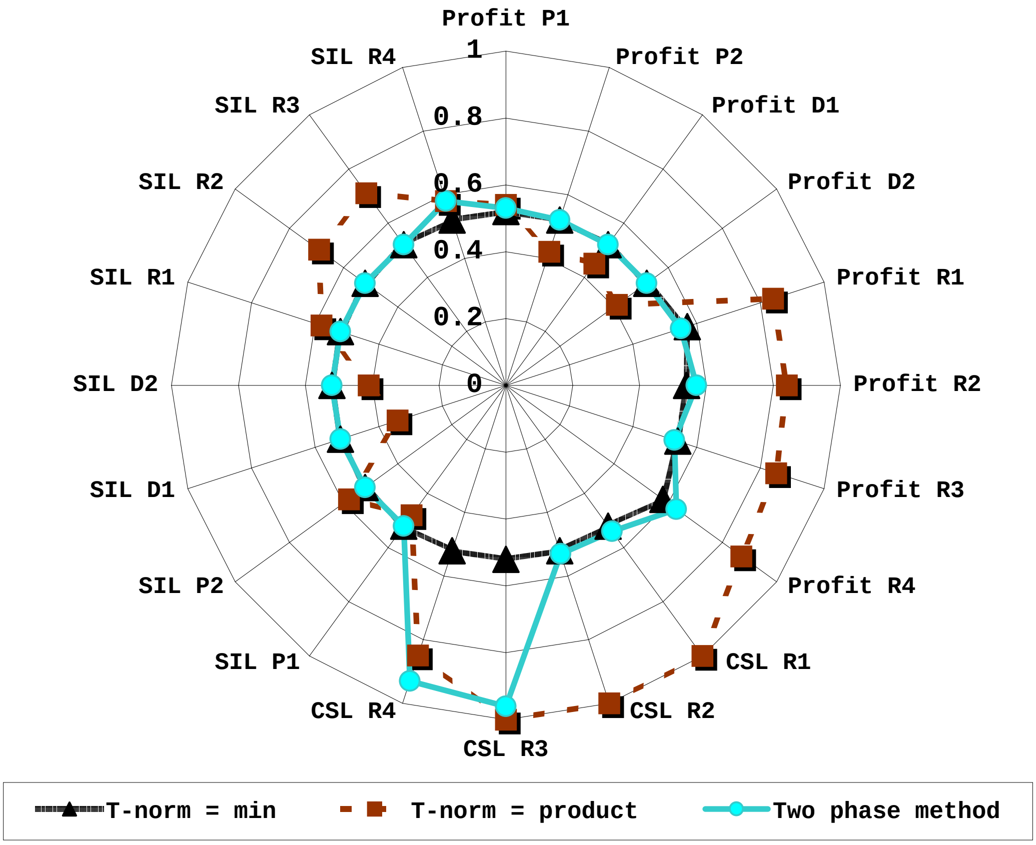
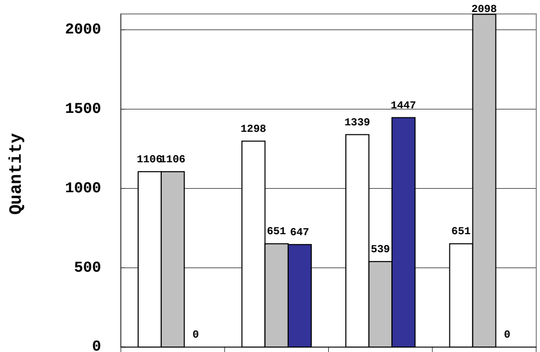


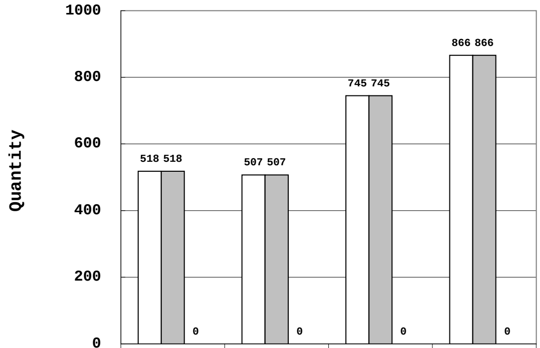
圖 **4.3** 產品需求量、銷售量與缺貨量。



	t1	t2	t3	t4
Demand	1106	1298	1339	651
Sales	1106	651	539	2098
Backlogs	0	647	1447	0

Time

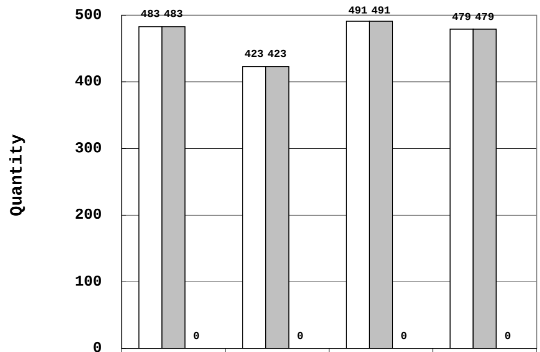
零售商 $r = 1$　產品 $i = 1$



	t1	t2	t3	t4
Demand	518	507	745	866
Sales	518	507	745	866
Backlogs	0	0	0	0

Time

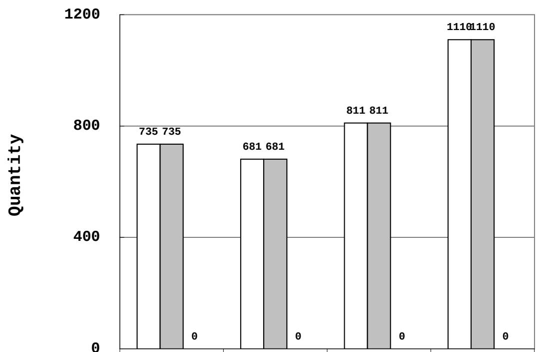
零售商 $r = 1$　產品 $i = 2$



	t1	t2	t3	t4
Demand	483	423	491	479
Sales	483	423	491	479
Backlogs	0	0	0	0

Time

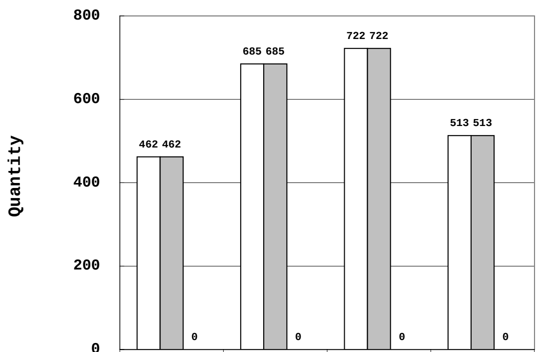
零售商 $r = 1$　產品 $i = 3$



	t1	t2	t3	t4
Demand	735	681	811	1110
Sales	735	681	811	1110
Backlogs	0	0	0	0

Time

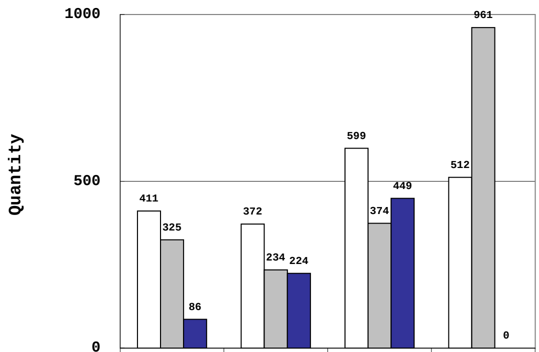
零售商 $r = 2$　產品 $i = 1$



	t1	t2	t3	t4
Demand	462	685	722	513
Sales	462	685	722	513
Backlogs	0	0	0	0

Time

零售商 $r = 2$　產品 $i = 2$

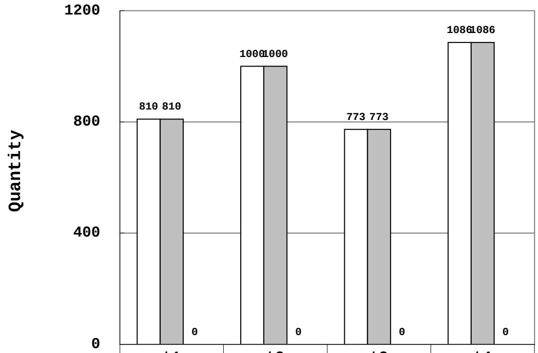


	t1	t2	t3	t4
Demand	411	372	599	512
Sales	325	234	374	961
Backlogs	86	224	449	0

Time

零售商 $r = 2$　產品 $i = 3$

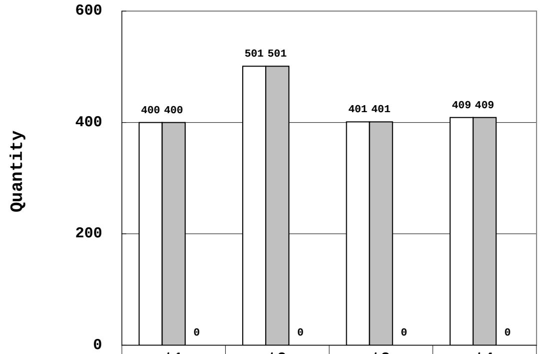
圖 **4.4** 產品需求量、銷售量與缺貨量。



	t1	t2	t3	t4
Demand	810	1000	773	1086
Sales	810	1000	773	1086
Backlogs	0	0	0	0

Time

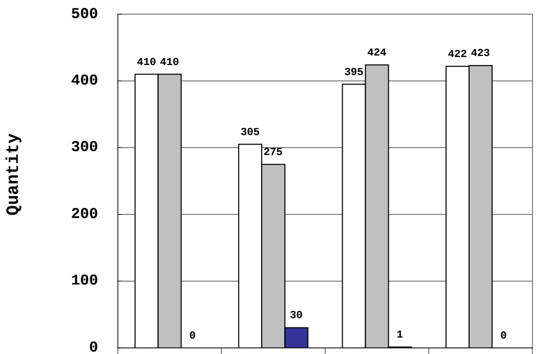
零售商 $r = 3$ 產品 $i = 1$



	t1	t2	t3	t4
Demand	400	501	401	409
Sales	400	501	401	409
Backlogs	0	0	0	0

Time

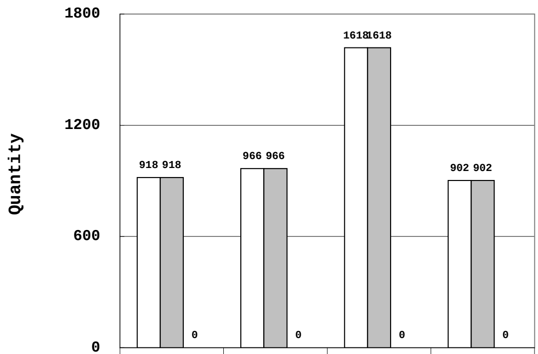
零售商 $r = 3$ 產品 $i = 2$



	t1	t2	t3	t4
Demand	410	305	395	422
Sales	410	275	424	423
Backlogs	0	30	1	0

Time

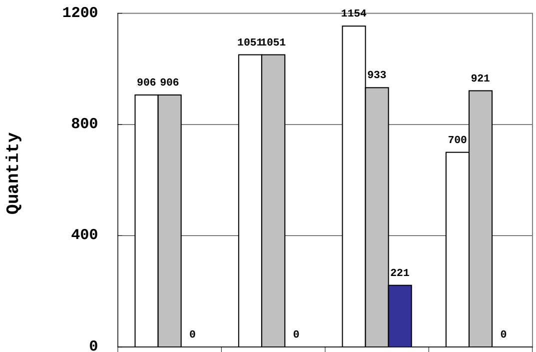
零售商 $r = 3$ 產品 $i = 3$



	t1	t2	t3	t4
Demand	918	966	1618	902
Sales	918	966	1618	902
Backlogs	0	0	0	0

Time

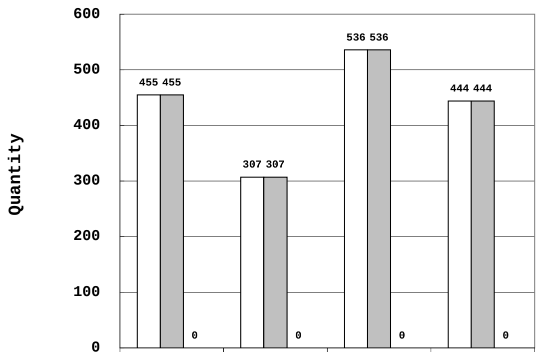
零售商 $r = 4$ 產品 $i = 1$



	t1	t2	t3	t4
Demand	906	1051	1154	700
Sales	906	1051	933	921
Backlogs	0	0	221	0

Time

零售商 $r = 4$ 產品 $i = 2$

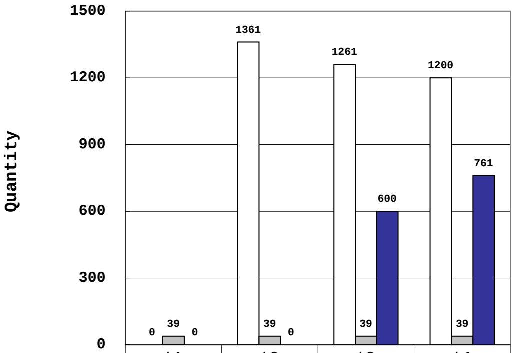


	t1	t2	t3	t4
Demand	455	307	536	444
Sales	455	307	536	444
Backlogs	0	0	0	0

Time

零售商 $r = 4$ 產品 $i = 3$

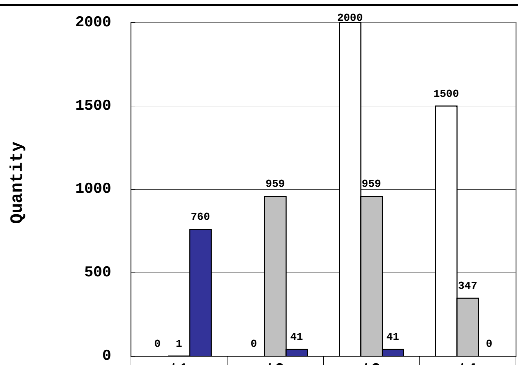
圖 **4.5** 工廠與配銷中心產品存貨量。



	t1	t2	t3	t4
Product 1	0	1361	1261	1200
Product 2	39	39	39	39
Product 3	0	0	600	761

Time

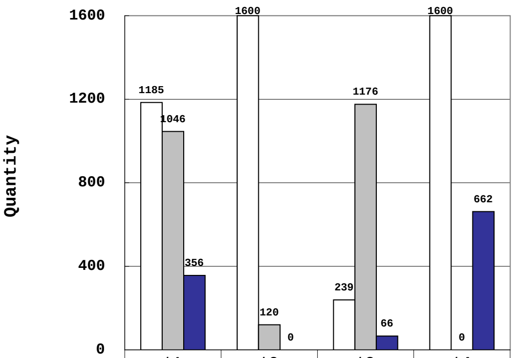
工廠 $p = 1$



	t1	t2	t3	t4
Product 1	0	0	2000	1500
Product 2	1	959	959	347
Product 3	760	41	41	0

Time

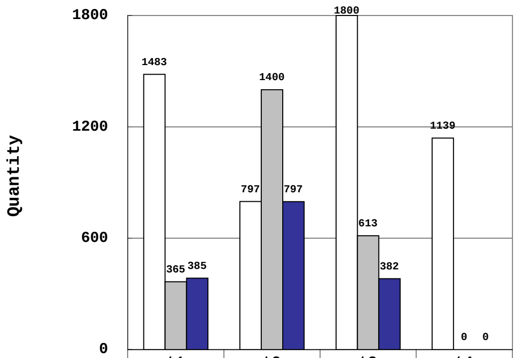
工廠 $p = 2$



	t1	t2	t3	t4
Product 1	1185	1600	239	1600
Product 2	1046	120	1176	0
Product 3	356	0	66	662

Time

配銷中心 $d = 1$

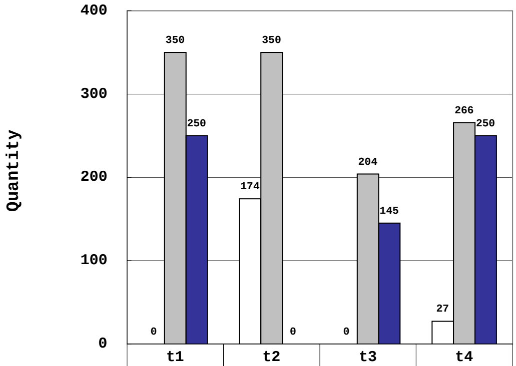


	t1	t2	t3	t4
Product 1	1483	797	1800	1139
Product 2	365	1400	613	0
Product 3	385	797	382	0

Time

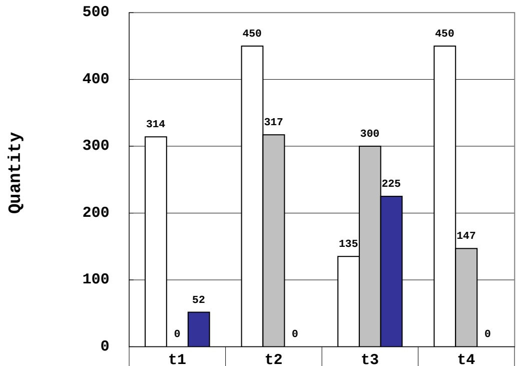
配銷中心 $d = 2$

圖 **4.6** 零售商產品存貨量。



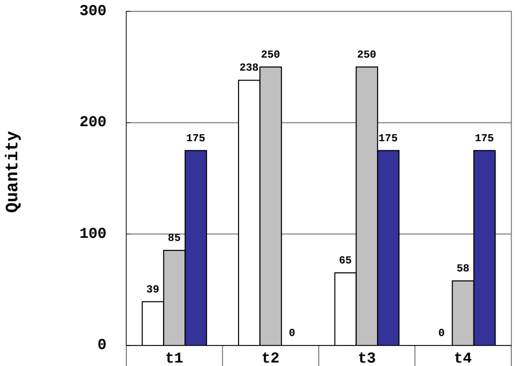
Time	t1	t2	t3	t4
□Product 1	0	174	0	27
▨Product 2	350	350	204	266
■Product 3	250	0	145	250

零售商 $r = 1$



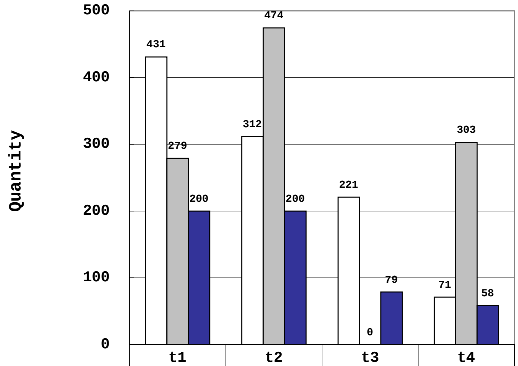
Time	t1	t2	t3	t4
□Product 1	314	450	135	450
▨Product 2	0	317	300	147
■Product 3	52	0	225	0

零售商 $r = 2$



Time	t1	t2	t3	t4
□Product 1	39	238	65	0
▨Product 2	85	250	250	58
■Product 3	175	0	175	175

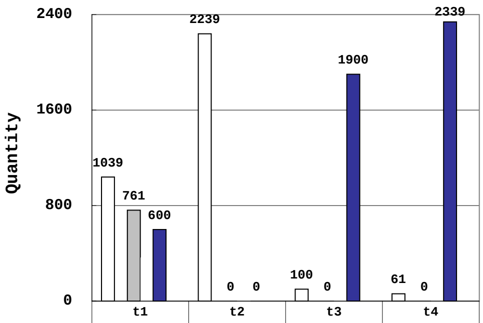
零售商 $r = 3$



Time	t1	t2	t3	t4
□Product 1	431	312	221	71
▨Product 2	279	474	0	303
■Product 3	200	200	79	58

零售商 $r = 4$

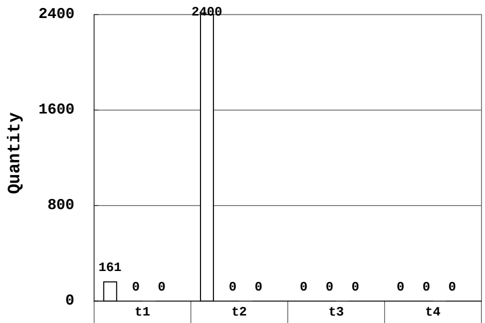
圖 **4.7** 產品單位售價與銷售量。



	t1	t2	t3	t4
Product 1	1039	2239	100	61
USP	203	194	211	211
Product 2	761	0	0	0
USP	364	364	364	364
Product 3	600	0	1900	2339
USP	606	606	542	542

Time

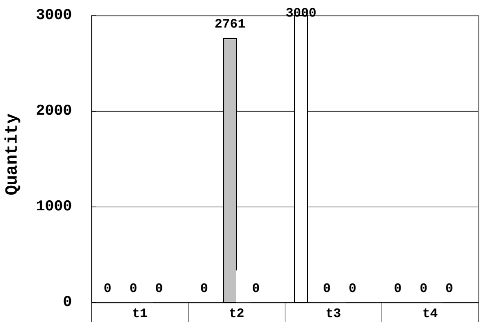
工廠 $p = 1$ 對配銷中心 $d = 1$



	t1	t2	t3	t4
Product 1	161	2400	0	0
USP	215	200	215	215
Product 2	0	0	0	0
USP	375	375	375	375
Product 3	0	0	0	0
USP	615	615	615	615

Time

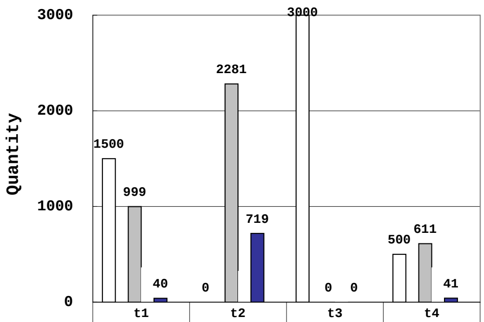
工廠 $p = 1$ 對配銷中心 $d = 2$



	t1	t2	t3	t4
Product 1	0	0	3000	0
USP	211	211	192	211
Product 2	0	2761	0	0
USP	369	335	369	369
Product 3	0	0	0	0
USP	606	606	606	606

Time

工廠 $p = 2$ 對配銷中心 $d = 1$

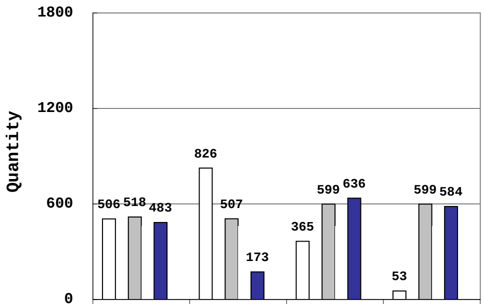


	t1	t2	t3	t4
Product 1	1500	0	3000	500
USP	197	207	186	207
Product 2	999	2281	0	611
USP	360	325	360	360
Product 3	40	719	0	41
USP	596	596	596	596

Time

工廠 $p = 2$ 對配銷中心 $d = 2$

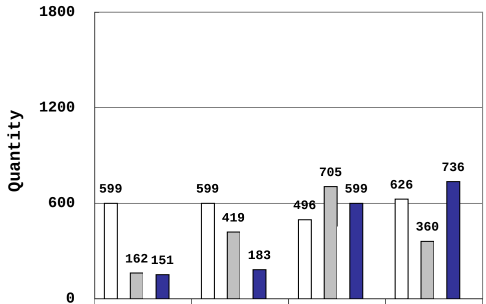
圖 **4.8** 產品單位售價與銷售量。



	t1	t2	t3	t4
□Product 1	506	826	365	53
USP	267	260	267	267
▨Product 2	518	507	599	599
USP	461	461	461	461
■Product 3	483	173	636	584
USP	749	749	732	749

Time

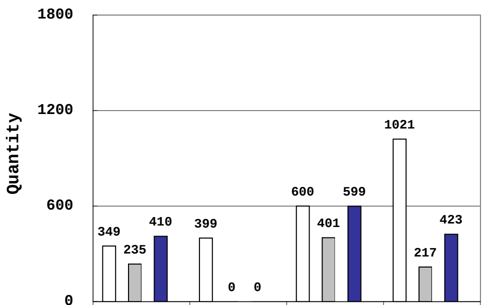
配銷中心 $d = 1$ 對零售商 $r = 1$



	t1	t2	t3	t4
□Product 1	599	599	496	626
USP	272	272	272	265
▨Product 2	162	419	705	360
USP	465	465	454	465
■Product 3	151	183	599	736
USP	753	753	753	737

Time

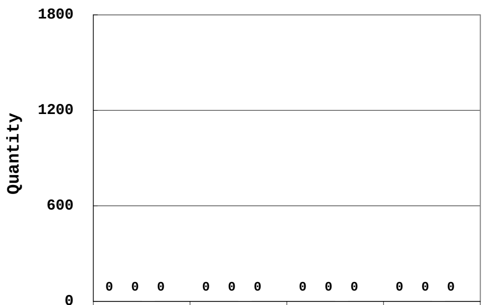
配銷中心 $d = 1$ 對零售商 $r = 2$



	t1	t2	t3	t4
□Product 1	349	399	600	1021
USP	276	276	270	270
▨Product 2	235	0	401	217
USP	470	470	470	470
■Product 3	410	0	599	423
USP	757	757	757	757

Time

配銷中心 $d = 1$ 對零售商 $r = 3$

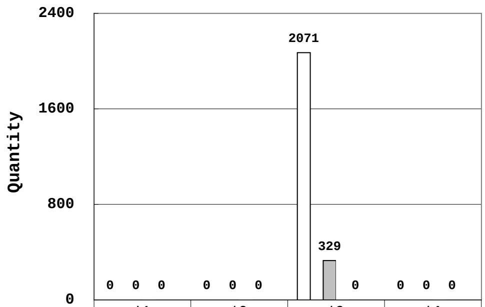


	t1	t2	t3	t4
□Product 1	0	0	0	0
USP	285	285	285	285
▨Product 2	0	0	0	0
USP	478	478	478	478
■Product 3	0	0	0	0
USP	765	765	765	765

Time

配銷中心 $d = 1$ 對零售商 $r = 4$

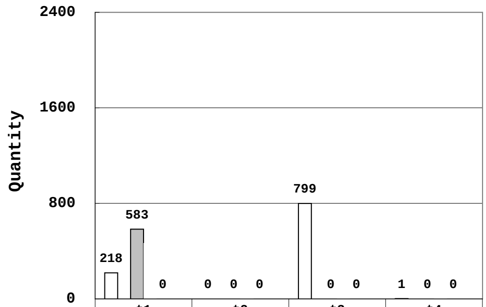
圖 **4.9** 產品單位售價與銷售量。



	t1	t2	t3	t4
Product 1	0	0	2071	0
USP	280	280	265	280
Product 2	0	0	329	0
USP	473	473	473	473
Product 3	0	0	0	0
USP	757	757	757	757

Time

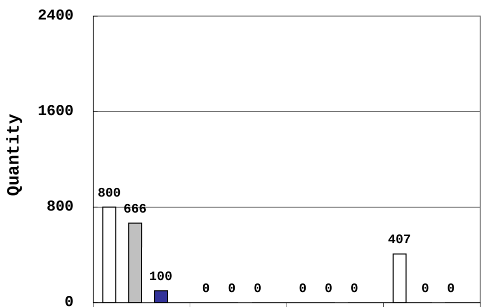
配銷中心 $d = 2$ 對零售商 $r = 1$



	t1	t2	t3	t4
Product 1	218	0	799	1
USP	271	271	271	271
Product 2	583	0	0	0
USP	464	464	464	464
Product 3	0	0	0	0
USP	749	749	749	749

Time

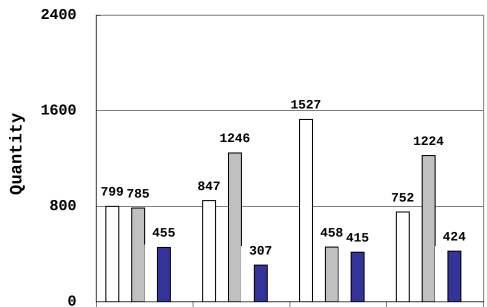
配銷中心 $d = 2$ 對零售商 $r = 2$



	t1	t2	t3	t4
Product 1	800	0	0	407
USP	258	267	267	267
Product 2	666	0	0	0
USP	460	460	460	460
Product 3	100	0	0	0
USP	745	745	745	745

Time

配銷中心 $d = 2$ 對零售商 $r = 3$

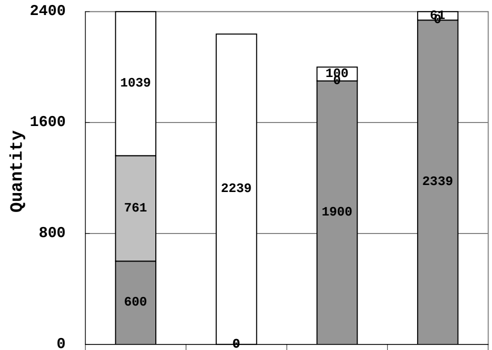


	t1	t2	t3	t4
Product 1	799	847	1527	752
USP	284	277	277	284
Product 2	785	1246	458	1224
USP	477	466	477	466
Product 3	455	307	415	424
USP	762	762	762	762

Time

配銷中心 $d = 2$ 對零售商 $r = 4$

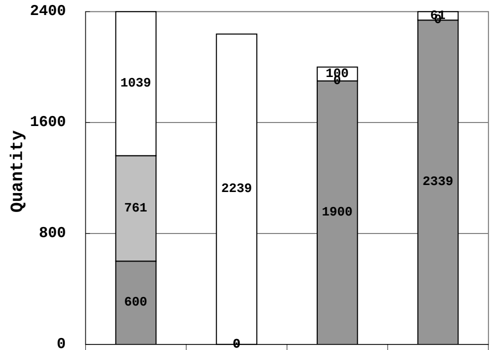
圖 **4.10** 工廠對配銷中心的產品運送規劃。



	t1	t2	t3	t4
□Product 1	1039	2239	100	61
▨Product 2	761	0	0	0
■Product 3	600	0	1900	2339

Time

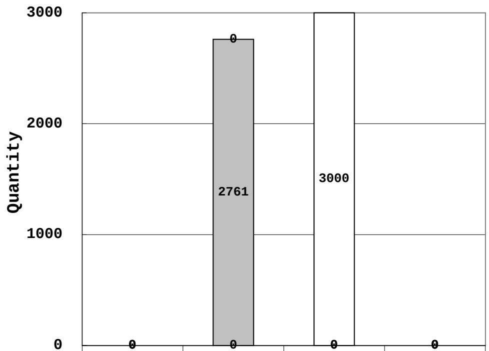
工廠 $p = 1$ 對配銷中心 $d = 1$



	t1	t2	t3	t4
□Product 1	1039	2239	100	61
▨Product 2	761	0	0	0
■Product 3	600	0	1900	2339

Time

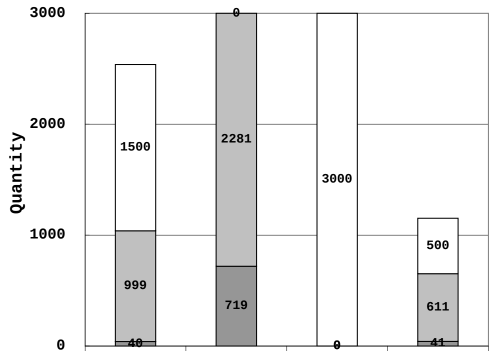
工廠 $p = 1$ 對配銷中心 $d = 2$



	t1	t2	t3	t4
□Product 1	0	0	3000	0
▨Product 2	0	2761	0	0
■Product 3	0	0	0	0

Time

工廠 $p = 2$ 對配銷中心 $d = 1$

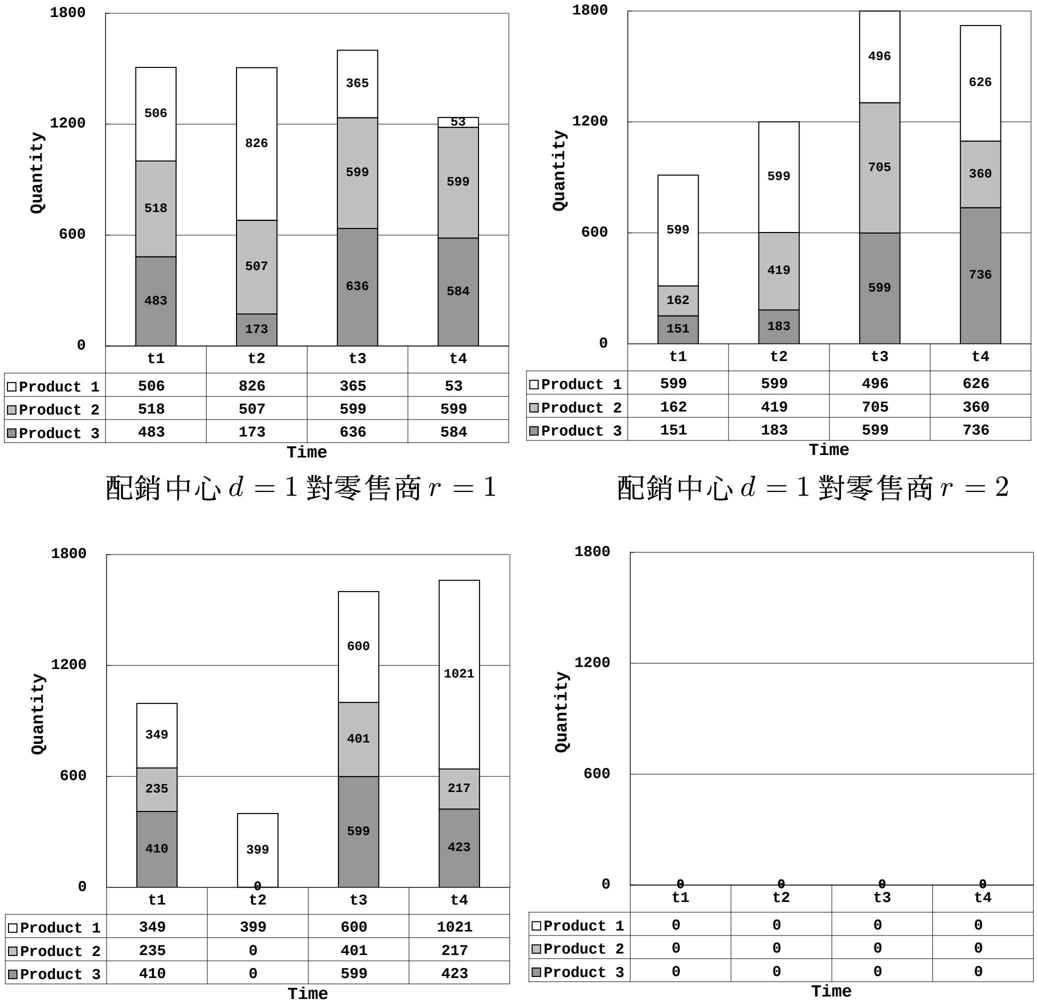


	t1	t2	t3	t4
□Product 1	1500	0	3000	500
▨Product 2	999	2281	0	611
■Product 3	40	719	0	41

Time

工廠 $p = 2$ 對配銷中心 $d = 2$

圖 **4.11** 配銷中心 $d = 1$ 對零售商的產品運送規劃。



配銷中心 $d = 1$ 對零售商 $r = 1$

	t1	t2	t3	t4
Product 1	506	826	365	53
Product 2	518	507	599	599
Product 3	483	173	636	584

配銷中心 $d = 1$ 對零售商 $r = 2$

	t1	t2	t3	t4
Product 1	599	599	496	626
Product 2	162	419	705	360
Product 3	151	183	599	736

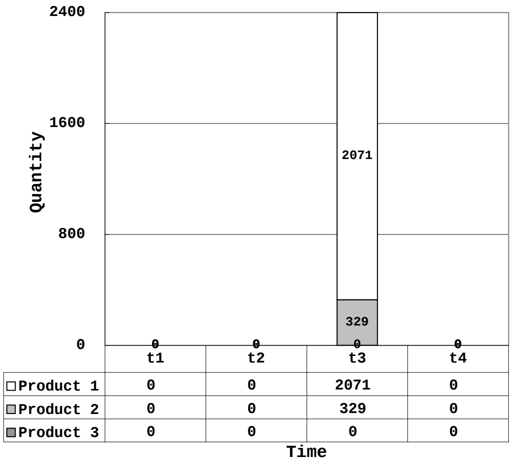
配銷中心 $d = 1$ 對零售商 $r = 3$

	t1	t2	t3	t4
Product 1	349	399	600	1021
Product 2	235	0	401	217
Product 3	410	0	599	423

配銷中心 $d = 1$ 對零售商 $r = 4$

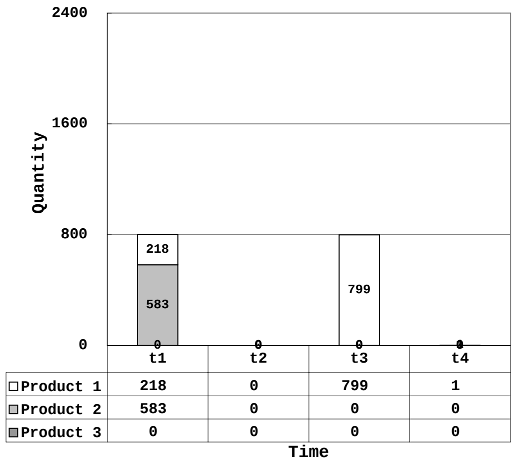
	t1	t2	t3	t4
Product 1	0	0	0	0
Product 2	0	0	0	0
Product 3	0	0	0	0

圖 **4.12** 配銷中心 $d = 2$ 對零售商的產品運送規劃。



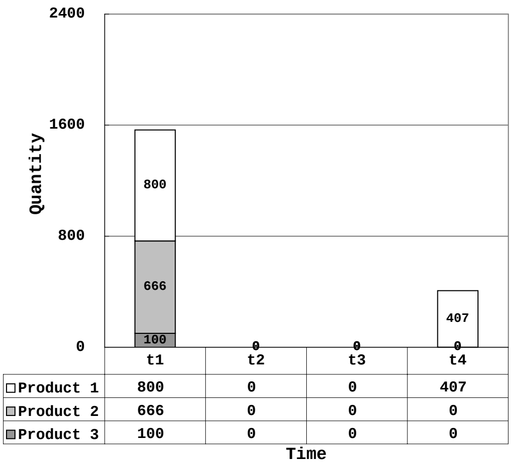
	t1	t2	t3	t4
Product 1	0	0	2071	0
Product 2	0	0	329	0
Product 3	0	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 1$



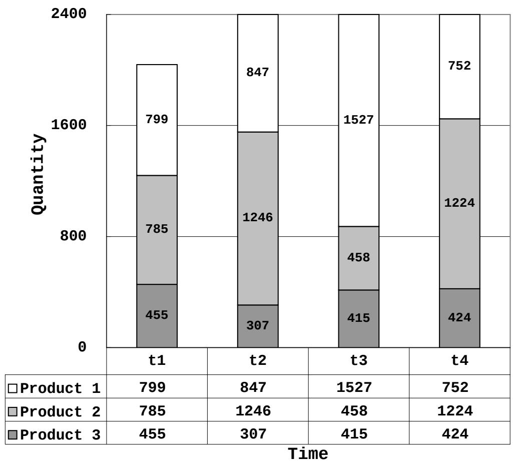
	t1	t2	t3	t4
Product 1	218	0	799	1
Product 2	583	0	0	0
Product 3	0	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 2$



	t1	t2	t3	t4
Product 1	800	0	0	407
Product 2	666	0	0	0
Product 3	100	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 3$



	t1	t2	t3	t4
Product 1	799	847	1527	752
Product 2	785	1246	458	1224
Product 3	455	307	415	424

配銷中心 $d = 2$ 對零售商 $r = 4$

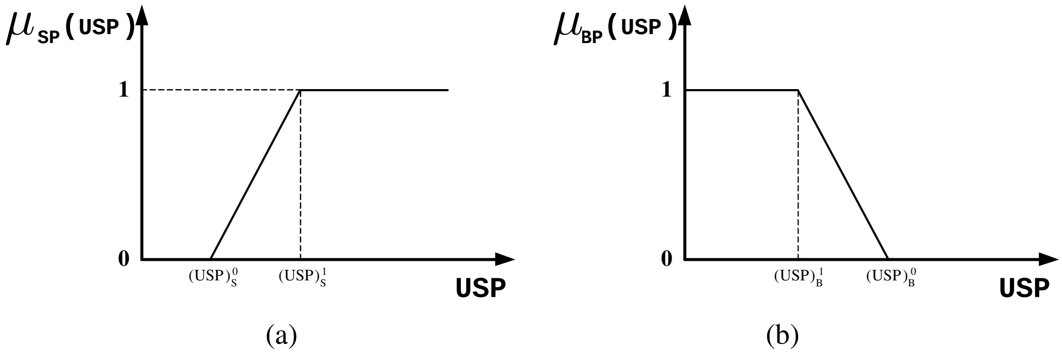
5

在產品價格不確定下之供應鏈網路最適化

5.1 產品價格不確定

在實際的商業環境中，產品的價格具有明顯的不確定性，而最後的價格通常是由買方與賣方透過協調來決定的。因此在供應鏈模式中，如何描述產品價格不確定及買賣雙方的協調過程，是一個不容忽視的重點。一個可能的方法是藉著長期收集的資料建立機率函數，用以描述不確定的產品價格。但是當無法得到可信賴的統計資料時，這個方法的可行性就不高。處於相互競爭關係的買賣雙方，對於產品價格有截然不同的偏好。以賣方的觀點而言，當產品價格高於某一個特定值 $(\mathrm{USP})_S^1$ 時，賣方會十分滿意；而當產品價格低於某一個特定值 $(\mathrm{USP})_S^0$ 時，賣方則無法接受，而不願意賣出產品。賣方對於產品價格的滿意度會隨著價格提高而上升。為了描述產品價格與賣方偏好口語化表達（即「不大滿意」、「有點滿意」等等）的關係，相當適合建立一個模糊集合 $\mathcal{SP}$ 和一個嚴格單調增加的隸屬度函數 $\mu_{\mathcal{SP}}(\mathrm{USP})$ 來衡量賣方對於產品價格的偏好。其中 $\mu_{\mathcal{SP}}(\mathrm{USP} \leq (\mathrm{USP})_S^0) = 0$ ，$\mu_{\mathcal{SP}}(\mathrm{USP} \geq (\mathrm{USP})_S^1) = 1$。同樣的道理，對於買方，也可以用一個模糊集合 $\mathcal{BP}$ 和一個嚴格單調增加的隸屬度函數 $\mu_{\mathcal{BP}}(\mathrm{USP})$ 來衡量買方對於產品價格的偏好。其中 $\mu_{\mathcal{BP}}(\mathrm{USP} \leq (\mathrm{USP})_B^1) = 1$ ，$\mu_{\mathcal{BP}}(\mathrm{USP} \geq (\mathrm{USP})_B^0) = 0$。

圖 **5.1** 賣方 (a) 與買方 (b) 的模糊售價隸屬度函數



決定使用何種隸屬度函數，通常是根據決策者的主觀判斷。 Leberling (1981) [32]建議使用超正切 (hyperbolic tangent) 函數，而 Hannan (1981) [26]則推薦不連續線性 (piece-wise linear) 函數。這些非線性函數雖然能對口語化項提供較詳細的描述，但相對的，就需要多瞭解買方與賣方對於產品價格的喜好程度 (Sakawa, 1993 [46])。選擇線性函數不僅可以減少資料需求的負擔，也不至於犧牲效能。因此，本研究將假設滿意度以固定速率增加或減少，並採用線性隸屬度函數來簡化隨後的計算，如圖 5.1 與式 (5.1) 所示。

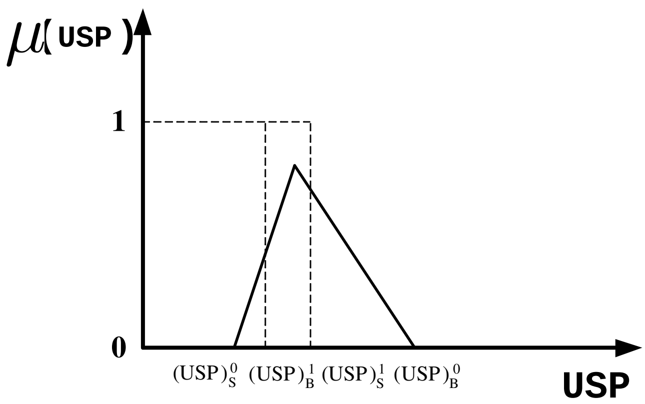
$$\begin{aligned}
\mu_{\mathcal{SP}}(\text{USP}) &= \begin{cases} 1 & \text{for} \quad \text{USP} \geq (\text{USP})_S^1 \\ \frac{\text{USP}-(\text{USP})_S^0}{(\text{USP})_S^1-(\text{USP})_S^0} & \text{for} \quad (\text{USP})_S^0 \leq \text{USP} \leq (\text{USP})_S^1 \\ 0 & \text{for} \quad (\text{USP})_S^0 \geq \text{USP} \end{cases} \\
\mu_{\mathcal{BP}}(\text{USP}) &= \begin{cases} 1 & \text{for} \quad (\text{USP})_B^1 \geq \text{USP} \\ \frac{(\text{USP})_B^0-\text{USP}}{(\text{USP})_B^0-(\text{USP})_B^1} & \text{for} \quad (\text{USP})_B^1 \leq \text{USP} \leq (\text{USP})_B^0 \\ 0 & \text{for} \quad \text{USP} \geq (\text{USP})_B^0 \end{cases}
\end{aligned} \tag{5.1}$$

產品最後的售價是由買賣雙方協調互相矛盾的模糊偏好而決定，而要計算 $\mathcal{SP}$ 和 $\mathcal{BP}$ 的模糊交集通常是使用 t-norm $\mathbb{T}$ 運算子。在一般情形下，本研究將優先採用 min 運算子作為 t-norm 運算子，如下所示。

$$\mu_{\mathcal{SP}\cap\mathcal{BP}}(\text{USP}) = \min\left(\mu_{\mathcal{SP}}(\text{USP}), \mu_{\mathcal{BP}}(\text{USP})\right) \tag{5.2}$$

同時考慮買賣雙方的觀點時的典型模糊售價隸屬度函數如圖 5.2 所示，而更進一步考慮與銷售量有關的模糊單位售價隸屬度函數，則如 圖 5.3 ，這個例子總共有三種經濟

圖 **5.2** *同時考慮買賣雙方的觀點時的典型模糊售價隸屬度函數*



批量銷售方式可以選擇。

5.2 在產品價格不確定下之供應鏈模式建構

在產品價格不確定下之供應鏈模式與第 2 章所提的模式幾乎相同，僅有一些小差異，將分別敘述如下。

5.2.1 系統參數

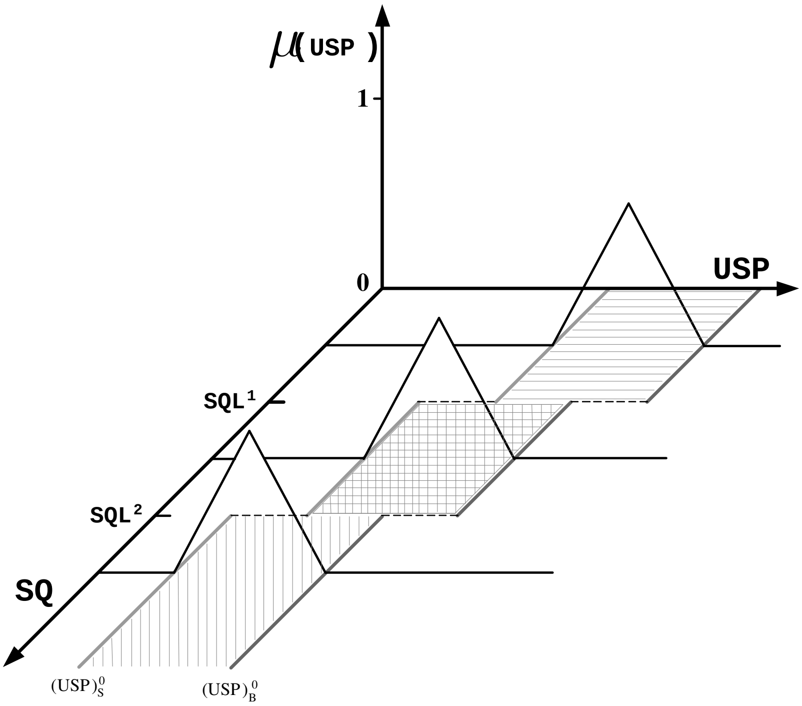
參數	$* \in$	物理意義
$\left(\mathrm{USP}^{i\vee}_{*}\right)^{\bullet}_{+}$	$\{pd, dr, rc\}$	訂定模糊單位售價隸屬度函數所需的參數 $+ \in \{S, B\}, \bullet \in \{0, 1\}, (*, \vee) \in \{(pd, \ell'), (dr, \ell), (rc, 1)\}$

5.2.2 系統變數

實數變數	$* \in$	物理意義
$\left(\mathrm{USP}^{i}_{*}\right)^{\bullet}_{+}$	$\{pdt, drt\}$	訂定模糊單位售價隸屬度函數所需的變數。 $+ \in \{S, B\}, \bullet \in \{0, 1\}$
USP^{i}_{*}	$\{pdt, drt, rc\}$	工廠 p 售予配銷中心 d、配銷中心 d 售予零售商 r、零售商 r 售予顧客 c 產品 i 的單位售價。

模糊變數	$* \in$	物理意義
$\mathcal{BP}^{i}_{*}$	$\{pd, dr, rc\}$	衡量買方對於產品售價偏好的模糊集合。
$\mathcal{SP}^{i}_{*}$	$\{pd, dr, rc\}$	衡量賣方對於產品售價偏好的模糊集合。

圖 **5.3** 與銷售量有關的典型模糊單位售價隸屬度函數



5.2.3 模糊售價限制式

在不同的銷售量下，買方與賣方對同一個價格的滿意度就會不一樣。買方購買量愈多，賣方就更願意以較低的價格賣出。因此，買方和賣方無法接受的價格，以及十分滿意的價格，便會與銷售量的多寡有關。而這部分限制式之目的，就是要決定在不同的銷售方式下，賣方無法接受的價格 $(\mathrm{USP})_S^0$ 和十分滿意的價格 $(\mathrm{USP})_S^1$，以及買方無法接受的價格 $(\mathrm{USP})_B^0$ 與十分滿意的價格 $(\mathrm{USP})_B^1$。

$$
\begin{aligned}
\mathrm{SQL}_{pd}^{i,\ell'-1}\mathrm{V}_{pdt}^{i\ell'} &\le \mathrm{SQ}_{pdt}^{i} < \mathrm{SQL}_{pd}^{i,\ell'}\mathrm{V}_{pdt}^{i\ell'} \quad \forall \ell' \in \{1,2,\ldots,L'-1\} && (5.3)\\
\mathrm{SQL}_{dr}^{i,\ell-1}\mathrm{V}_{drt}^{i\ell} &\le \mathrm{SQ}_{drt}^{i} < \mathrm{SQL}_{dr}^{i,\ell}\mathrm{V}_{drt}^{i\ell} \quad \forall \ell \in \{1,2,\ldots,L-1\} && (5.4)\\
\mathrm{SQL}_{pd}^{i,L'-1}\mathrm{V}_{pdt}^{iL'} &\le \mathrm{SQ}_{pdt}^{i} \le \mathrm{SQL}_{pd}^{i,L'}\mathrm{V}_{pdt}^{iL'} && (5.5)\\
\mathrm{SQL}_{dr}^{i,L-1}\mathrm{V}_{drt}^{iL} &\le \mathrm{SQ}_{drt}^{i} \le \mathrm{SQL}_{dr}^{i,L}\mathrm{V}_{drt}^{iL} && (5.6)\\
\sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}_{pdt}^{i\ell'} &= 1 \qquad \sum_{\forall \ell \in \mathcal{L}} \mathrm{V}_{drt}^{i\ell} = 1 && (5.7)\\
\left(\mathrm{USP}_{pdt}^{i}\right)_{+}^{\bullet} &= \sum_{\forall \ell' \in \mathcal{L}'} \mathrm{V}_{pdt}^{i\ell'}\left(\mathrm{USP}_{pd}^{i\ell'}\right)_{+}^{\bullet} && (5.8)\\
\left(\mathrm{USP}_{drt}^{i}\right)_{+}^{\bullet} &= \sum_{\forall \ell \in \mathcal{L}'} \mathrm{V}_{drt}^{i\ell}\left(\mathrm{USP}_{dr}^{i\ell}\right)_{+}^{\bullet} && (5.9)\\
&\quad + \in \{S,B\},\ \bullet \in \{0,1\}\\
&\quad \forall p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ \ell' \in \mathcal{L}',\ \ell \in \mathcal{L},\ t \in \mathcal{T}
\end{aligned}
$$

此部分將取代2.4.3節中式 (2.13) 至式 (2.19) 。

5.3 在產品價格不確定下最大化整體收益

為了多瞭解產品價格不確定對於供應鏈網路的影響，暫時先不考慮各成員間的公平收益分配、顧客服務水準以及安全存貨水準等目標，而只探討在產品價格不確定下，最大化整體收益的供應鏈網路最適化問題。由於要同時最大化整體收益與每個成員對於產品價格的滿意度，所以整個供應鏈仍然是一個「多目標混合整數非線性規劃問題」，如式 (5.10) 所示。

$$
\begin{aligned}
&\max_{\mathbf{x}'\in\boldsymbol{\Omega}} J(\mathbf{x}) = \sum_{\forall t\in\mathcal{T}}\left(\sum_{\forall p\in\mathcal{P}}\mathrm{Z}_{pt}+\sum_{\forall d\in\mathcal{D}}\mathrm{Z}_{dt}+\sum_{\forall r\in\mathcal{R}}\mathrm{Z}_{rt}\right)\\
&\text{and} \max_{\mathbf{x}'\in\boldsymbol{\Omega}} \mu_{\mathcal{SP}^i_*}\left(\mathrm{USP}^i_*\right)\\
&\text{and} \max_{\mathbf{x}'\in\boldsymbol{\Omega}} \mu_{\mathcal{BP}^i_*}\left(\mathrm{USP}^i_*\right)\\
&* \in \{pdt, drt, rc\}, \forall p\in\mathcal{P}, d\in\mathcal{D}, r\in\mathcal{R}, c\in\mathcal{C}, i\in\mathcal{I}, t\in\mathcal{T}\\
&\mathbf{x}' = \left\{\begin{array}{r|r}
\alpha^i_{pt},\beta^i_{pt},\gamma^i_{pt},o^i_{pt};\mathrm{SQ}^i_{pdt};\mathrm{SQ}^i_{drt};\mathrm{SQ}^i_{rct};\mathrm{USP}^i_{pdt}; & i\in\mathcal{I},p\in\mathcal{P},d\in\mathcal{D},r\in\mathcal{R},\\
\mathrm{USP}^i_{drt};\mathrm{USP}^i_{rc};\mathrm{TQ}^{k'}_{pdt},\mathrm{TQ}^k_{drt},\mathrm{Y}^{k'}_{pdt},\mathrm{Y}^k_{drt}; & c\in\mathcal{C},t\in\mathcal{T},\ell'\in\mathcal{L}',\\
\mathrm{V}^{i\ell'}_{pdt},\mathrm{V}^{i\ell}_{drt};\mathrm{I}^i_{pt},\mathrm{I}^i_{dt},\mathrm{I}^i_{rt};\mathrm{B}^i_{rt};\mathrm{D}^i_{pt},\mathrm{D}^i_{dt},\mathrm{D}^i_{rt}; & \ell\in\mathcal{L},k'\in\mathcal{K}',k\in\mathcal{K}
\end{array}\right\}
\end{aligned}
\tag{5.10}
$$

值得注意的是，除了零售商與顧客間的產品售價外，供應鏈內部的售價變動只會影響各成員間的收益分配，並不會影響整體收益。因此供應鏈內部的售價，可以由個別的買賣雙方自行決定，也就是價格 USP^i_* 可以直接由下列的式子決定。

$$
\begin{aligned}
&\max_{\mathrm{USP}^i_*}\min\left(\mu_{\mathcal{SP}^i_*}\left(\mathrm{USP}^i_*\right),\mu_{\mathcal{BP}^i_*}\left(\mathrm{USP}^i_*\right)\right)\\
&* \in \{pdt, drt\}, \forall p\in\mathcal{P}, d\in\mathcal{D}, r\in\mathcal{R}, i\in\mathcal{I}, t\in\mathcal{T}
\end{aligned}
\tag{5.11}
$$

這裡採用 min 運算子來計算買賣雙方的模糊偏好交集。因此，在式 (5.10) 中，只剩下零售商與顧客間的產品售價尚未決定，簡化後的問題如式 (5.12) 所示。

$$
\begin{aligned}
&\max_{\mathbf{x}\in\boldsymbol{\Omega}} J(\mathbf{x}) = \sum_{\forall t\in\mathcal{T}}\left(\sum_{\forall p\in\mathcal{P}}\mathrm{Z}_{pt}+\sum_{\forall d\in\mathcal{D}}\mathrm{Z}_{dt}+\sum_{\forall r\in\mathcal{R}}\mathrm{Z}_{rt}\right)\\
&\text{and} \max_{\mathbf{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{SP}^i_{rc}}\left(\mathrm{USP}^i_{rc}\right)\\
&\text{and} \max_{\mathbf{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{BP}^i_{rc}}\left(\mathrm{USP}^i_{rc}\right) \qquad \forall r\in\mathcal{R}, c\in\mathcal{C}, i\in\mathcal{I}\\
&\mathbf{x} = \left\{\begin{array}{r|r}
\alpha^i_{pt},\beta^i_{pt},\gamma^i_{pt},o^i_{pt};\mathrm{SQ}^i_{pdt};\mathrm{SQ}^i_{drt};\mathrm{SQ}^i_{rct}; & i\in\mathcal{I},p\in\mathcal{P},d\in\mathcal{D},r\in\mathcal{R},\\
\mathrm{USP}^i_{rc};\mathrm{TQ}^{k'}_{pdt},\mathrm{TQ}^k_{drt},\mathrm{Y}^{k'}_{pdt},\mathrm{Y}^k_{drt}; & c\in\mathcal{C},t\in\mathcal{T},\ell'\in\mathcal{L}',\\
\mathrm{V}^{i\ell'}_{pdt},\mathrm{V}^{i\ell}_{drt};\mathrm{I}^i_{pt},\mathrm{I}^i_{dt},\mathrm{I}^i_{rt};\mathrm{B}^i_{rt};\mathrm{D}^i_{pt},\mathrm{D}^i_{dt},\mathrm{D}^i_{rt}; & \ell\in\mathcal{L},k'\in\mathcal{K}',k\in\mathcal{K}
\end{array}\right\}
\end{aligned}
\tag{5.12}
$$

先將整體收益 $J(\mathbf{x})$ 轉換成對模糊收益目標 $\mathcal{J}$ 的滿意度，成為新的多目標模糊最適化問題。同時對模糊收益目標和零售商與顧客間的模糊售價，作模糊交集運算，得到模糊決策集合 $\mathcal{FD}$。

$$
\mathcal{FD} = \mathcal{J}\cap\mathcal{SP}^i_{rc}\cap\mathcal{BP}^i_{rc} \qquad \forall i\in\mathcal{I}, r\in\mathcal{R}, c\in\mathcal{C} \tag{5.13}
$$

整體的滿意度 $\mu_{\mathcal{FD}}(\mathbf{x})$，可經由 t-norm 運算子聚集對模糊收益目標的滿意度和零售商與顧客對售價的滿意度來決定。

$$\mu_{\mathcal{FD}}(\mathbf{x}) = \mathbb{T}\left[\mu_{\mathcal{J}}; \mu_{\mathcal{SP}^i_{rc}}, \mu_{\mathcal{BP}^i_{rc}} \middle| \forall i \in \mathcal{I}, r \in \mathcal{R}, c \in \mathcal{C}\right] \tag{5.14}$$

在式 (5.14) 中可觀察到，在計算整體的滿意度時，關於價格偏好的項目有 $2IRC$ 個，與收益有關的項目卻只有一個，似乎過於強調價格偏好的重要性。因此，為了平衡考量價格偏好與收益的重要性，本研究將模糊交集分成兩個階段。所有零售商與顧客的價格偏好，先同時在第一階段經由 t-norm 運算子 $\mathbb{T}_1$ 聚集。然後，在第二階段，經由 t-norm 運算子 $\mathbb{T}_2$ 聚集模糊收益的滿意度與第一階段得到的價格偏好，如下所示。

$$\mu_{\mathcal{FD}}(\mathbf{x}) = \mathbb{T}_2\left[\mu_{\mathcal{J}}, \mathbb{T}_1\left(\mu_{\mathcal{SP}^i_{rc}}, \mu_{\mathcal{BP}^i_{rc}} \middle| \forall i \in \mathcal{I}, r \in \mathcal{R}, c \in \mathcal{C}\right)\right] \tag{5.15}$$

以平衡性的考量而言，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 比較適合採用算數平均計算子。但是算數平均計算子容易造成隸屬度函數值分佈不均，所以本研究建議使用兩階段模糊多目標規畫法。在第一階段，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 都採用 min 運算子，最大化滿意度最低的目標。

$$\begin{aligned} \mu_{\mathcal{FD}}(\mathbf{x}^*) &= \max_{\mathbf{x}\in\mathbf{\Omega}} \min\left[\mu_{\mathcal{J}}; \mu_{\mathcal{SP}^i_{rc}}, \mu_{\mathcal{BP}^i_{rc}} \middle| \forall i \in \mathcal{I}, r \in \mathcal{R}, c \in \mathcal{C}\right] \\ &= \mu_{\text{min}} \end{aligned} \tag{5.16}$$

在第二階段，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 都採用算數平均計算子，在具備最低滿意度的保證下，盡量提升個別隸屬度函數的值。

$$\begin{aligned} \mu_{\mathcal{FD}}(\mathbf{x}^*) &= \max_{\mathbf{x}\in\mathbf{\Omega}^+} \frac{1}{2}\left[\mu_{\mathcal{J}} + \frac{1}{2IRC}\sum_{\forall i\in\mathcal{I}}\sum_{\forall r\in\mathcal{R}}\sum_{\forall c\in\mathcal{C}}\left(\mu_{\mathcal{SP}^i_{rc}} + \mu_{\mathcal{BP}^i_{rc}}\right)\right] \\ \mathbf{\Omega}^+ &= \mathbf{\Omega} \cap \left\{\mu_{\mathcal{J}} \ge \mu_{\text{min}}; \mu_{\mathcal{SP}^i_{rc}} \ge \mu_{\text{min}}, \mu_{\mathcal{BP}^i_{rc}} \ge \mu_{\text{min}} \middle| \forall i \in \mathcal{I}, r \in \mathcal{R}, c \in \mathcal{C}\right\} \end{aligned} \tag{5.17}$$

5.3.1 模式情境模擬分析與討論

情境模擬將延用前一章的例子，相關的參數設定皆相同。訂定模糊單位售價隸屬度函數所需的參數則列於表 5.1 與表 5.2 ，其中列出在不同銷售方式下，賣方無法接受的

價格 $(\text{USP})_S^0$ 和十分滿意的價格 $(\text{USP})_S^1$，以及買方無法接受的價格 $(\text{USP})_B^0$ 與十分滿意的價格 $(\text{USP})_B^1$。

結果與討論

求解的過程，可整理如下：

步驟 1: 對整體收益求取最樂觀的解 $\overline{J^1}$ 與最悲觀的解 $\underline{J^0}$。

$$\overline{J^1} = 14,559,034 \quad \text{and} \quad \underline{J^0} = 5,765,355 \tag{5.18}$$

然後，訂定整體收益隸屬度函數下。

$$\mu_{\mathcal{J}}(J) = \begin{cases} 1 & \text{for} \quad J \geq 14,559,034 \\ \frac{J-5,765,355}{8,793,679} & \text{for} \quad 5,765,355 \leq J \leq 14,559,034 \\ 0 & \text{for} \quad 5,765,355 \geq J \end{cases} \tag{5.19}$$

步驟 2: （階段一）以 min 運算子最大化滿意度最低的目標， $\mu_{\text{min}} = 0.6$。

步驟 3: （階段二）在具備最低滿意度的保證下，以算數平均運算子盡量提升個別隸屬度函數的值。

表 5.3 列出各種最適化方法之比較。若使用最大化個別滿意度之方式來決定零售商與顧客間的產品售價，由於總銷售量與價格都已經決定，總收入也就固定不變。因此要最大化收益，唯一能作的就是最小化總成本，其包含存貨成本、處理成本、運送成本、以及製造成本。最後的總收益滿意度只有 $\mu_{\mathcal{J}} = 0.9$。若使用算數平均運算子求解，總成本與前一個方法相同，但是可以增加總收入而使得總收益滿意度提高至 $\mu_{\mathcal{J}} = 0.94$。提高零售商售予顧客的產品價格，雖可增加總收入，但也會引起顧客不滿而降低購買意願。若顧客的滿意度太低，則會有流失市場之虞，因此維持適當的顧客滿意度是必要的。而兩階段模糊最適化法，顯然可以提供最低滿意度的保證。此外，由表 5.3 亦可以觀察到：使用 min 運算子求得的總成本比使用算數平均運算子的結果高出許多，這是因為 min 運算子不具嚴格單調的特性，所以會得到非唯一局部最適解。

表 **5.1** 訂定模糊單位售價隸屬度函數所需的參數

		賣方		買方				賣方		買方	
$\bullet$	$i\ p\ d\ r\ \ell$	$(\bullet)^0_S$	$(\bullet)^1_S$	$(\bullet)^1_B$	$(\bullet)^0_B$	$\bullet$	$i\ p\ d\ r\ \ell$	$(\bullet)^0_S$	$(\bullet)^1_S$	$(\bullet)^1_B$	$(\bullet)^0_B$
	1 1 1 1	259	273	267	276		2 2 1 1	458	484	469	488
	1 1 1 2	254	264	260	267		2 2 1 2	449	470	458	473
	1 1 1 3	248	256	253	258		2 2 1 3	440	456	447	459
	1 1 2 1	263	274	268	281		2 2 2 1	451	472	461	477
	1 1 2 2	258	267	262	273		2 2 2 2	441	458	448	462
	1 1 2 3	253	260	256	264		2 2 2 3	430	444	436	447
	1 1 3 1	266	283	275	286		2 2 3 1	448	463	454	472
	1 1 3 2	262	275	269	278		2 2 3 2	437	449	442	457
	1 1 3 3	257	268	263	270		2 2 3 3	426	436	429	441
	1 1 4 1	273	288	278	296		2 2 4 1	461	481	470	493
	1 1 4 2	270	282	274	289		2 2 4 2	453	469	460	479
	1 1 4 3	267	276	269	281		2 2 4 3	444	457	450	465
	1 2 1 1	269	288	277	290		3 1 1 1	728	762	748	770
	1 2 1 2	264	279	270	281		3 1 1 2	715	742	731	749
	1 2 1 3	258	270	263	271		3 1 1 3	702	723	714	728
	1 2 2 1	262	276	268	280		3 1 2 1	731	757	744	775
	1 2 2 2	255	267	260	270		3 1 2 2	719	740	729	755
$\mathrm{USP}^{i\ell}_{dr}$	1 2 2 3	248	258	253	260	$\mathrm{USP}^{i\ell}_{dr}$	3 1 2 3	706	723	715	734
	1 2 3 1	258	269	262	275		3 1 3 1	734	772	754	780
	1 2 3 2	251	260	254	265		3 1 3 2	723	754	739	760
	1 2 3 3	244	250	246	254		3 1 3 3	711	735	724	740
	1 2 4 1	273	287	279	295		3 1 4 1	740	771	750	790
	1 2 4 2	268	279	273	286		3 1 4 2	730	756	738	771
	1 2 4 3	263	272	267	277		3 1 4 3	720	740	726	752
	2 1 1 1	448	468	460	473		3 2 1 1	731	778	751	784
	2 1 1 2	439	455	449	459		3 2 1 2	719	757	735	762
	2 1 1 3	430	442	437	445		3 2 1 3	706	736	719	740
	2 1 2 1	453	468	460	478		3 2 2 1	724	763	742	774
	2 1 2 2	444	456	450	465		3 2 2 2	711	743	725	751
	2 1 2 3	435	444	439	451		3 2 2 3	697	722	708	728
	2 1 3 1	456	479	468	483		3 2 3 1	723	752	734	768
	2 1 3 2	448	466	457	470		3 2 3 2	708	732	717	745
	2 1 3 3	439	454	447	457		3 2 3 3	693	711	700	722
	2 1 4 1	462	482	468	494		3 2 4 1	734	768	750	789
	2 1 4 2	455	471	460	481		3 2 4 2	723	751	736	768
	2 1 4 3	448	461	452	469		3 2 4 3	711	733	721	746

表 **5.2** 訂定模糊單位售價隸屬度函數所需的參數

						賣方		買方									賣方		買方	
$\bullet$	i	p	d	r	ℓ'	$(\bullet)_S^0$	$(\bullet)_S^1$	$(\bullet)_B^1$	$(\bullet)_B^0$	$\bullet$	i	p	d	r	c	ℓ'	$(\bullet)_S^0$	$(\bullet)_S^1$	$(\bullet)_B^1$	$(\bullet)_B^0$
	1	1	1		1	202	213	207	220		3	1	1			1	577	614	594	636
	1	1	1		2	195	204	199	210		3	1	1			2	550	580	564	599
	1	1	1		3	188	196	192	200		3	1	1			3	523	547	534	561
	1	1	2		1	204	221	212	225		3	1	2			1	583	634	607	648
	1	1	2		2	199	212	205	216		3	1	2			2	560	602	579	613
	1	1	2		3	193	203	198	206	$\mathrm{USP}_{pd}^{i\ell'}$	3	1	2			3	537	569	552	578
	1	2	1		1	198	216	203	224		3	2	1			1	568	620	581	645
	1	2	1		2	191	205	195	212		3	2	1			2	543	585	554	606
	1	2	1		3	184	195	187	200		3	2	1			3	518	551	526	567
	1	2	2		1	196	213	207	219		3	2	2			1	557	616	593	635
	1	2	2		2	188	202	196	206		3	2	2			2	530	579	560	594
$\mathrm{USP}_{pd}^{i\ell'}$	1	2	2		3	179	190	186	194		3	2	2			3	503	541	526	553
	2	1	1		1	347	368	357	382		1			1	1		320	344	332	360
	2	1	1		2	336	354	344	365		1			2	1		305	337	310	345
	2	1	1		3	325	339	332	348		1			3	1		310	335	322	350
	2	1	2		1	359	385	371	391		1			4	1		315	341	325	355
	2	1	2		2	348	368	357	374		2			1	1		540	577	557	600
	2	1	2		3	336	352	343	356	USP_{rc}^{i1}	2			2	1		510	546	528	570
	2	2	1		1	348	376	356	390		2			3	1		520	558	535	580
	2	2	1		2	335	358	341	369		2			4	1		530	578	552	590
	2	2	1		3	322	339	326	348		3			1	1		840	898	863	930
	2	2	2		1	340	370	358	379		3			2	1		810	866	836	900
	2	2	2		2	326	351	341	358		3			3	1		820	874	847	910
	2	2	2		3	312	331	324	337		3			4	1		830	901	863	920

表 **5.3** 各種最適化方法之比較

單位售價			最大化個別的滿意度			min			算數平均運算子			兩階段法		
	i	r	USP	$\mu_{\mathcal{BP}^i_{rc}}$	$\mu_{\mathcal{SP}^i_{rc}}$	USP	$\mu_{\mathcal{BP}^i_{rc}}$	$\mu_{\mathcal{SP}^i_{rc}}$	USP	$\mu_{\mathcal{BP}^i_{rc}}$	$\mu_{\mathcal{SP}^i_{rc}}$	USP	$\mu_{\mathcal{BP}^i_{rc}}$	$\mu_{\mathcal{SP}^i_{rc}}$
USP^i_{rc}	1	1	339	0.77	0.77	343	0.60	0.96	352	0.33	1.00	343	0.60	0.96
	1	2	324	0.60	0.60	324	0.60	0.60	332	0.40	1.00	324	0.60	0.60
	1	3	329	0.75	0.75	333	0.60	0.92	336	0.48	1.00	333	0.60	0.92
	1	4	333	0.72	0.72	337	0.60	0.86	340	0.47	1.00	337	0.60	0.86
	2	1	568	0.75	0.75	574	0.60	0.92	577	0.53	1.00	574	0.60	0.92
	2	2	538	0.77	0.77	545	0.60	0.97	546	0.57	1.00	545	0.60	0.97
	2	3	548	0.72	0.72	553	0.60	0.86	559	0.48	1.00	553	0.60	0.86
	2	4	563	0.70	0.70	567	0.60	0.78	578	0.33	1.00	567	0.60	0.78
	3	1	882	0.72	0.72	890	0.60	0.86	900	0.40	1.00	890	0.60	0.86
	3	2	852	0.75	0.75	862	0.60	0.92	866	0.53	1.00	862	0.60	0.92
	3	3	862	0.77	0.77	873	0.60	0.97	878	0.48	1.00	873	0.60	0.97
	3	4	880	0.70	0.70	886	0.60	0.78	901	0.33	1.00	886	0.60	0.78
總收入			17,227,300			17,397,600			17,579,200			17,397,600		
成本	存貨		199,000			487,300			199,000			199,000		
	處理		1,210,600			1,361,200			1,210,600			1,210,600		
	運送		727,500			1,122,100			727,500			727,500		
	製造		1,438,000			3,159,000			1,438,000			1,438,000		
	小計		3,575,100			6,129,600			3,575,100			3,575,100		
總收益			13,652,200			11,268,000			14,004,100			13,822,500		
$\mu_{\mathcal{J}}$			0.90			0.63			0.94			0.92		

5.4 在產品價格不確定下之多目標供應鏈網路最適化

同時考量各成員間的公平收益分配、顧客服務水準、安全存貨水準以及每個成員對於產品價格的滿意度，形成一個「多目標混合整數非線性規劃問題」，如式 (5.20) 所示。

$$
\begin{aligned}
&\max_{\mathbf{x}\in\boldsymbol{\Omega}} (J_1(\mathbf{x}),\ldots,J_M(\mathbf{x})) = (\mathrm{Z}_p,\ \mathrm{Z}_d,\ \mathrm{Z}_r;\ \mathrm{SIL}_p,\ \mathrm{SIL}_d,\ \mathrm{SIL}_r;\ \mathrm{CSL}_r)\\
&\text{and}\ \ \max_{\mathbf{x}\in\boldsymbol{\Omega}}\ \mu_{\mathcal{SP}^i_*}\left(\mathrm{USP}^i_*\right)\\
&\text{and}\ \ \max_{\mathbf{x}\in\boldsymbol{\Omega}}\ \mu_{\mathcal{BP}^i_*}\left(\mathrm{USP}^i_*\right)\\
&* \in \{pdt, drt, rc\}, \forall p\in\mathcal{P}, d\in\mathcal{D}, r\in\mathcal{R}, c\in\mathcal{C}, i\in\mathcal{I}, t\in\mathcal{T}\\
&\mathbf{x} = \left\{ \begin{array}{r|r} \alpha^i_{pt},\beta^i_{pt},\gamma^i_{pt},o^i_{pt};\mathrm{SQ}^i_{pdt};\mathrm{SQ}^i_{drt};\mathrm{SQ}^i_{rct};\mathrm{USP}^i_{pdt}; & i\in\mathcal{I},p\in\mathcal{P},d\in\mathcal{D},r\in\mathcal{R},\\ \mathrm{USP}^i_{drt};\mathrm{USP}^i_{rc};\mathrm{TQ}^{k'}_{pdt},\mathrm{TQ}^{k}_{drt},\mathrm{Y}^{k'}_{pdt},\mathrm{Y}^{k}_{drt}; & c\in\mathcal{C},t\in\mathcal{T},\ell'\in\mathcal{L}',\\ \mathrm{V}^{i\ell'}_{pdt},\mathrm{V}^{i\ell}_{drt};\mathrm{I}^i_{pt},\mathrm{I}^i_{dt},\mathrm{I}^i_{rt};\mathrm{B}^i_{rt};\mathrm{D}^i_{pt},\mathrm{D}^i_{dt},\mathrm{D}^i_{rt}; & \ell\in\mathcal{L},k'\in\mathcal{K}',k\in\mathcal{K} \end{array} \right\}
\end{aligned}
\tag{5.20}
$$

因為供應鏈內部的售價變動會影響各成員間收益分配，而成員間的公平收益分配為目標之一，所以不能個別由買賣雙方自行決定。先將目標 $J_m(\mathbf{x})$ 轉換成對模糊目標 $\mathcal{J}_m$ 的滿意度，成為新的多目標模糊最適化問題。同時對各模糊目標和模糊售價作模糊交集運算，得到模糊決策集合 $\mathcal{FD}$。

$$
\begin{aligned}
\mathcal{FD} = \mathcal{J}_m \cap \mathcal{SP}^i_{pdt} \cap \mathcal{SP}^i_{drt} \cap \mathcal{SP}^i_{rc} \cap \mathcal{BP}^i_{pdt} \cap \mathcal{BP}^i_{drt} \cap \mathcal{BP}^i_{rc}\\
\forall m\in\mathcal{M},\ i\in\mathcal{I},\ p\in\mathcal{P},\ d\in\mathcal{D},\ r\in\mathcal{R},\ c\in\mathcal{C},\ t\in\mathcal{T}
\end{aligned}
\tag{5.21}
$$

整體的滿意度 $\mu_{\mathcal{FD}}(\mathbf{x})$，可經由 t-norm 運算子聚集對各模糊目標的滿意度和買賣雙方對售價的滿意度來決定。

$$
\mu_{\mathcal{FD}}(\mathbf{x}) = \mathbb{T}\left(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pdt}},\mu_{\mathcal{SP}^i_{drt}},\mu_{\mathcal{SP}^i_{rc}};\mu_{\mathcal{BP}^i_{pdt}},\mu_{\mathcal{BP}^i_{drt}},\mu_{\mathcal{BP}^i_{rc}}\middle|\,\forall m,i,p,d,r,c,t\right) \tag{5.22}
$$

在式 (5.22) 中可注意到，在計算整體滿意度時，與一對買賣雙方，如工廠 p 與配銷中心 d 或配銷中心 d 與零售商 r，有關的價格偏好項目有 $2IT$ 個。此外，與另一對買賣雙方，如零售商 r 與顧客 c，有關的價格偏好項目則有 $2I$ 個。以上顯然都過於強調價格偏好的重要性，因此為了平衡考量各目標與價格偏好的重要性，本研究將模糊交集分成兩個階段：先將各對買賣雙方的價格偏好，在第一階段經由 t-norm 運算子 $\mathbb{T}_1$ 聚集。接著

於第二階段，經由 t-norm 運算子 $\mathbb{T}_2$ 聚集各模糊目標的滿意度與第一階段得到的各對買賣雙方價格偏好，如下所示。

$$\begin{aligned}\mu_{\mathcal{FD}}(\mathbf{x}) \;=\; & \mathbb{T}_2\Big[\mu_{\mathcal{J}_m}, \mathbb{T}_1^{pd}\Big(\mu_{\mathcal{SP}^i_{pdt}}, \mu_{\mathcal{BP}^i_{pdt}}\Big|\forall i\in\mathcal{I}, t\in\mathcal{T}\Big),\\ & \mathbb{T}_1^{dr}\Big(\mu_{\mathcal{SP}^i_{drt}}, \mu_{\mathcal{BP}^i_{drt}}\Big|\forall i\in\mathcal{I}, t\in\mathcal{T}\Big),\\ & \mathbb{T}_1^{rc}\Big(\mu_{\mathcal{SP}^i_{rc}}, \mu_{\mathcal{BP}^i_{rc}}\Big|\forall i\in\mathcal{I}\Big)\Big|\forall m,p,d,r,c\Big]\end{aligned} \tag{5.23}$$

以平衡性的考量而言，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 比較適合採用算數平均計算子。但是算數平均計算子容易造成隸屬度函數值分佈不均，所以本研究建議使用兩階段模糊多目標規畫法。在第一階段，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 都採用 min 運算子，最大化滿意度最低的目標。

$$\begin{aligned}\max_{\mathbf{x}\in\mathbf{\Omega}}\mu_{\mathcal{FD}} &= \max_{\mathbf{x}\in\mathbf{\Omega}}\min\Big(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pdt}},\mu_{\mathcal{SP}^i_{drt}},\mu_{\mathcal{SP}^i_{rc}};\mu_{\mathcal{BP}^i_{pdt}},\mu_{\mathcal{BP}^i_{drt}},\mu_{\mathcal{BP}^i_{rc}}\Big|\forall m,i,p,d,r,c,t\Big)\\ &\equiv \mu_{\min}\end{aligned} \tag{5.24}$$

在第二階段，$\mathbb{T}_1$ 和 $\mathbb{T}_2$ 都採用算數平均計算子，在具備最低滿意度的保證下，盡量提升個別隸屬度函數的值。

$$\mu_{\mathcal{FD}}(\mathbf{x}^*) = \max_{\mathbf{x}\in\mathbf{\Omega}^+}\frac{\left[\begin{aligned}\sum_{\forall m\in\mathcal{M}}\mu_{\mathcal{J}_m} &+ \sum_{\forall p\in\mathcal{P}}\sum_{\forall d\in\mathcal{D}}\left(\frac{1}{2IT}\sum_{\forall i\in\mathcal{I}}\sum_{\forall t\in\mathcal{T}}\left(\mu_{\mathcal{SP}^i_{pdt}}+\mu_{\mathcal{BP}^i_{pdt}}\right)\right)\\ &+ \sum_{\forall d\in\mathcal{D}}\sum_{\forall r\in\mathcal{R}}\left(\frac{1}{2IT}\sum_{\forall i\in\mathcal{I}}\sum_{\forall t\in\mathcal{T}}\left(\mu_{\mathcal{SP}^i_{drt}}+\mu_{\mathcal{BP}^i_{drt}}\right)\right)\\ &+ \sum_{\forall r\in\mathcal{R}}\sum_{\forall c\in\mathcal{C}}\left(\frac{1}{2I}\sum_{\forall i\in\mathcal{I}}\left(\mu_{\mathcal{SP}^i_{rc}}+\mu_{\mathcal{BP}^i_{rc}}\right)\right)\end{aligned}\right]}{2P+2D+3R+PD+DR+RC}$$

$$\Omega^+ = \Omega\cap\Big\{\mu_{\mathcal{J}_m},\mu_{\mathcal{SP}^i_*},\mu_{\mathcal{BP}^i_*}\geq\mu_{\min}\Big|*\in\{pdt,drt,rc\};\forall m,i,p,d,r,c,t\Big\} \tag{5.25}$$

5.4.1 模式情境模擬分析與討論

情境模擬將延用前一章的例子，相關的參數設定皆相同。而訂定模糊單位售價隸屬度函數所需的參數則與上一節的例子相同，如表 5.1 所示。此多目標生產與配送規劃模式包含 3878 個方程式、 1268 個連續變數和 672 個 0-1 變數。

結果與討論

多目標生產與配送規劃模式求解的過程，可整理如下：

步驟 1: 分別對單一目標求取最樂觀的解 $\overline{J_m^1}$ 與最悲觀的解 $\underline{J_m^0}$，並建立理想解償付表，如表 5.4 和表 5.5 所示。然後，選擇目標函數的可接受範圍 $[J_m^0, J_m^1]$，如表 5.6 所示。本研究決定直接以 $\overline{J_m^1}$ 作為所有目標的上限 J_m^1。由於收益的 $\underline{J_m^0}$ 有一些是負值，並不適合作為下限，因此選擇理想解償付表中，最低的正值作為 J_m^0。同時也選擇理想解償付表中的最低值作為，安全存貨水準和顧客服務水準的下限 J_m^0。

步驟 2: （階段一）以 min 運算子最大化滿意度最低的目標，$\mu_{\min} = 0.45$。

步驟 3: （階段二）在具備最低滿意度的保證下，以算數平均運算子盡量提升個別隸屬度函數的值。

表 **5.4** 理想解償付表

		$J_m(x^*)$							
		$Z_{p=1}$	$Z_{p=2}$	$Z_{d=1}$	$Z_{d=2}$	$Z_{r=1}$	$Z_{r=2}$	$Z_{r=3}$	$Z_{r=4}$
	$Z_{p=1}$	4,849,095	1,392,088	835,871	711,353	−418,710	422,245	382,578	781,712
	$Z_{p=2}$	1,548,669	5,620,679	388,390	−118,023	703,231	1,018,242	172,273	824,353
	$Z_{d=1}$	1,525,554	833,513	3,985,165	2,177,910	209,691	218,340	−474,074	−1,084,046
	$Z_{d=2}$	1,772,353	2,565,585	1,460,226	4,527,048	−34,329	−925,524	−64,148	−790,186
	$Z_{r=1}$	1,527,911	1,971,963	1,290,209	1,149,489	1,589,110	412,772	329,874	712,442
	$Z_{r=2}$	1,707,349	1,252,812	256,818	1,680,242	998,564	1,243,161	641,713	927,382
	$Z_{r=3}$	905,009	2,435,253	1,190,986	1,173,928	775,899	660,459	1,149,759	590,261
	$Z_{r=4}$	1,141,475	2,204,287	477,373	1,179,252	1,009,334	592,584	530,503	1,536,114
	$SIL_{p=1}$	2,091,514	1,931,575	1,300,668	617,668	692,525	680,942	307,722	874,457
$J(x^*_m)$	$SIL_{p=2}$	981,674	1,435,844	1,256,368	1,168,157	646,954	580,299	199,895	834,640
	$SIL_{d=1}$	1,913,951	1,778,674	133,739	1,758,280	1,228,621	762,155	652,427	940,490
	$SIL_{d=2}$	1,589,030	1,315,910	1,574,933	−47,696	937,585	522,190	574,477	590,433
	$SIL_{r=1}$	1,819,707	2,067,451	1,318,174	1,542,665	393,944	548,688	484,819	488,992
	$SIL_{r=2}$	1,752,525	2,365,488	1,118,015	1,293,645	1,231,264	507,630	453,109	767,448
	$SIL_{r=3}$	1,666,705	2,107,644	312,436	1,810,847	969,989	607,206	620,090	871,204
	$SIL_{r=4}$	2,040,176	2,168,252	1,610,188	762,386	1,248,058	1,038,630	262,442	292,120
	$CSL_{r=1}$	1,963,295	1,954,689	1,132,485	1,604,497	798,665	588,271	422,746	452,462
	$CSL_{r=2}$	1,018,479	1,874,597	501,286	2,165,219	870,175	403,943	−137,849	697,678
	$CSL_{r=3}$	1,682,603	2,295,894	1,360,029	1,462,137	387,240	485,056	695,237	131,355
	$CSL_{r=4}$	1,952,586	1,496,203	1,573,880	1,611,047	1,303,508	423,042	−235,752	1,130,103

表 **5.5** 理想解償付表

		$J_m(x^*)$											
		$SIL_{p=1}$	$SIL_{p=2}$	$SIL_{d=1}$	$SIL_{d=2}$	$SIL_{r=1}$	$SIL_{r=2}$	$SIL_{r=3}$	$SIL_{r=4}$	$CSL_{r=1}$	$CSL_{r=2}$	$CSL_{r=3}$	$CSL_{r=4}$
	$Z_{p=1}$	0.06	0.07	0.32	0.27	0.19	0.17	0.08	0.07	0.83	0.78	0.90	0.78
	$Z_{p=2}$	0.11	0.03	0.27	0.40	0.25	0.28	0.31	0.15	0.78	0.78	0.82	0.80
	$Z_{d=1}$	0.00	0.06	0.00	0.31	0.12	0.60	0.58	0.42	0.80	0.82	0.87	0.84
	$Z_{d=2}$	0.02	0.10	0.15	0.11	0.23	0.32	0.15	0.66	0.78	0.80	0.78	0.93
	$Z_{r=1}$	0.00	0.00	0.30	0.35	0.00	0.17	0.20	0.33	0.80	0.85	0.78	0.85
	$Z_{r=2}$	0.18	0.20	0.34	0.28	0.31	0.00	0.35	0.19	0.90	0.82	0.82	0.80
	$Z_{r=3}$	0.00	0.18	0.38	0.25	0.17	0.17	0.00	0.00	0.85	0.80	0.78	0.79
	$Z_{r=4}$	0.00	0.00	0.51	0.27	0.13	0.25	0.18	0.14	0.85	0.82	0.82	0.78
	$SIL_{p=1}$	0.82	0.08	0.28	0.34	0.21	0.24	0.32	0.13	0.78	0.78	0.78	0.82
$J(x^*_m)$	$SIL_{p=2}$	0.08	0.90	0.31	0.27	0.00	0.25	0.15	0.06	0.78	0.82	0.80	0.78
	$SIL_{d=1}$	0.11	0.04	0.99	0.19	0.09	0.31	0.17	0.16	0.80	0.81	0.82	0.78
	$SIL_{d=2}$	0.09	0.00	0.21	0.99	0.17	0.06	0.37	0.15	0.81	0.78	0.87	0.79
	$SIL_{r=1}$	0.19	0.08	0.29	0.33	1.00	0.25	0.12	0.08	0.80	0.86	0.81	0.78
	$SIL_{r=2}$	0.00	0.05	0.17	0.11	0.45	1.00	0.25	0.17	0.78	0.78	0.80	0.82
	$SIL_{r=3}$	0.00	0.00	0.34	0.21	0.00	0.18	1.00	0.00	0.83	0.81	0.86	0.81
	$SIL_{r=4}$	0.00	0.14	0.28	0.31	0.45	0.35	0.23	1.00	0.83	0.83	0.85	0.78
	$CSL_{r=1}$	0.19	0.00	0.33	0.23	0.42	0.42	0.08	0.29	1.00	0.79	0.80	0.82
	$CSL_{r=2}$	0.00	0.16	0.31	0.25	0.07	0.18	0.50	0.28	0.78	1.00	0.84	0.88
	$CSL_{r=3}$	0.10	0.11	0.21	0.29	0.27	0.21	0.24	0.37	0.80	0.78	1.00	0.79
	$CSL_{r=4}$	0.10	0.00	0.25	0.40	0.29	0.09	0.15	0.42	0.78	0.78	0.78	1.00

表 **5.6** 訂定模糊目標隸屬度函數所需的參數

m	J_m	$\underline{J_m^0}$	J_m^0	J_m^1	$\overline{J_m^1}$
1	$\mathrm{Z}_{p=1}$	$-1,437,784$	$905,009$	$4,849,095$	$4,849,095$
2	$\mathrm{Z}_{p=2}$	$-1,297,977$	$833,513$	$5,620,679$	$5,620,679$
3	$\mathrm{Z}_{d=1}$	$-3,936,082$	$133,739$	$3,985,165$	$3,985,165$
4	$\mathrm{Z}_{d=2}$	$-3,868,513$	$617,668$	$4,527,048$	$4,527,048$
5	$\mathrm{Z}_{r=1}$	$-2,664,441$	$209,691$	$1,589,110$	$1,589,110$
6	$\mathrm{Z}_{r=2}$	$-2,557,497$	$218,340$	$1,243,161$	$1,243,161$
7	$\mathrm{Z}_{r=3}$	$-2,503,984$	$172,273$	$1,149,759$	$1,149,759$
8	$\mathrm{Z}_{r=4}$	$-2,172,127$	$131,355$	$1,536,114$	$1,536,114$
9	$\mathrm{SIL}_{p=1}$	0.00	0.00	0.82	0.82
10	$\mathrm{SIL}_{p=2}$	0.00	0.00	0.90	0.90
11	$\mathrm{SIL}_{d=1}$	0.00	0.00	0.99	0.99
12	$\mathrm{SIL}_{d=2}$	0.00	0.11	0.99	0.99
13	$\mathrm{SIL}_{r=1}$	0.00	0.00	1.00	1.00
14	$\mathrm{SIL}_{r=2}$	0.00	0.00	1.00	1.00
15	$\mathrm{SIL}_{r=3}$	0.00	0.00	1.00	1.00
16	$\mathrm{SIL}_{r=4}$	0.00	0.00	1.00	1.00
17	$\mathrm{CSL}_{r=1}$	0.78	0.78	1.00	1.00
18	$\mathrm{CSL}_{r=2}$	0.78	0.78	1.00	1.00
19	$\mathrm{CSL}_{r=3}$	0.78	0.78	1.00	1.00
20	$\mathrm{CSL}_{r=4}$	0.78	0.78	1.00	1.00

將使用單一階段與兩階段運算法求解的結果整理如表 5.7 所示，其中列出了各成員收益、安全存貨水準、以及顧客服務水準等目標函數值與其隸屬度函數值。此外，為了方便比較，可以對照圖 5.4 。從結果可以看出選擇 min 運算子時，可以讓滿意度較低的隸屬度函數盡量獲得提升，進而得到較為平均的隸屬度函數分佈。整體而言，各目標的隸屬度函數值都約略在 0.45 附近。但是， min 運算子不具嚴格單調的特性，會有非唯一局部最適解的情形發生。選擇算數平均運算子時，雖其具有嚴格單調的性質，可以求得唯一最適解，但容易造成隸屬度函數值分佈不均的情形。如工廠 $p = 2$ 與配銷中心 $d = 1$ 和 $d = 2$ 的收益，以及配銷中心 $d = 1$ 和 $d = 2$ 的安全存貨水準，都偏低，而零售商的收益則偏高。這樣的結果，與想要求得目標間相互妥協解的本意有所衝突。而使用兩階段模糊最適化法，則可以在具備最低滿意度 0.45 的保證下，得到令人滿意的妥協解。

表 5.8 和表 5.9 為買方與賣方對產品售價滿意度。與供應鏈內部相關的售價，有時落於有利於買方的位置，有時則落於有利於賣方的位置，此乃成員間平均分配收益所導致的結果。而零售商售予顧客的售價則皆落於對賣方有利的位置，此乃是整體的供應鏈要獲取最大利益之必然結果。但是，若顧客的滿意度太低，則會有流失市場之虞，因此維持適當的顧客滿意度必要的。而兩階段模糊最適化法，顯然可以提供最低滿意度的保證。

表 5.10 列出工廠的製造排程。值得注意的是，工廠的製造排程與前一章例子之結果是相同的。也就是說，產品的售價變化並不會影響工廠的製造排程。 圖 5.5 和圖 5.6 為零售商的存貨與缺貨量，以及顧客需求量。 圖 5.7 為工廠與配銷中心的存貨量，而圖 5.8 則為零售商的存貨量。 圖 5.9 至圖 5.11 呈現產品單位售價與銷售量的關係。由圖中可以觀察到，為了節省購買成本，買方會盡量選擇較大的經濟批量採購方式，以壓低產品的單位售價。 圖 5.12 為工廠對配銷中心的產品運送規劃，而 圖 5.13 和圖 5.14 則為配銷中心對零售商的產品運送規劃。為了節省運送成本，出貨端會盡量選擇較大的經濟批量運送方式。

表 **5.7** 模式求解的結果

目標		min		算數平均運算子		兩階段法	
		目標值	滿意度	目標值	滿意度	目標值	滿意度
收益	$p=1$	$2,664,071$	0.45	$2,890,304$	0.50	$2,749,585$	0.47
	$p=2$	$2,968,589$	0.45	$2,543,579$	0.36	$2,968,589$	0.45
	$d=1$	$1,851,475$	0.45	$1,725,350$	0.41	$1,851,475$	0.45
	$d=2$	$2,361,251$	0.45	$1,920,544$	0.33	$2,361,251$	0.45
	$r=1$	$824,912$	0.45	$1,084,524$	0.63	$824,912$	0.45
	$r=2$	$675,410$	0.45	$917,038$	0.68	$702,890$	0.47
	$r=3$	$608,232$	0.45	$819,040$	0.66	$624,698$	0.46
	$r=4$	$812,220$	0.48	$1,015,641$	0.63	$898,116$	0.55
安全存貨水準	$p=1$	0.39	0.48	0.43	0.52	0.47	0.57
	$p=2$	0.40	0.45	0.49	0.54	0.40	0.45
	$d=1$	0.44	0.45	0.35	0.35	0.44	0.45
	$d=2$	0.50	0.45	0.40	0.33	0.50	0.45
	$r=1$	0.45	0.45	0.57	0.57	0.47	0.47
	$r=2$	0.49	0.49	0.71	0.71	0.52	0.52
	$r=3$	0.45	0.45	0.71	0.71	0.56	0.56
	$r=4$	0.46	0.46	0.66	0.66	0.62	0.62
顧客服務水準	$r=1$	0.88	0.45	1.00	1.00	0.94	0.74
	$r=2$	0.88	0.45	1.00	1.00	0.96	0.83
	$r=3$	0.88	0.45	1.00	1.00	0.99	0.96
	$r=4$	0.89	0.48	0.98	0.92	1.00	1.00

圖 **5.4** 單一階段與兩階段運算法之比較

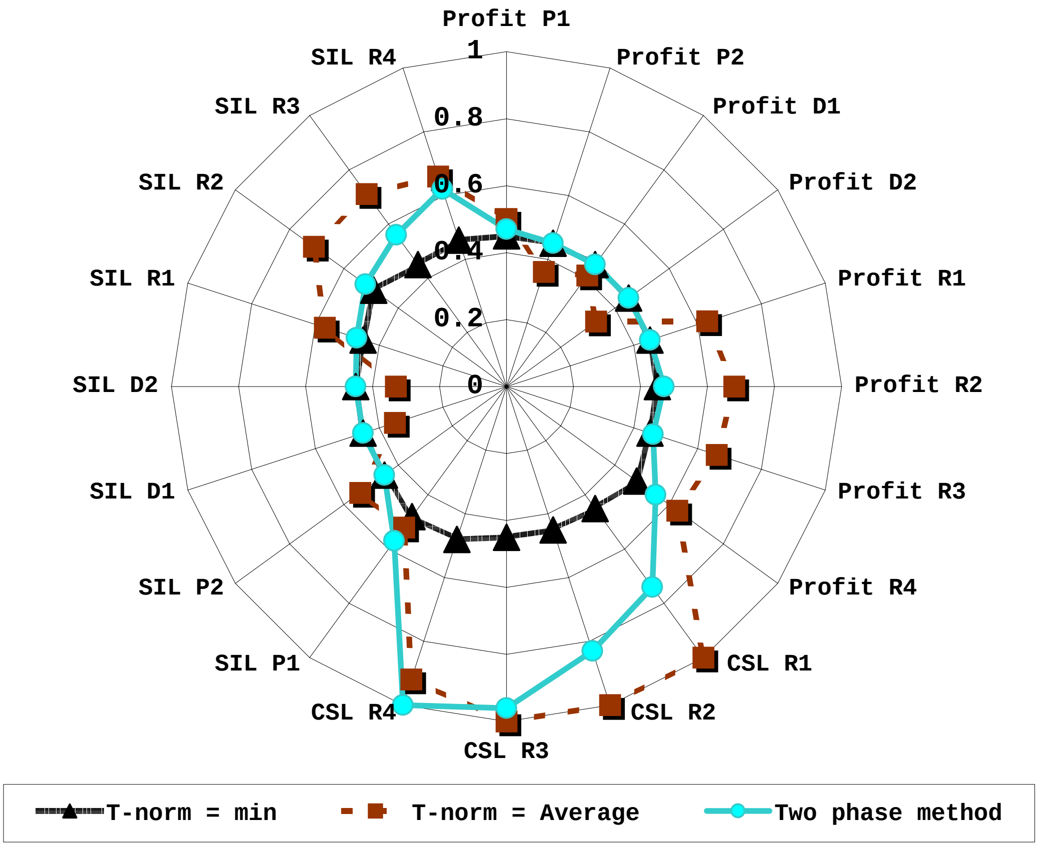


表 **5.8** 買方與賣方對產品售價滿意度

	$i\ p\ d\ r\ t$	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$		$i\ p\ d\ r\ t$	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$		$i\ p\ d\ r\ t$	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$
	1 1 1 1	1.00	0.47		1 1 1 1	1.00	0.59		2 2 1 1	0.99	0.45
	1 1 1 2	1.00	0.47		1 1 1 2	1.00	0.59		2 2 1 2	0.99	0.45
	1 1 1 3	0.53	1.00		1 1 1 3	1.00	0.59		2 2 1 3	0.99	0.45
	1 1 1 4	0.53	1.00		1 1 1 4	1.00	0.59		2 2 1 4	0.99	0.45
	1 1 2 1	1.00	0.46		1 1 2 1	0.57	1.00		2 2 2 1	0.45	0.9
	1 1 2 2	1.00	0.46		1 1 2 2	0.57	1.00		2 2 2 2	1.00	0.46
	1 1 2 3	1.00	0.46		1 1 2 3	0.57	1.00		2 2 2 3	1.00	0.46
	1 1 2 4	1.00	0.46		1 1 2 4	0.57	1.00		2 2 2 4	1.00	0.46
	1 2 1 1	0.45	0.95		1 1 3 1	1.00	0.53		2 2 3 1	0.48	1.00
	1 2 1 2	0.45	0.95		1 1 3 2	1.00	0.53		2 2 3 2	0.48	1.00
	1 2 1 3	0.45	0.95		1 1 3 3	1.00	0.53		2 2 3 3	0.48	1.00
	1 2 1 4	0.45	0.95		1 1 3 4	1.00	0.53		2 2 3 4	0.48	1.00
	1 2 2 1	0.91	0.67		1 1 4 1	0.47	1.00		2 2 4 1	0.53	1.00
	1 2 2 2	1.00	0.61		1 1 4 2	0.47	1.00		2 2 4 2	0.53	1.00
	1 2 2 3	0.45	1.00		1 1 4 3	0.47	1.00		2 2 4 3	0.53	1.00
	1 2 2 4	1.00	0.61		1 1 4 4	0.47	1.00		2 2 4 4	0.53	1.00
	2 1 1 1	1.00	0.47		1 2 1 1	0.99	0.45		3 1 1 1	1.00	0.59
	2 1 1 2	0.53	1.00		1 2 1 2	0.99	0.45		3 1 1 2	1.00	0.59
	2 1 1 3	0.53	1.00		1 2 1 3	0.99	0.45		3 1 1 3	1.00	0.59
	2 1 1 4	0.53	1.00		1 2 1 4	0.99	0.45		3 1 1 4	1.00	0.59
	2 1 2 1	1.00	0.46		1 2 2 1	1.00	0.46		3 1 2 1	0.57	1.00
	2 1 2 2	1.00	0.46		1 2 2 2	1.00	0.46		3 1 2 2	0.57	1.00
	2 1 2 3	1.00	0.46		1 2 2 3	1.00	0.46		3 1 2 3	0.57	1.00
USP^{i}_{pdt}	2 1 2 4	1.00	0.46	USP^{i}_{drt}	1 2 2 4	1.00	0.46	USP^{i}_{drt}	3 1 2 4	0.57	1.00
	2 2 1 1	0.45	0.95		1 2 3 1	0.48	1.00		3 1 3 1	1.00	0.53
	2 2 1 2	0.45	0.95		1 2 3 2	0.48	1.00		3 1 3 2	1.00	0.53
	2 2 1 3	0.45	0.95		1 2 3 3	0.48	1.00		3 1 3 3	1.00	0.53
	2 2 1 4	0.45	0.95		1 2 3 4	0.48	1.00		3 1 3 4	1.00	0.53
	2 2 2 1	0.45	1.00		1 2 4 1	0.53	1.00		3 1 4 1	0.47	1.00
	2 2 2 2	0.45	1.00		1 2 4 2	0.53	1.00		3 1 4 2	0.47	1.00
	2 2 2 3	1.00	0.61		1 2 4 3	0.53	1.00		3 1 4 3	0.47	1.00
	2 2 2 4	1.00	0.61		1 2 4 4	0.53	1.00		3 1 4 4	0.47	1.00
	3 1 1 1	1.00	0.47		2 1 1 1	1.00	0.59		3 2 1 1	0.99	0.45
	3 1 1 2	0.53	1.00		2 1 1 2	1.00	0.59		3 2 1 2	0.99	0.45
	3 1 1 3	1.00	0.47		2 1 1 3	1.00	0.59		3 2 1 3	0.99	0.45
	3 1 1 4	1.00	0.47		2 1 1 4	1.00	0.59		3 2 1 4	0.99	0.45
	3 1 2 1	1.00	0.46		2 1 2 1	0.57	1.00		3 2 2 1	1.00	0.46
	3 1 2 2	1.00	0.46		2 1 2 2	0.57	1.00		3 2 2 2	1.00	0.46
	3 1 2 3	1.00	0.46		2 1 2 3	0.57	1.00		3 2 2 3	1.00	0.46
	3 1 2 4	1.00	0.46		2 1 2 4	0.57	1.00		3 2 2 4	1.00	0.46
	3 2 1 1	0.45	0.95		2 1 3 1	1.00	0.53		3 2 3 1	0.48	1.00
	3 2 1 2	0.45	0.95		2 1 3 2	1.00	0.53		3 2 3 2	0.48	1.00
	3 2 1 3	0.45	0.95		2 1 3 3	1.00	0.53		3 2 3 3	0.48	1.00
	3 2 1 4	0.45	0.95		2 1 3 4	1.00	0.53		3 2 3 4	0.48	1.00
	3 2 2 1	0.45	1.00		2 1 4 1	0.47	1.00		3 2 4 1	0.53	1.00
	3 2 2 2	1.00	0.61		2 1 4 2	0.47	1.00		3 2 4 2	0.53	1.00
	3 2 2 3	1.00	0.61		2 1 4 3	0.47	1.00		3 2 4 3	0.53	1.00
	3 2 2 4	1.00	0.61		2 1 4 4	0.47	1.00		3 2 4 4	0.53	1.00

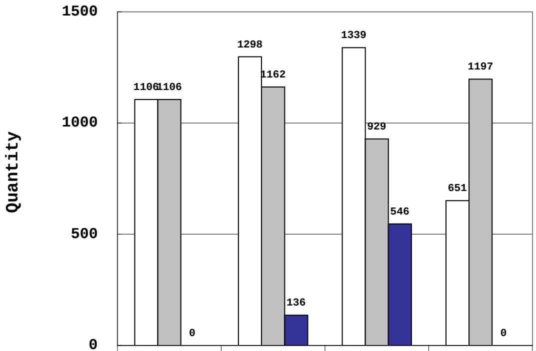
表 **5.9** 買方與賣方對產品售價滿意度

	i	r	USP	$\mu_{\mathcal{BP}^i_{rc}}$	$\mu_{\mathcal{SP}^i_{rc}}$
USP^i_{rc}	1	1	344	0.57	1.00
	1	2	329	0.45	0.77
	1	3	335	0.53	1.00
	1	4	341	0.48	1.00
	2	1	577	0.53	1.00
	2	2	546	0.57	1.00
	2	3	559	0.48	1.00
	2	4	573	0.45	0.90
	3	1	898	0.48	1.00
	3	2	866	0.53	1.00
	3	3	874	0.57	1.00
	3	4	895	0.45	0.90

表 **5.10** 工廠製造排程

$p =$		1				2			
$t =$		1	2	3	4	1	2	3	4
	i								
α^i_{pt}	1	1	0	0	0	0	1	0	0
	2	0	0	0	0	1	0	0	0
	3	0	1	1	0	0	0	0	0
β^i_{pt}	1	1	0	0	0	0	1	1	1
	2	0	0	0	0	1	0	0	0
	3	0	1	1	1	0	0	0	0
γ^i_{pt}	1	0	0	0	0	0	1	0	0
	2	0	0	0	0	0	0	0	0
	3	0	1	0	0	0	0	0	0
o^i_{pt}	1	0	0	0	0	0	0	0	0
	2	0	0	0	0	1	0	0	0
	3	0	0	0	0	0	0	0	0

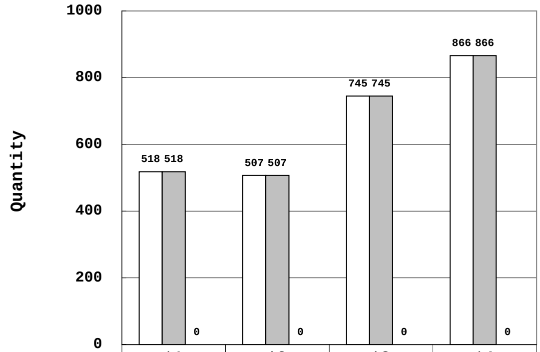
圖 **5.5** 產品需求量、銷售量與缺貨量。



	t1	t2	t3	t4
Demand	1106	1298	1339	651
Sales	1106	1162	929	1197
Backlogs	0	136	546	0

Time

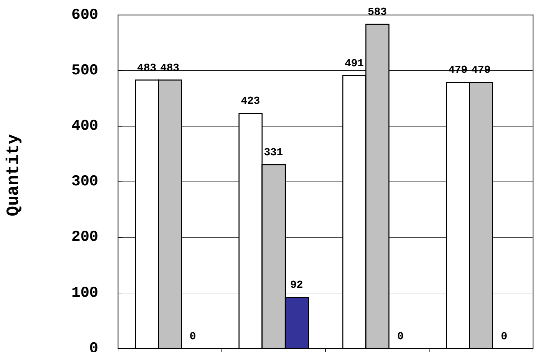
零售商 $r = 1$ 產品 $i = 1$



	t1	t2	t3	t4
Demand	518	507	745	866
Sales	518	507	745	866
Backlogs	0	0	0	0

Time

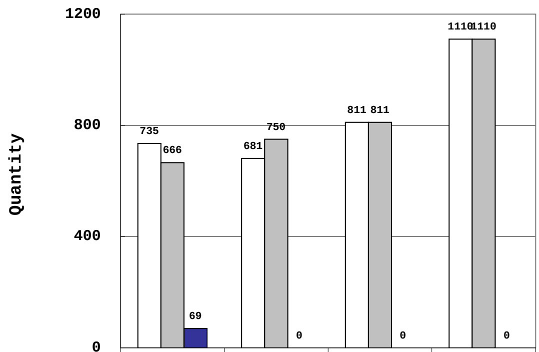
零售商 $r = 1$ 產品 $i = 2$



	t1	t2	t3	t4
Demand	483	423	491	479
Sales	483	331	583	479
Backlogs	0	92	0	0

Time

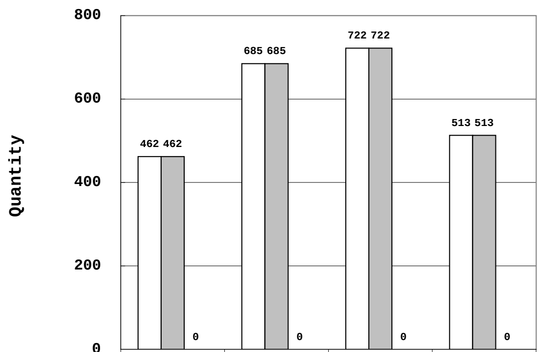
零售商 $r = 1$ 產品 $i = 3$



	t1	t2	t3	t4
Demand	735	681	811	1110
Sales	666	750	811	1110
Backlogs	69	0	0	0

Time

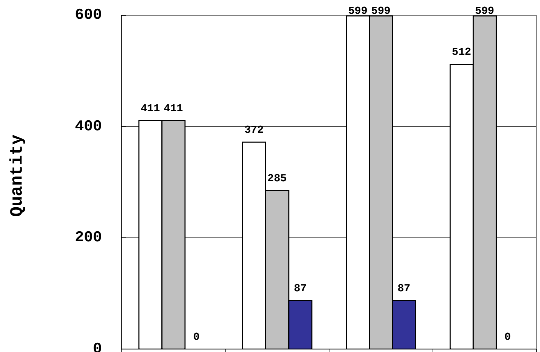
零售商 $r = 2$ 產品 $i = 1$



	t1	t2	t3	t4
Demand	462	685	722	513
Sales	462	685	722	513
Backlogs	0	0	0	0

Time

零售商 $r = 2$ 產品 $i = 2$

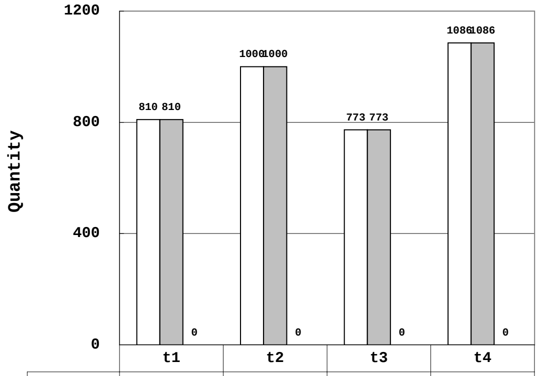


	t1	t2	t3	t4
Demand	411	372	599	512
Sales	411	285	599	599
Backlogs	0	87	87	0

Time

零售商 $r = 2$ 產品 $i = 3$

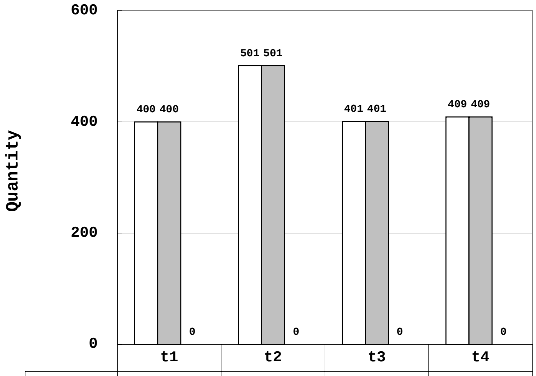
圖 5.6 產品需求量、銷售量與缺貨量。



	t1	t2	t3	t4
□Demand	810	1000	773	1086
■Sales	810	1000	773	1086
■Backlogs	0	0	0	0

Time

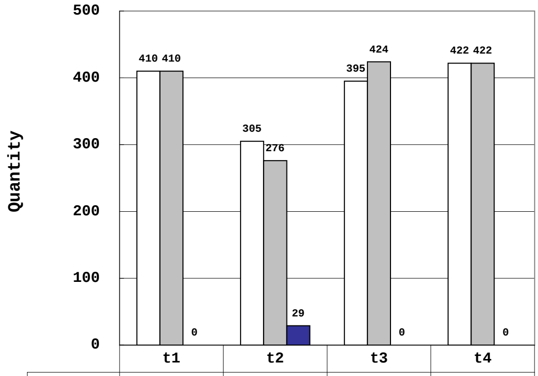
零售商 $r = 3$ 產品 $i = 1$



	t1	t2	t3	t4
□Demand	400	501	401	409
■Sales	400	501	401	409
■Backlogs	0	0	0	0

Time

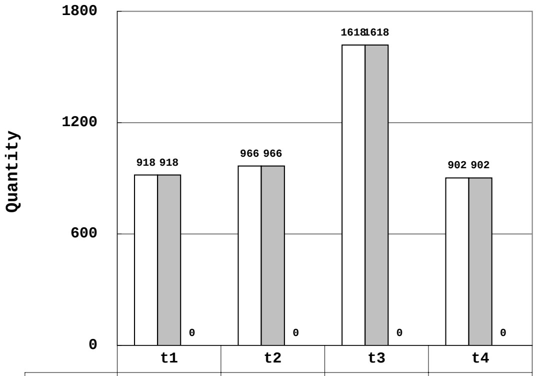
零售商 $r = 3$ 產品 $i = 2$



	t1	t2	t3	t4
□Demand	410	305	395	422
■Sales	410	276	424	422
■Backlogs	0	29	0	0

Time

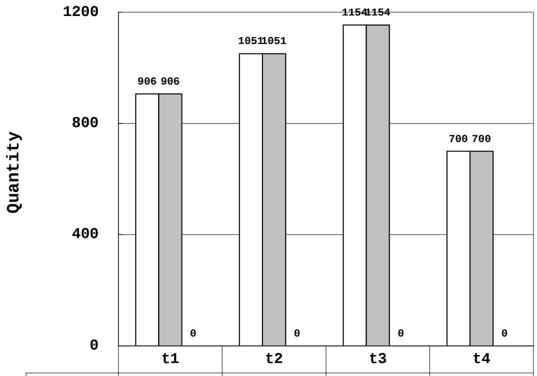
零售商 $r = 3$ 產品 $i = 3$



	t1	t2	t3	t4
□Demand	918	966	1618	902
■Sales	918	966	1618	902
■Backlogs	0	0	0	0

Time

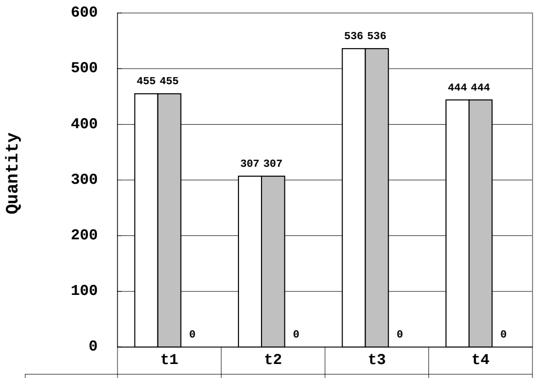
零售商 $r = 4$ 產品 $i = 1$



	t1	t2	t3	t4
□Demand	906	1051	1154	700
■Sales	906	1051	1154	700
■Backlogs	0	0	0	0

Time

零售商 $r = 4$ 產品 $i = 2$

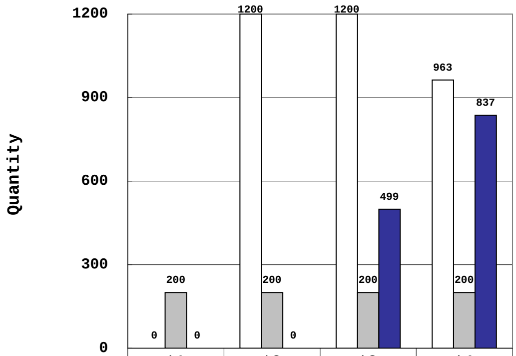


	t1	t2	t3	t4
□Demand	455	307	536	444
■Sales	455	307	536	444
■Backlogs	0	0	0	0

Time

零售商 $r = 4$ 產品 $i = 3$

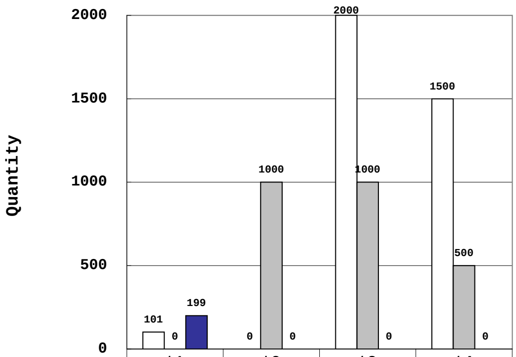
圖 **5.7** 工廠與配銷中心產品存貨量。



	t1	t2	t3	t4
Product 1	0	1200	1200	963
Product 2	200	200	200	200
Product 3	0	0	499	837

Time

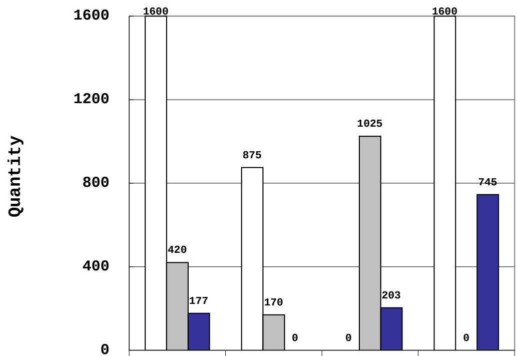
工廠 $p = 1$



	t1	t2	t3	t4
Product 1	101	0	2000	1500
Product 2	0	1000	1000	500
Product 3	199	0	0	0

Time

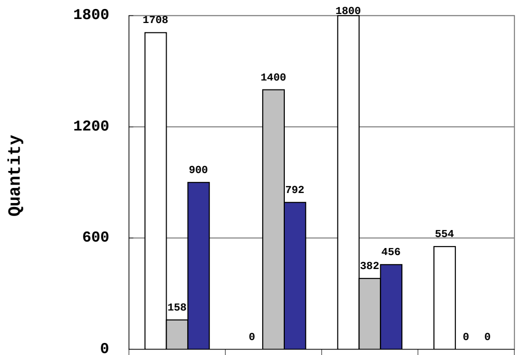
工廠 $p = 2$



	t1	t2	t3	t4
Product 1	1600	875	0	1600
Product 2	420	170	1025	0
Product 3	177	0	203	745

Time

配銷中心 $d = 1$

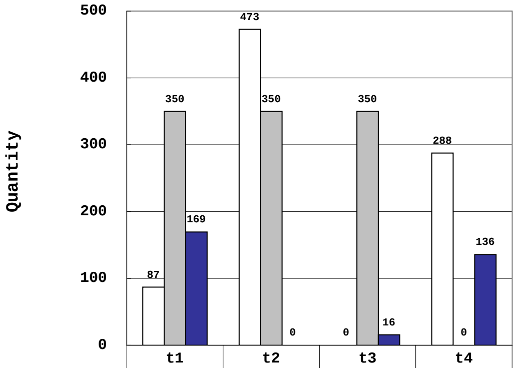


	t1	t2	t3	t4
Product 1	1708	0	1800	554
Product 2	158	1400	382	0
Product 3	900	792	456	0

Time

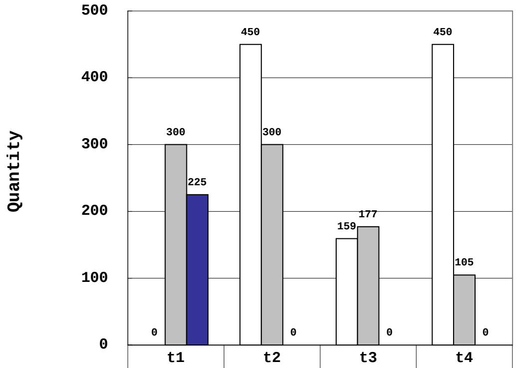
配銷中心 $d = 2$

圖 5.8 零售商產品存貨量。



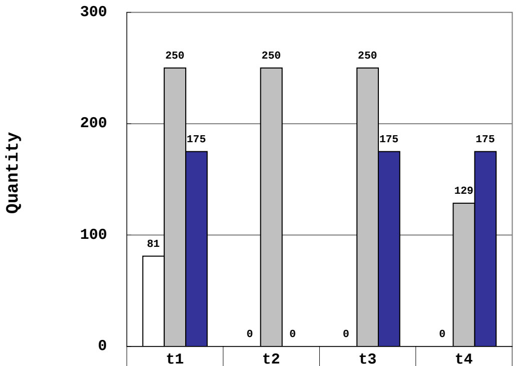
Time	t1	t2	t3	t4
Product 1	87	473	0	288
Product 2	350	350	350	0
Product 3	169	0	16	136

零售商 $r = 1$



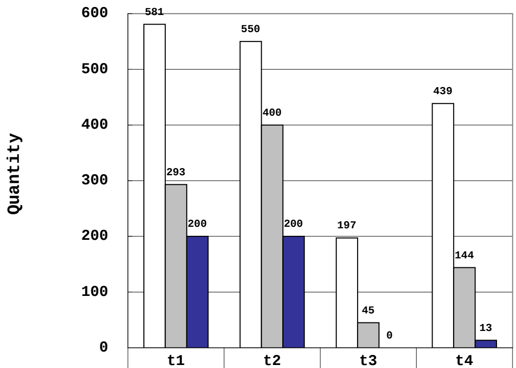
Time	t1	t2	t3	t4
Product 1	0	450	159	450
Product 2	300	300	177	105
Product 3	225	0	0	0

零售商 $r = 2$



Time	t1	t2	t3	t4
Product 1	81	0	0	0
Product 2	250	250	250	129
Product 3	175	0	175	175

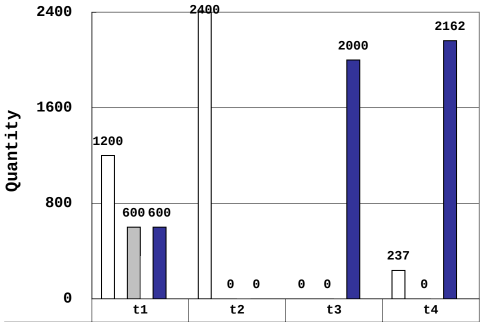
零售商 $r = 3$



Time	t1	t2	t3	t4
Product 1	581	550	197	439
Product 2	293	400	45	144
Product 3	200	200	0	13

零售商 $r = 4$

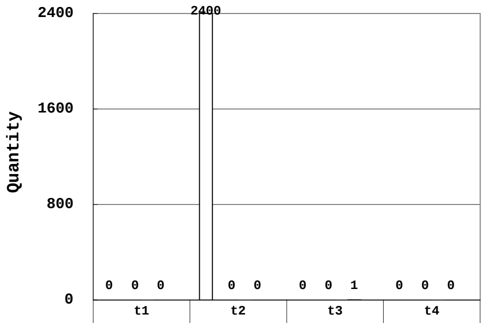
圖 **5.9** 產品單位售價與銷售量。



	t1	t2	t3	t4
Product 1	1200	2400	0	237
USP	199	192	213	213
Product 2	600	0	0	0
USP	357	368	368	368
Product 3	600	0	2000	2162
USP	594	614	534	534

Time

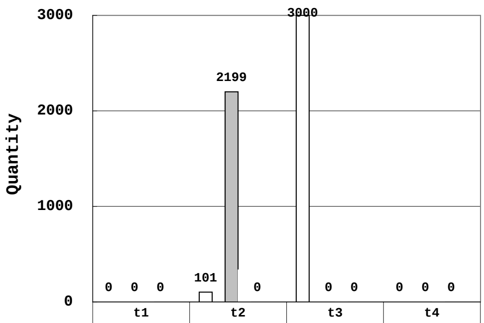
工廠 $p = 1$ 對配銷中心 $d = 1$



	t1	t2	t3	t4
Product 1	0	2400	0	0
USP	212	198	212	212
Product 2	0	0	0	0
USP	371	371	371	371
Product 3	0	0	1	0
USP	607	607	607	607

Time

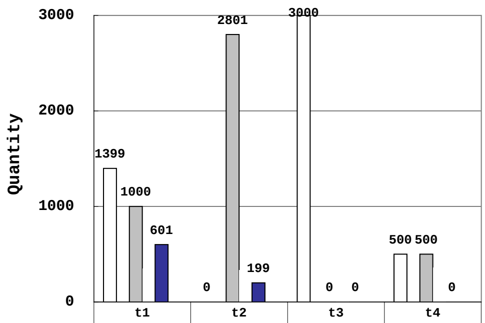
工廠 $p = 1$ 對配銷中心 $d = 2$



	t1	t2	t3	t4
Product 1	0	101	3000	0
USP	215	215	194	215
Product 2	0	2199	0	0
USP	374	338	374	374
Product 3	0	0	0	0
USP	617	617	617	617

Time

工廠 $p = 2$ 對配銷中心 $d = 1$

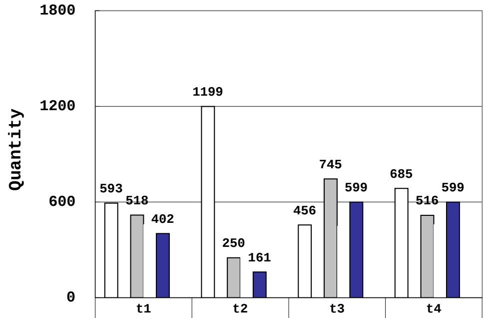


	t1	t2	t3	t4
Product 1	1399	0	3000	500
USP	197	207	190	207
Product 2	1000	2801	0	500
USP	351	331	358	358
Product 3	601	199	0	0
USP	616	593	593	593

Time

工廠 $p = 2$ 對配銷中心 $d = 2$

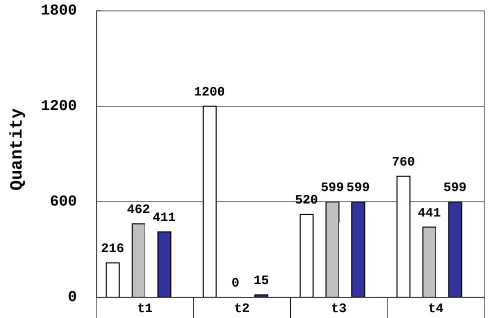
圖 **5.10** 產品單位售價與銷售量。



	t1	t2	t3	t4
Product 1	593	1199	456	685
USP	267	260	267	260
Product 2	518	250	745	516
USP	460	460	449	460
Product 3	402	161	599	599
USP	748	748	748	748

Time

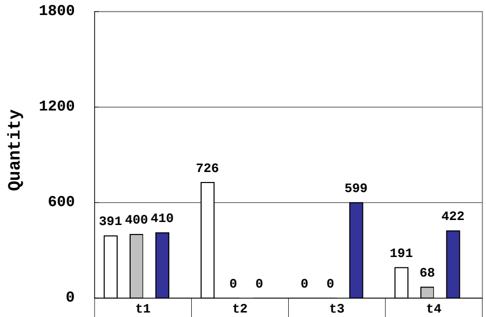
配銷中心 $d = 1$ 對零售商 $r = 1$



	t1	t2	t3	t4
Product 1	216	1200	520	760
USP	274	260	274	267
Product 2	462	0	599	441
USP	468	468	468	468
Product 3	411	15	599	599
USP	757	757	757	757

Time

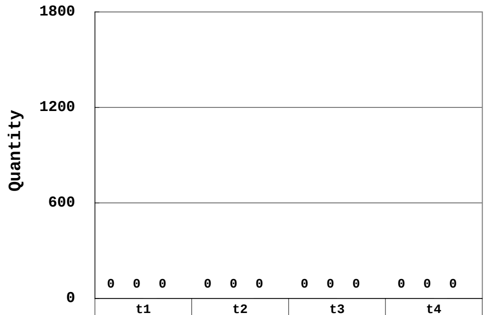
配銷中心 $d = 1$ 對零售商 $r = 2$



	t1	t2	t3	t4
Product 1	391	726	0	191
USP	275	269	275	275
Product 2	400	0	0	68
USP	468	468	468	468
Product 3	410	0	599	422
USP	754	754	754	754

Time

配銷中心 $d = 1$ 對零售商 $r = 3$

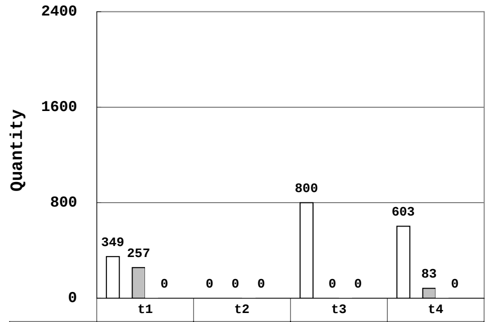


	t1	t2	t3	t4
Product 1	0	0	0	0
USP	288	288	288	288
Product 2	0	0	0	0
USP	482	482	482	482
Product 3	0	0	0	0
USP	771	771	771	771

Time

配銷中心 $d = 1$ 對零售商 $r = 4$

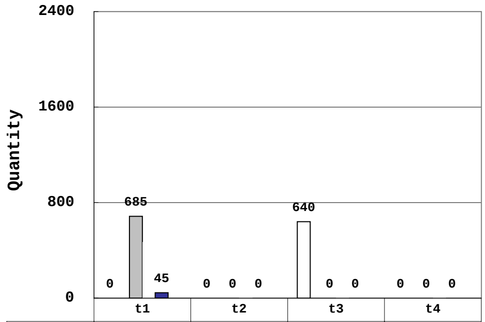
圖 **5.11** 產品單位售價與銷售量。



	t1	t2	t3	t4
Product 1	349	0	800	603
USP	277	277	270	277
Product 2	257	0	0	83
USP	469	469	469	469
Product 3	0	0	0	0
USP	752	752	752	752

Time

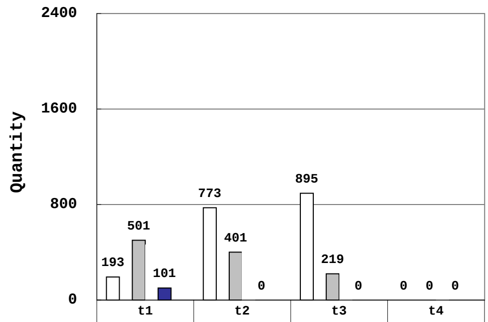
配銷中心 $d = 2$ 對零售商 $r = 1$



	t1	t2	t3	t4
Product 1	0	0	640	0
USP	268	268	268	268
Product 2	685	0	0	0
USP	470	461	461	461
Product 3	45	0	0	0
USP	742	742	742	742

Time

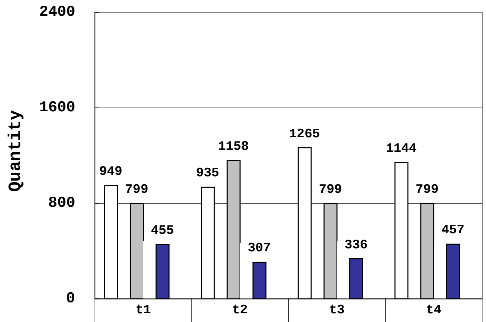
配銷中心 $d = 2$ 對零售商 $r = 2$



	t1	t2	t3	t4
Product 1	193	773	895	0
USP	269	269	260	269
Product 2	501	401	219	0
USP	463	463	463	463
Product 3	101	0	0	0
USP	752	752	752	752

Time

配銷中心 $d = 2$ 對零售商 $r = 3$

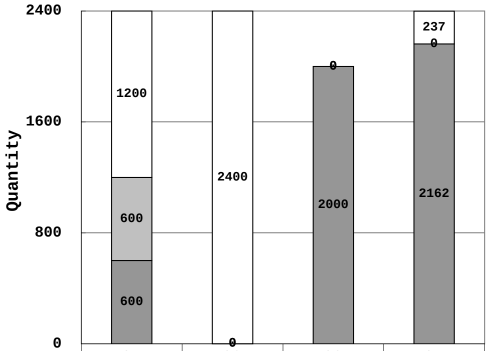


	t1	t2	t3	t4
Product 1	949	935	1265	1144
USP	279	279	279	279
Product 2	799	1158	799	799
USP	481	469	481	481
Product 3	455	307	336	457
USP	769	769	769	769

Time

配銷中心 $d = 2$ 對零售商 $r = 4$

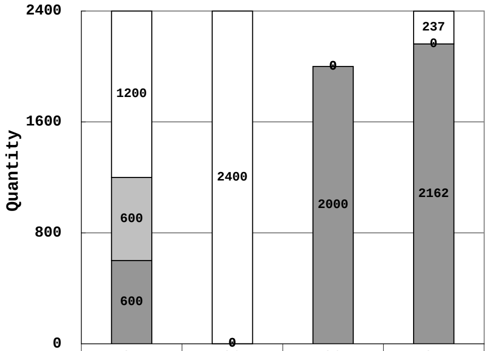
圖 **5.12** 工廠對配銷中心的產品運送規劃。



	t1	t2	t3	t4
Product 1	1200	2400	0	237
Product 2	600	0	0	0
Product 3	600	0	2000	2162

Time

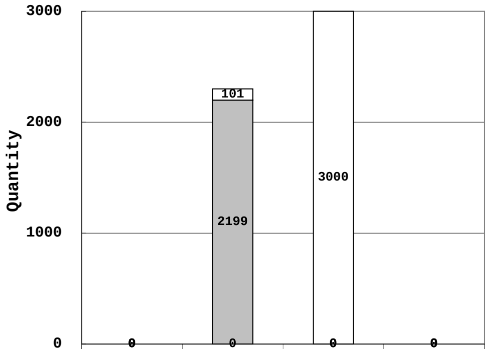
工廠 $p = 1$ 對配銷中心 $d = 1$



	t1	t2	t3	t4
Product 1	1200	2400	0	237
Product 2	600	0	0	0
Product 3	600	0	2000	2162

Time

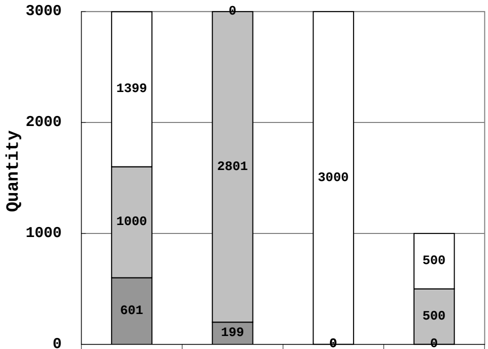
工廠 $p = 1$ 對配銷中心 $d = 2$



	t1	t2	t3	t4
Product 1	0	101	3000	0
Product 2	0	2199	0	0
Product 3	0	0	0	0

Time

工廠 $p = 2$ 對配銷中心 $d = 1$

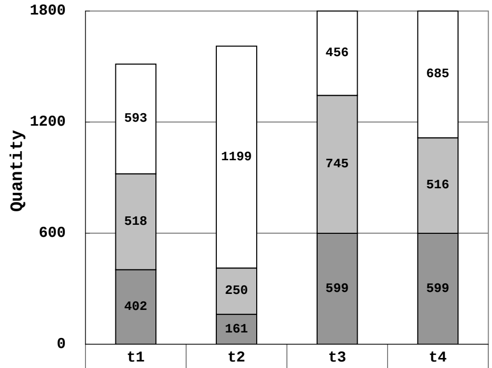


	t1	t2	t3	t4
Product 1	1399	0	3000	500
Product 2	1000	2801	0	500
Product 3	601	199	0	0

Time

工廠 $p = 2$ 對配銷中心 $d = 2$

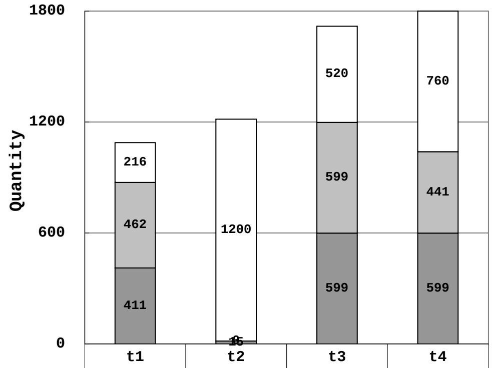
圖 5.13 配銷中心 $d = 1$ 對零售商的產品運送規劃。



	t1	t2	t3	t4
□Product 1	593	1199	456	685
▩Product 2	518	250	745	516
■Product 3	402	161	599	599

Time

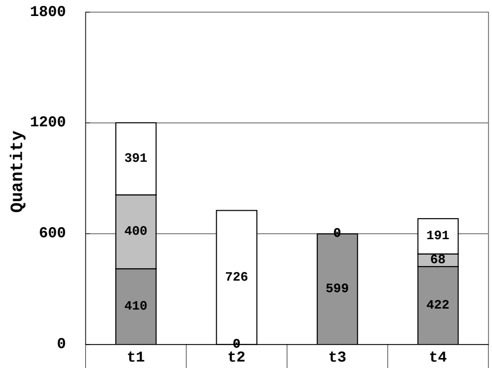
配銷中心 $d = 1$ 對零售商 $r = 1$



	t1	t2	t3	t4
□Product 1	216	1200	520	760
▩Product 2	462	0	599	441
■Product 3	411	15	599	599

Time

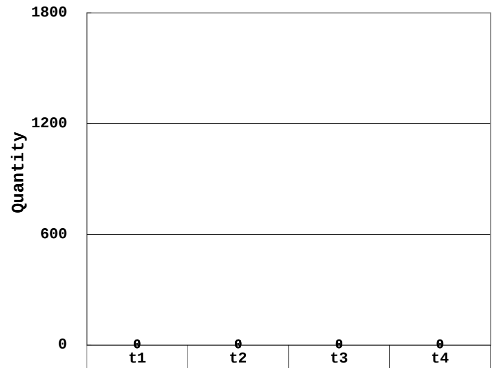
配銷中心 $d = 1$ 對零售商 $r = 2$



	t1	t2	t3	t4
□Product 1	391	726	0	191
▩Product 2	400	0	0	68
■Product 3	410	0	599	422

Time

配銷中心 $d = 1$ 對零售商 $r = 3$

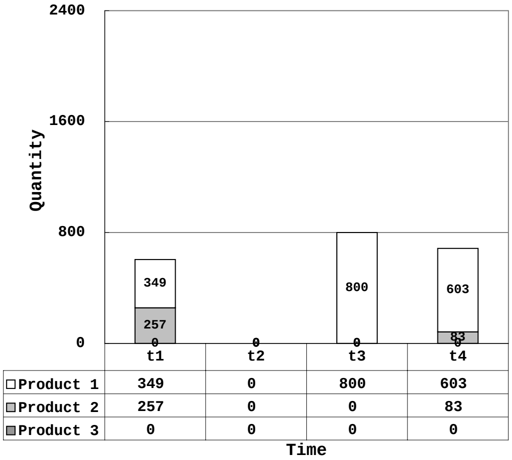


	t1	t2	t3	t4
□Product 1	0	0	0	0
▩Product 2	0	0	0	0
■Product 3	0	0	0	0

Time

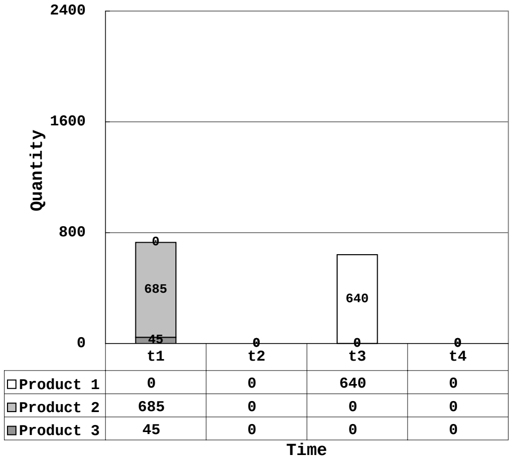
配銷中心 $d = 1$ 對零售商 $r = 4$

圖 **5.14** 配銷中心 $d = 2$ 對零售商的產品運送規劃。



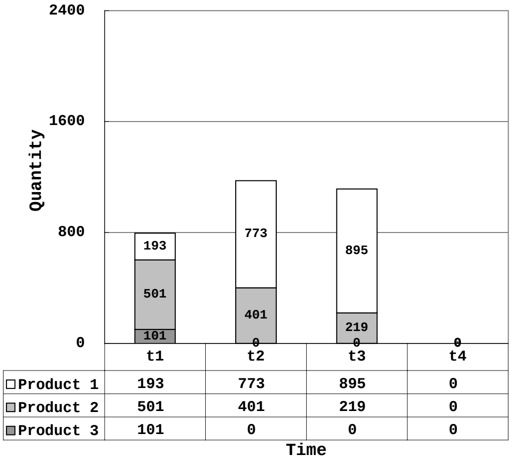
	t1	t2	t3	t4
Product 1	349	0	800	603
Product 2	257	0	0	83
Product 3	0	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 1$



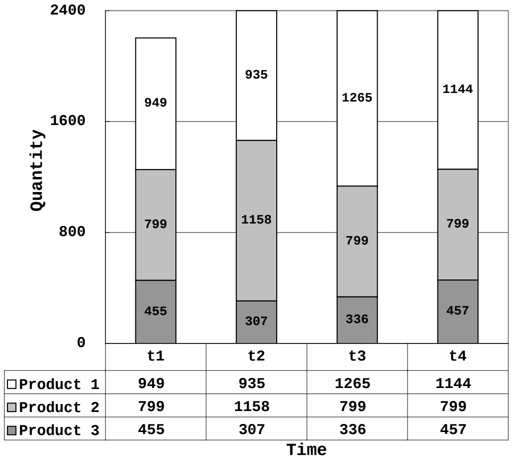
	t1	t2	t3	t4
Product 1	0	0	640	0
Product 2	685	0	0	0
Product 3	45	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 2$



	t1	t2	t3	t4
Product 1	193	773	895	0
Product 2	501	401	219	0
Product 3	101	0	0	0

配銷中心 $d = 2$ 對零售商 $r = 3$



	t1	t2	t3	t4
Product 1	949	935	1265	1144
Product 2	799	1158	799	799
Product 3	455	307	336	457

配銷中心 $d = 2$ 對零售商 $r = 4$

6

在產品需求與價格不確定下之供應鏈網路最適化

6.1 產品需求不確定

在今日競爭激烈的商業環境中，由於生產技術進步，使得產品的生命週期被快速壓縮，再加上消費者意識高漲、家庭成員數減少，消費者所重視的是「少量多樣性」的商品。不僅產品推陳出新的腳步加快，消費者的需求更是時有改變，產品需求在短期內的變化已不容忽視，所以在作供應鏈網路生產與配送規劃時，必須將其納入考量。要將不確定參數加入供應鏈模式中，最重要的步驟就是決定不確定參數的表現方式 (Gupta and Maranas, 2003 [25])。經常被採用的描述方式共有三種：

1. 以機率分佈為基礎 (distribution-based) 的方法：以常態分佈和相關平均值與標準差來描述不確定參數。

2. 以模糊理論為基礎 (fuzzy-based) 的方法：使用模糊數和相關隸屬度函數來描述不確定參數。

3. 以情境為基礎 (scenario-based) 的方法：運用數個情境 (scenarios) 和相關發生機率來描述不確定參數。

本研究選擇以情境為基礎之方法來描述不確定的產品需求。這個方法的首要步驟是：決定可能發生的情境和相關的發生機率，$\mathrm{PPD}_s, s \in \mathcal{S}$，其中 $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s = 1$。然後，所有變數都會變成與情境有關，而變數的期望值就成為各情境相關值的權重平均。也就是說，對於變數 v，必須先解出其在各情境下的值 $v_s, s \in \mathcal{S}$，而 v 的期望值就等於 $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s v_s$。由於變數會增加，成為原定量 (deterministic) 模式的 S 倍，因此為了簡化問題，將暫時不考慮經濟批量銷售，所以產品售價便與銷售量無關。在產品需求與價格不確定下之供應鏈網路模式將詳述如下。

6.2 模式之符號、系統參數與系統變數

6.2.1 符號說明

與2.3.1節相較，除了去除與可選擇之經濟批量銷售方式有關的 ℓ' 與 ℓ 外，需增加下列的符號。

符號	集合	總數	物理意義
$s \in$	$\mathcal{S}$	$[\mathcal{S}] = S$	s 為情境編號；$\mathcal{S}$ 為情境集合；S 為情境總數。

6.2.2 系統參數

與2.3.2節相較，除了去除與經濟批量銷售方式有關的參數 SQL 外，只有下列三個參數有所不同。

參數	$* \in$	物理意義
FCD^{i}_{*ts}	$\{rc\}$	在第 s 個情境中，零售商 r 在第 t 期時，面臨顧客 c 對於產品 i 的需求量。
PPD_{*}	$\{s\}$	情境 s 發生的機率。
$\left(\mathrm{USP}^{i}_{*}\right)^{\bullet}_{+}$	$\{pd, dr, rc\}$	訂定模糊單位售價隸屬度函數所需的參數。$+ \in \{S, B\}, \bullet \in \{0, 1\}$

6.2.3 系統變數

以情境為基礎之方法來描述不確定項時，所有變數都會變成與情境有關，如下列所示。

0,1 變數	$* \in$	值等於 1 時的物理意義
Y^{k}_{*ts}	$\{dr\}$	在第 s 個情境中，配銷中心 d 在第 t 期時，決定使用第 k 種經濟批量運送方式將產品運往零售商 r。
$\mathrm{Y}^{k'}_{*ts}$	$\{pd\}$	在第 s 個情境中，工廠 p 在第 t 期時，決定使用第 k' 種經濟批量運送方式將產品運往配銷中心 d。
α^{i}_{*ts}	$\{p\}$	在第 s 個情境中，工廠 p 決定在第 t 期於正常工時製造產品 i。
β^{i}_{*ts}	$\{p\}$	在第 s 個情境中，工廠 p 的生產線於第 t 期時設定為製造產品 i。
γ^{i}_{*ts}	$\{p\}$	在第 s 個情境中，工廠 p 決定於第 t 期時更換生產線設定為製造產品 i。
o^{i}_{*ts}	$\{p\}$	在第 s 個情境中，工廠 p 決定在第 t 期於加班工時製造產品 i。

實數變數	$* \in$	物理意義
B^i_{*ts}	$\{r\}$	在第 s 個情境中，零售商 r 於第 t 期末的產品 i 缺貨量。
D^i_{*ts}	$\{p,d,r\}$	在第 s 個情境中，工廠 p、配銷中心 d、零售商 r 於第 t 期末的產品 i 安全存貨短缺量。
I^i_{*ts}	$\{p,d,r\}$	在第 s 個情境中，工廠 p、配銷中心 d、零售商 r 於第 t 期末的產品 i 存貨量。
J_*	$\{m\}$	目標的期望值
PSP_{*ts}	$\{p,d,r\}$	在第 s 個情境中，工廠 p、配銷中心 d、零售商 r 於第 t 期的總銷售收益。
RI_*	$\{m'\}$	目標的韌性指標。
SQ^i_{*ts}	$\{pd,dr,rc\}$	在第 s 個情境中，工廠 p 售予配銷中心 d、配銷中心 d 售予零售商 r、零售商 r 售予顧客 c 產品 i 於第 t 期的銷售量。
TIC_{*ts}	$\{p,d,r\}$	在第 s 個情境中，工廠 p、配銷中心 d、零售商 r 於第 t 期的總存貨成本。
THC_{*ts}	$\{p,d,r\}$	在第 s 個情境中，工廠 p、配銷中心 d、零售商 r 於第 t 期的總處理成本。
TMC_{*ts}	$\{p\}$	在第 s 個情境中，工廠 p 於第 t 期的總製造成本。
TPC_{*ts}	$\{d,r\}$	在第 s 個情境中，配銷中心 d、零售商 r 於第 t 期的總購買成本。
TQ^k_{*ts}	$\{dr\}$	在第 s 個情境中，配銷中心 d 將產品運往零售商 r，使用第 k 種經濟批量運送方式的實際運送量。
$\mathrm{TQ}^{k'}_{*ts}$	$\{pd\}$	在第 s 個情境中，工廠 p 將產品運往配銷中心 d，使用第 k' 種經濟批量運送方式的實際運送量。
TQ_{*ts}	$\{pd,dr\}$	在第 s 個情境中，工廠 p 將產品運往配銷中心 d、配銷中心 d 將產品運往零售商 r 的總運送量。
TTC_{*ts}	$\{p,d\}$	在第 s 個情境中，工廠 p、配銷中心 d 於第 t 期的總運送成本。
USP^i_{*s}	$\{pd,dr,rc\}$	在第 s 個情境中，工廠 p 售予配銷中心 d、配銷中心 d 售予零售商 r 產品 i 的單位售價。
SIL_{*t}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的期望安全存貨水準。
CSL_{*t}	$\{d\}$	零售商 r 於第 t 期的期望顧客服務水準。
Z_{*t}	$\{p,d,r\}$	工廠 p、配銷中心 d、零售商 r 於第 t 期的期望淨收益。
模糊變數	$* \in$	**物理意義**
$\mathcal{BP}^i_*$	$\{pd,dr,rc\}$	衡量買方對於產品售價偏好的模糊集合。
$\mathcal{SP}^i_*$	$\{pd,dr,rc\}$	衡量賣方對於產品售價偏好的模糊集合。

6.3 目標函數與限制式

這部分的限制式與2.4節幾乎相同，除了所有變數都會變成與情境有關，所以限制式的相關說明便不再贅述。

6.3.1 工廠的生產製造限制

$$\sum_{\forall i \in \mathcal{I}} \beta^i_{pts} = 1 \tag{6.1}$$

$$o^i_{pts} \leq \alpha^i_{pts} \leq \beta^i_{pts} \tag{6.2}$$

$$\gamma^i_{pts} \geq \beta^i_{pts} - \beta^i_{p,t-1,s} \tag{6.3}$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{\forall t \in \mathcal{T}} o^i_{pts} \leq \mathrm{MTO}_p \tag{6.4}$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{n=0}^{N} o^i_{p,t-n,s} \leq N \tag{6.5}$$

$$\text{where } i \in \mathcal{I}, p \in \mathcal{P}, t \in \mathcal{T}, s \in \mathcal{S}$$

限制式的相關說明可參考2.4.1節。

6.3.2 產品運送限制

$$\mathrm{TCL}_{pd}^{k'-1}\mathrm{Y}_{pdts}^{k'} \;<\; \mathrm{TQ}_{pdts}^{k'} \;\leq\; \mathrm{TCL}_{pd}^{k'}\mathrm{Y}_{pdts}^{k'} \tag{6.6}$$

$$\mathrm{TCL}_{dr}^{k-1}\mathrm{Y}_{drts}^{k} \;<\; \mathrm{TQ}_{drts}^{k} \;\leq\; \mathrm{TCL}_{dr}^{k}\mathrm{Y}_{drts}^{k} \tag{6.7}$$

$$\sum_{\forall k'\in\mathcal{K}'} \mathrm{Y}_{pdts}^{k'} \;\leq\; 1 \qquad \sum_{\forall k\in\mathcal{K}} \mathrm{Y}_{drts}^{k} \;\leq\; 1 \tag{6.8}$$

$$\mathrm{TQ}_{pdts} \;=\; \sum_{\forall k'\in\mathcal{K}'} \mathrm{TQ}_{pdts}^{k'} \;=\; \sum_{\forall i\in\mathcal{I}} \mathrm{SQ}_{pdts}^{i} \tag{6.9}$$

$$\mathrm{TQ}_{drts} \;=\; \sum_{\forall k\in\mathcal{K}} \mathrm{TQ}_{drts}^{k} \;=\; \sum_{\forall i\in\mathcal{I}} \mathrm{SQ}_{drts}^{i} \tag{6.10}$$

$$\sum_{\forall p\in\mathcal{P}} \mathrm{TQ}_{pdts} \;\leq\; \mathrm{MITC}_{d} \tag{6.11}$$

$$\sum_{\forall r\in\mathcal{R}} \mathrm{TQ}_{drts} \;\leq\; \mathrm{MOTC}_{d} \tag{6.12}$$

$$\forall d\in\mathcal{D},\; p\in\mathcal{P},\; r\in\mathcal{R},\; k'\in\mathcal{K}',\; k\in\mathcal{K},\; t\in\mathcal{T},\; s\in\mathcal{S}$$

限制式的相關說明可參考2.4.2節。

6.3.3 存貨限制

$$\mathrm{I}_{rts}^{i} \;=\; \mathrm{I}_{r,t-1,s}^{i} + \sum_{\forall d\in\mathcal{D}} \mathrm{SQ}_{dr,t-\mathrm{TLT}_{dr},s}^{i} - \sum_{\forall c\in\mathcal{C}} \mathrm{SQ}_{rcts}^{i} \tag{6.13}$$

$$\mathrm{I}_{dts}^{i} \;=\; \mathrm{I}_{d,t-1,s}^{i} + \sum_{\forall p\in\mathcal{P}} \mathrm{SQ}_{pd,t-\mathrm{TLT}_{pd},s}^{i} - \sum_{\forall r\in\mathcal{R}} \mathrm{SQ}_{drts}^{i} \tag{6.14}$$

$$\mathrm{I}_{pts}^{i} \;=\; \mathrm{I}_{p,t-1,s}^{i} + \mathrm{FMQ}_{p}^{i}\alpha_{p,t-1,s}^{i} + \mathrm{OMQ}_{p}^{i}o_{p,t-1,s}^{i} - \sum_{\forall d\in\mathcal{D}} \mathrm{SQ}_{pdts}^{i} \tag{6.15}$$

$$\mathrm{B}_{rts}^{i} \;=\; \mathrm{B}_{r,t-1,s}^{i} + \sum_{\forall c\in\mathcal{C}} \mathrm{FCD}_{rcts}^{i} - \sum_{\forall c\in\mathcal{C}} \mathrm{SQ}_{rcts}^{i}, \quad \mathrm{B}_{rTs}^{i} = 0 \tag{6.16}$$

$$\sum_{\forall i\in\mathcal{I}} \mathrm{I}_{*ts}^{i} \;\leq \mathrm{MIC}_{*} \tag{6.17}$$

$$\mathrm{SIQ}_{*}^{i} \;-\; \mathrm{I}_{*ts}^{i} \;\leq\; \mathrm{D}_{*ts}^{i} \tag{6.18}$$

$$\mathrm{I}_{*ts}^{i}, \mathrm{SQ}_{*ts}^{i}, \mathrm{B}_{*ts}^{i}, \mathrm{D}_{*ts}^{i} \;\geq\; 0 \tag{6.19}$$

$$\text{where } * \;\in\; \{p,d,r\},\;\text{ and } p\in\mathcal{P},\; d\in\mathcal{D},\; r\in\mathcal{R},\; i\in\mathcal{I},\; t\in\mathcal{T},\; s\in\mathcal{S}$$

限制式的相關說明可參考2.4.4節。

6.3.4 成本與收益

$$
\begin{aligned}
\mathrm{TMC}_{pts} &= \sum_{\forall i \in \mathcal{I}} \Big[\mathrm{FMC}_p^i \gamma_{pts}^i + \mathrm{FIC}_p^i(\beta_{pts}^i - \alpha_{pts}^i) + \mathrm{UMC}_p^i \mathrm{FMQ}_p^i \alpha_{pts}^i \\
&\qquad + \mathrm{OMC}_p^i \mathrm{OMQ}_p^i o_{pts}^i\Big] && (6.20)\\
\mathrm{TPC}_{dts} &= \sum_{\forall p \in \mathcal{P}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{pds}^i \mathrm{SQ}_{pdts}^i, \qquad \mathrm{TPC}_{rts} = \sum_{\forall d \in \mathcal{D}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{drs}^i \mathrm{SQ}_{drts}^i && (6.21)\\
\mathrm{TIC}_{*ts} &= \sum_{\forall i \in \mathcal{I}} \mathrm{UIC}_*^i \mathrm{I}_{*ts}^i \qquad * \in \{p, d, r\} && (6.22)\\
\mathrm{THC}_{pts} &= \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_p^i \left(\mathrm{FMQ}_p^i \alpha_{p,t-1,s}^i + \mathrm{OMQ}_p^i o_{p,t-1,s}^i + \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}_{pdts}^i\right) && (6.23)\\
\mathrm{THC}_{dts} &= \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_d^i \left(\sum_{\forall p \in \mathcal{P}} \mathrm{SQ}_{pd,t-\mathrm{TLT}_{pd},s}^i + \sum_{\forall r \in \mathcal{R}} \mathrm{SQ}_{drts}^i\right) && (6.24)\\
\mathrm{THC}_{rts} &= \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_r^i \left(\sum_{\forall d \in \mathcal{D}} \mathrm{SQ}_{dr,t-\mathrm{TLT}_{dr},s}^i + \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}_{rcts}^i\right) && (6.25)\\
\mathrm{TTC}_{pts} &= \sum_{\forall k' \in \mathcal{K}'} \sum_{\forall p \in \mathcal{P}} \left(\mathrm{FTC}_{pd}^{k'} \mathrm{Y}_{pdts}^{k'} + \mathrm{UTC}_{pd}^{k'} \mathrm{TQ}_{pdts}^{k'}\right) && (6.26)\\
\mathrm{TTC}_{dts} &= \sum_{\forall k \in \mathcal{K}} \sum_{\forall r \in \mathcal{R}} \left(\mathrm{FTC}_{dr}^{k} \mathrm{Y}_{drts}^{k} + \mathrm{UTC}_{dr}^{k} \mathrm{TQ}_{drts}^{k}\right) && (6.27)\\
\mathrm{PSP}_{pts} &= \sum_{\forall d \in \mathcal{D}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{pds}^i \mathrm{SQ}_{pdts}^i, \quad \mathrm{PSP}_{dts} = \sum_{\forall r \in \mathcal{R}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{drs}^i \mathrm{SQ}_{drts}^i, \\
\mathrm{PSP}_{rts} &= \sum_{\forall c \in \mathcal{C}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{rcs}^i \mathrm{SQ}_{rcts}^i && (6.28)\\
&\qquad \forall p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ t \in \mathcal{T}
\end{aligned}
$$

限制式的相關說明可參考2.4.5節。

6.3.5 目標函數

目標一：同時最大化各成員的淨收益

$$
\begin{aligned}
\mathrm{Z}_* &= \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{Z}_{*s} && * \in \{p, d, r\} \\
\text{where} \\
\mathrm{Z}_{ps} &= \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{pts} - \mathrm{TMC}_{pts} - \mathrm{TTC}_{pts} - \mathrm{TIC}_{pts} - \mathrm{THC}_{pts}) && \forall\, p \in \mathcal{P}, s \in \mathcal{S} \\
\mathrm{Z}_{ds} &= \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{dts} - \mathrm{TPC}_{dts} - \mathrm{TTC}_{dts} - \mathrm{TIC}_{dts} - \mathrm{THC}_{dts}) && \forall\, d \in \mathcal{D}, s \in \mathcal{S} \\
\mathrm{Z}_{rs} &= \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{rts} - \mathrm{TPC}_{rts} - \mathrm{THC}_{rts} - \mathrm{TIC}_{rts}) && \forall\, r \in \mathcal{R}, s \in \mathcal{S}
\end{aligned}
\tag{6.29}
$$

目標二：最大化平均安全存貨水準

$$
\begin{aligned}
\mathrm{SIL}_* &= \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{SIL}_{*s}, \qquad * \in \{p, d, r\} \\
\text{where} \quad \mathrm{SIL}_{*s} &= \frac{100}{I\,T} \sum_{\forall t \in \mathcal{T}} \sum_{\forall i \in \mathcal{I}} \left(1 - \frac{\mathrm{D}^i_{*ts}}{\mathrm{SIQ}^i_*}\right) \%, \quad \forall s \in \mathcal{S}
\end{aligned}
\tag{6.30}
$$

目標三：最大化平均顧客服務水準

$$
\begin{aligned}
\mathrm{CSL}_r &= \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{CSL}_{rs}, \qquad \forall r \in \mathcal{R} \\
\text{where} \quad \mathrm{CSL}_{rs} &= \frac{100}{I\,T} \sum_{\forall t \in \mathcal{T}} \sum_{\forall i \in \mathcal{I}} \left(\frac{\sum_{\forall c \in \mathcal{C}} \mathrm{SQ}^i_{rcts}}{\mathrm{B}^i_{r,t-1,s} + \sum_{\forall c \in \mathcal{C}} \mathrm{FCD}^i_{rcts}} \right) \%, \quad \forall s \in \mathcal{S}
\end{aligned}
\tag{6.31}
$$

目標四：最大化在需求不確定下目標的韌性 (robustness)

在不同情境下，目標值可能會有所不同。有時雖然目標的期望值符合決策者之期待，但在實際面對某些情境時，目標值卻變得很差，而令人無法接受。因此，如何降低目標值在不同情境中的變動，也就是增加決策的韌性，便成為亟待解決的重要問題。對於要最大化的目標，決策者並不會在意大於期望值的目標值。因此本研究提出一個衡量韌性的指標，下方局部平均值 (lower partial mean)，只懲罰小

於期望值 $J_{m'}$ 的目標值 $J_{m's}$，並以情境發生的機率為權重因子。

$$\mathrm{RI}_{m'} = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \min\{0, J_{m's} - J_{m'}\}, \qquad \forall m' \in \mathcal{M}' \tag{6.32}$$

其中 $\mathcal{M}'$ 是在式 (6.29) ～式 (6.31) 中之目標的集合，其大小為 $[\mathcal{M}'] = M' = 2P + 2D + 3R$。

6.3.6 生產與配送規劃之供應鏈模式整合

將前面6.3.1、6.3.2 、6.3.3、6.3.4、6.3.5節所討論的限制式與目標函數整合成一個『多目標混合整數非線性規劃問題』，如式 (6.34) 所示。

$$\max_{\mathbf{x}\in\boldsymbol{\Omega}} \quad (J_1(\mathbf{x}), \ldots, J_M(\mathbf{x})) = \begin{pmatrix} \mathrm{Z}_p,\ \mathrm{Z}_d,\ \mathrm{Z}_r;\ \mathrm{SIL}_p,\ \mathrm{SIL}_d,\ \mathrm{SIL}_r;\ \mathrm{CSL}_r;\ \mathrm{RI}_{m'}; \\ \forall p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ m' \in \mathcal{M}' \end{pmatrix} \tag{6.33}$$

$$\mathbf{x} = \left\{ \begin{array}{r} \alpha^i_{pts}, \beta^i_{pts}, \gamma^i_{pts}, o^i_{pts}; \mathrm{SQ}^i_{*ts}; \mathrm{USP}^i_{*s}; \mathrm{TQ}^{k'}_{pdts}, \mathrm{TQ}^k_{drts}, \\ \mathrm{Y}^{k'}_{pdts}, \mathrm{Y}^k_{drts}; \mathrm{I}^i_{pts}, \mathrm{I}^i_{dts}, \mathrm{I}^i_{rts}; \mathrm{B}^i_{rts}; \mathrm{D}^i_{pts}, \mathrm{D}^i_{dts}, \mathrm{D}^i_{rts} \\ * \in \{pd, dr, rc\}; i \in \mathcal{I},\ p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R}, \\ c \in \mathcal{C},\ k' \in \mathcal{K}',\ k \in \mathcal{K},\ t \in \mathcal{T},\ s \in \mathcal{S} \end{array} \right\} \tag{6.34}$$

6.4 模式之情境模擬

考慮由一個工廠、兩個配銷中心、兩個零售商與兩種產品組成的供應鏈網路。其中配銷中心 $d1$ 被設定為一規模較小 (運送量、存貨量較小) 但運送快速 (當期送達) 的配銷中心。在整個供應鏈系統中以快速配送方式，將產品從工廠運送到零售商，以便在零售商面對產品需求突然增加時，仍能藉由配銷中心 $d1$ 快速即時的配送獲得產品，以維持一定的服務水準。而配銷中心 $d2$ 以大量運送方式對零售商進行配送，可保持經濟批量運送來節省運送成本，但每一層級間需要 1 期的運送前置時間。配銷中心 $d1$ 雖然具有快速配送的優勢，運送成本卻比較高。

整個生產排程與配送規劃共有 5 週期；每一期的最低顧客服務水準限制為 0.7；可選擇的經濟批量運送方式有三種 ($[\mathcal{K}] = [\mathcal{K}'] = 3$)；連續加班的期數不能超過兩次 ($N = 2$)。

表 **6.1** 產品需求的情境與相關的發生機率

情境 s			1	2	3	4	5	6	7
PPD_s			0.15	0.2	0.12	0.24	0.09	0.13	0.07
i	r	t	FCD^i_{rts}						
1	1	1	160	160	160	160	160	160	160
1	1	2	170	170	170	160	150	150	150
1	1	3	180	180	180	160	140	140	140
1	1	4	190	180	170	160	150	140	130
1	1	5	200	180	160	160	160	140	120
1	2	1	180	180	180	180	180	180	180
1	2	2	200	200	180	200	160	160	160
1	2	3	220	220	180	220	140	140	140
1	2	4	220	240	180	200	140	120	160
1	2	5	220	260	180	180	140	100	180
2	1	1	240	240	240	240	240	240	240
2	1	2	240	270	210	210	270	270	210
2	1	3	240	300	180	180	300	300	180
2	1	4	240	270	210	150	330	300	180
2	1	5	240	240	240	120	360	300	180
2	2	1	280	280	280	280	280	280	280
2	2	2	320	240	320	320	240	240	280
2	2	3	360	200	360	360	200	200	280
2	2	4	320	200	400	360	160	240	280
2	2	5	280	200	400	360	120	280	280

產品需求的情境與相關的發生機率如表 6.1 所示，不同零售商所面對的顧客群之產品需求，可能會一直增加或先增加然後持平或先增加然後減少或先減少然後增加或先減少然後持平或持續減少。以第一個情境為例：其發生的機率為 0.15，零售商 $r = 1$ 所面對的產品 $i = 1$ 之需求，隨著時間而增加；零售商 $r = 2$ 所面對的產品 $i = 1$ 之需求，則先增加然後持平。成本參數與其他參數分別列於表 6.2 和表 6.4 ，而訂定模糊單位售價隸屬度函數所需的參數則如表 6.3 所示

整個多目標生產與配送規劃模式包含 5702 個方程式、 4079 個連續變數和 910 個 0-1 變數。

表 **6.2** 成本參數

單位存貨成本	i	p	d	r	\$
UIC_r^i	1			1	50
	1			2	40
	2			1	30
	2			2	24
UIC_d^i	1		1		45
	1		2		20
	2		1		27
	2		2		12
UIC_p^i	1	1			15
	2	1			9
單位處理成本					
UHC_r^i	1			1	15
	1			2	12
	2			1	9
	2			2	7
UHC_d^i	1		1		12
	1		2		6
	2		1		7
	2		2		4
UHC_p^i	1	1			5
	2	1			3

單位運送成本	k	p	d	r	\$
UTC_{dr}^k	1		1	1	60
	2		1	1	45
	3		1	1	33
	1		1	2	50
	2		1	2	37
	3		1	2	27
	1		2	1	25
	2		2	1	18
	3		2	1	14
	1		2	2	30
	2		2	2	22
	3		2	2	16
$\mathrm{UTC}_{pd}^{k'}$	1	1	1		40
	2	1	1		30
	3	1	1		20
	1	1	2		20
	2	1	2		15
	3	1	2		10
單位製造成本	i	p			\$
UMC_p^i	1	1			60
	2	1			30
OMC_p^i	1	1			90
	2	1			45

固定運送成本	k	p	d	r	\$
FTC_{dr}^k	1		1	1	1800
	2		1	1	2700
	3		1	1	3200
	1		1	2	1500
	2		1	2	2200
	3		1	2	2600
	1		2	1	3000
	2		2	1	5250
	3		2	1	6750
	1		2	2	2000
	2		2	2	3500
	3		2	2	4500
$\mathrm{FTC}_{pd}^{k'}$	1	1	1		2000
	2	1	1		3000
	3	1	1		3500
	1	1	2		3200
	2	1	2		5600
	3	1	2		7200
固定換線 / 閒置成本	i	p			\$
FMC_p^i	1	1			48000
	2	1			36000
FIC_p^i	1	1			4800
	2	1			3600

表 **6.3** 訂定模糊單位售價隸屬度函數所需的參數

		賣方		買方				賣方		買方	
$\bullet$	$i\ p\ d\ r$	$(\bullet)_S^0$	$(\bullet)_S^1$	$(\bullet)_B^1$	$(\bullet)_B^0$	$\bullet$	$i\ p\ d\ r$	$(\bullet)_S^0$	$(\bullet)_S^1$	$(\bullet)_B^1$	$(\bullet)_B^0$
USP_{dr}^i	1 1 1	1350	1450	1400	1500	USP_{pd}^i	1 1 1	850	950	900	1000
	1 1 2	1400	1500	1450	1550		1 1 2	750	850	800	900
	1 2 1	1250	1350	1300	1400		2 1 1	400	500	450	550
	1 2 2	1200	1300	1250	1350		2 1 2	300	400	350	450
	2 1 1	650	750	700	800	USP_{rc}^i	1 1	1650	1750	1700	1800
	2 1 2	700	800	750	850		1 2	1600	1700	1650	1750
	2 2 1	600	700	650	750		2 1	1000	1100	1050	1150
	2 2 2	550	650	600	700		2 2	950	1050	1000	1100

表 **6.4** 其他參數

運送前置時間			安全存貨量			最大運量		
	p d r			i p d r			k p d r	
	1 1	0		1 1	150		1 1 1	60
TLT_{dr}	1 2	0	SIQ_r^i	1 2	150		2 1 1	120
	2 1	1		2 1	250		3 1 1	180
	2 2	1		2 2	250		1 1 2	60
TLT_{pd}	1 1	0		1 1	200		2 1 2	120
	1 2	1	SIQ_d^i	1 2	300	TCL_{dr}^k	3 1 2	180
最大存貨量				2 1	300		1 2 1	220
	p d r			2 2	500		2 2 1	440
MIC_r	1	600	SIQ_p^i	1 1	400		3 2 1	660
	2	800		2 1	600		1 2 2	220
MIC_d	1	1000	批次製造量				2 2 2	440
	2	4000		i p			3 2 2	660
MIC_p	1	2500	FMQ_p^i	1 1	1200		1 1 1	100
最大總加班期數				2 1	1500		2 1 1	200
	p		OMQ_p^i	1 1	300	$\mathrm{TCL}_{pd}^{k'}$	3 1 1	300
MTO_p	1	3		2 1	400		1 1 2	400
							2 1 2	800
							3 1 2	1200
			最大進出貨量					
				d			d	
			MITC_d	1	300	MOTC_d	1	300
				2	1200		2	1200

6.5 結果與討論

多目標生產與配送規劃模式求解的過程，可整理如下：

步驟 1: 分別對單一目標求取最樂觀的解 $\overline{J_m^1}$ 與最悲觀的解 $\underline{J_m^0}$。然後，選擇目標函數的可接受範圍 $[J_m^0, J_m^1]$，如表 6.6 所示。先建立理想解償付表如表 6.5 所示。直接以理想解償付表的最大值與最小值，作為安全存貨水準和顧客服務水準的可接受範圍。因為收益的變動比較大，因此建議以理想解償付表中次高值作為上限 J_m^1 ，而以最低的正收益作為下限 J_m^0。為了強調韌性指標的重要性，建議以理想解償付表中，第五低的值作為下限 J_m^0，而以最樂觀的解 0 作為上限 J_m^1。

步驟 2: （階段一）以 min 運算子最大化滿意度最低的目標， $\mu_{\min} = 0.53$

步驟 3: （階段二）在具備最低滿意度的保證下，以 product 運算子盡量提升個別隸屬度函數的值。

因為產品售價與時間無關，所以與買賣雙方對售價滿意度有關的項目便不會太多，因此不一定要使用算數平均運算子。而 product 運算子對個別的隸屬度函數變化比較敏感，在提升個別的隸屬度函數方面，有比較好的效果，所以這個例子採用 product 運算子。

將使用單一階段與兩階段運算法求解的結果整理如表 6.7 所示，其中列出了各成員收益、安全存貨水準、顧客服務水準以及韌性指標等目標函數值與其隸屬度函數值。此外，為了方便比較，可以對照圖 6.1 及圖 6.2 。從結果可以看出選擇 min 運算子時，可以讓滿意度較低的隸屬度函數都能盡量獲得提升，進而得到較為平均的隸屬度函數分佈。整體而言，各目標的隸屬度函數值都約略在 0.53 附近。但是， min 運算子不具嚴格單調的特性，會有非唯一局部最適解之情形發生。選擇 product 運算子時，雖其具有嚴格單調的性質，可求得唯一最適解，但容易造成隸屬度函數值分佈不均的情形。如零售商 $r = 1$ 與配銷中心 $d = 1$ 的收益，以及配銷中心 $d = 2$ 的安全存貨水準都偏低。這樣的結果，與想要求得目標間相互妥協解的本意有所衝突。使用兩階段模糊最適化法，則可得到令人滿意的妥協解。

表 **6.5** 理想解償付表

		$J_m(x^*)$											
		$\mathrm{Z}_{p=1}$	$\mathrm{Z}_{d=1}$	$\mathrm{Z}_{d=2}$	$\mathrm{Z}_{r=1}$	$\mathrm{Z}_{r=2}$	$\mathrm{SIL}_{p=1}$	$\mathrm{SIL}_{d=1}$	$\mathrm{SIL}_{d=2}$	$\mathrm{SIL}_{r=1}$	$\mathrm{SIL}_{r=2}$	$\mathrm{CSL}_{r=1}$	$\mathrm{CSL}_{r=2}$
	$\mathrm{Z}_{p=1}$	$4,623,672$	$-290,481$	$-467,993$	$-66,190$	$378,442$	0.09	0.89	0.38	0.69	0.45	0.80	0.79
	$\mathrm{Z}_{d=1}$	$2,578,221$	$1,104,309$	$928,878$	$-331,591$	$-107,931$	0.50	0.07	0.50	0.67	0.58	0.86	0.86
	$\mathrm{Z}_{d=2}$	$2,334,497$	$178,486$	$3,155,891$	$-797,333$	$-755,271$	0.32	0.59	0.02	0.56	0.53	0.84	0.82
	$\mathrm{Z}_{r=1}$	$2,338,916$	$37,429$	$762,862$	$1,345,449$	$348,385$	0.47	0.73	0.38	0.06	0.53	0.86	0.80
	$\mathrm{Z}_{r=2}$	$2,399,587$	$-114,566$	$840,698$	$114,141$	$1,553,022$	0.43	0.76	0.39	0.62	0.04	0.83	0.84
$J(x_m^*)$	$\mathrm{SIL}_{p=1}$	$2,273,758$	$306,059$	$814,994$	$639,630$	$498,635$	0.92	0.49	0.35	0.54	0.39	0.78	0.77
	$\mathrm{SIL}_{d=1}$	$2,442,893$	$149,166$	$760,583$	$241,220$	$568,705$	0.42	0.97	0.38	0.70	0.49	0.80	0.76
	$\mathrm{SIL}_{d=2}$	$2,478,343$	$260,017$	$888,137$	$66,280$	$455,904$	0.38	0.72	0.95	0.48	0.36	0.77	0.77
	$\mathrm{SIL}_{r=1}$	$2,348,545$	$173,654$	$1,109,662$	$-124,708$	$648,639$	0.42	0.71	0.39	0.94	0.42	0.81	0.78
	$\mathrm{SIL}_{r=2}$	$2,664,123$	$570,869$	$892,511$	$-41,741$	$276,206$	0.44	0.66	0.29	0.74	0.93	0.83	0.80
	$\mathrm{CSL}_{r=1}$	$2,533,777$	$107,139$	$866,952$	$28,323$	$597,719$	0.39	0.82	0.40	0.53	0.48	1.00	0.78
	$\mathrm{CSL}_{r=2}$	$2,484,884$	$192,277$	$855,998$	$29,145$	$596,632$	0.45	0.76	0.42	0.67	0.32	0.81	0.96
		$\mathrm{RI}_{\mathrm{Z}_{p=1}}$	$\mathrm{RI}_{\mathrm{Z}_{d=1}}$	$\mathrm{RI}_{\mathrm{Z}_{d=2}}$	$\mathrm{RI}_{\mathrm{Z}_{r=1}}$	$\mathrm{RI}_{\mathrm{Z}_{r=2}}$	$\mathrm{RI}_{\mathrm{SIL}_{p=1}}$	$\mathrm{RI}_{\mathrm{SIL}_{d=1}}$	$\mathrm{RI}_{\mathrm{SIL}_{d=2}}$	$\mathrm{RI}_{\mathrm{SIL}_{r=1}}$	$\mathrm{RI}_{\mathrm{SIL}_{r=2}}$	$\mathrm{RI}_{\mathrm{CSL}_{r=1}}$	$\mathrm{RI}_{\mathrm{CSL}_{r=2}}$
	$\mathrm{Z}_{p=1}$	$-178,497$	$-71,420$	$-94,462$	$-73,922$	$-170,170$	$-.066$	$-.073$	$-.012$	$-.020$	$-.085$	$-.017$	$-.026$
	$\mathrm{Z}_{d=1}$	$-172,497$	$-101,687$	$-169,495$	$-200,097$	$-84,493$	$-.044$	$-.073$	$-.045$	$-.086$	$-.024$	$-.022$	$-.025$
	$\mathrm{Z}_{d=2}$	$-160,485$	$-9,135$	$-138,878$	$-76,272$	$-244,216$	$-.048$	0.00	$-.024$	$-.027$	$-.071$	$-.032$	$-.025$
	$\mathrm{Z}_{r=1}$	$-46,935$	$-75,487$	$-20,799$	$-47,447$	$-107,369$	$-.034$	$-.069$	$-.006$	$-.028$	$-.069$	$-.036$	$-.022$
	$\mathrm{Z}_{r=2}$	$-9,226$	$-63,297$	$-159,639$	$-130,202$	$-113,714$	$-.005$	$-.026$	$-.057$	$-.057$	$-.044$	$-.012$	$-.015$
$J(x_m^*)$	$\mathrm{SIL}_{p=1}$	$-204,289$	$-81,035$	$-154,748$	$-59,715$	$-139,514$	$-.048$	$-.067$	$-.025$	$-.034$	$-.076$	0.000	$-.007$
	$\mathrm{SIL}_{d=1}$	$-129,519$	$-62,691$	$-193,525$	$-149,626$	$-128,164$	$-.039$	$-.060$	$-.028$	$-.022$	$-.066$	$-.011$	$-.019$
	$\mathrm{SIL}_{d=2}$	$-40,559$	$-61,627$	$-188,704$	$-78,999$	$-198,440$	$-.046$	$-.058$	$-.049$	$-.018$	$-.063$	$-.012$	$-.013$
	$\mathrm{SIL}_{r=1}$	$-95,039$	$-43,324$	$-148,899$	$-94,324$	$-97,162$	$-.059$	$-.044$	$-.034$	$-.034$	$-.008$	$-.023$	$-.017$
	$\mathrm{SIL}_{r=2}$	$-73,047$	$-41,060$	$-193,354$	$-117,435$	$-204,592$	$-.048$	$-.019$	$-.039$	$-.056$	$-.063$	$-.014$	0.000
	$\mathrm{CSL}_{r=1}$	$-66,775$	$-65,029$	$-104,873$	$-109,680$	$-113,246$	$-.028$	$-.038$	$-.016$	$-.055$	$-.035$	$-.006$	$-.007$
	$\mathrm{CSL}_{r=2}$	$-78,853$	$-47,335$	$-145,368$	$-128,402$	$-125,506$	$-.006$	$-.027$	$-.039$	$-.034$	$-.015$	$-.011$	$-.003$

表 **6.6** 訂定模糊目標隸屬度函數所需的參數

m	J_m	$\underline{J_m^0}$	J_m^0	J_m^1	$\overline{J_m^1}$	m	J_m	$\underline{J_m^0}$	J_m^0
1	$\mathrm{Z}_{p=1}$	$242,032$	$2,273,758$	$2,664,123$	$4,623,672$	13	$\mathrm{RI}_{\mathrm{Z}_{p=1}}$	$-204,289$	$-129,519$
2	$\mathrm{Z}_{d=1}$	$-824,650$	$37,429$	$570,869$	$1,104,309$	14	$\mathrm{RI}_{\mathrm{Z}_{d=1}}$	$-101,687$	$-75,487$
3	$\mathrm{Z}_{d=2}$	$-3,242,066$	$762,862$	$1,109,662$	$3,155,891$	15	$\mathrm{RI}_{\mathrm{Z}_{d=2}}$	$-193,525$	$-159,639$
4	$\mathrm{Z}_{r=1}$	$-1,142,110$	$28,323$	$639,630$	$1,345,449$	16	$\mathrm{RI}_{\mathrm{Z}_{r=1}}$	$-200,097$	$-117,435$
5	$\mathrm{Z}_{r=2}$	$-1,358,013$	$276,206$	$648,639$	$1,553,022$	17	$\mathrm{RI}_{\mathrm{Z}_{r=2}}$	$-244,216$	$-139,514$
6	$\mathrm{SIL}_{p=1}$	0.00	0.09	0.92	0.92	18	$\mathrm{RI}_{\mathrm{SIL}_{p=1}}$	-0.066	-0.048
7	$\mathrm{SIL}_{d=1}$	0.00	0.07	0.97	0.97	19	$\mathrm{RI}_{\mathrm{SIL}_{d=1}}$	-0.073	-0.060
8	$\mathrm{SIL}_{d=2}$	0.00	0.02	0.95	0.95	20	$\mathrm{RI}_{\mathrm{SIL}_{d=2}}$	-0.057	-0.039
9	$\mathrm{SIL}_{r=1}$	0.00	0.06	0.94	0.94	21	$\mathrm{RI}_{\mathrm{SIL}_{r=1}}$	-0.086	-0.034
10	$\mathrm{SIL}_{r=2}$	0.00	0.04	0.93	0.93	22	$\mathrm{RI}_{\mathrm{SIL}_{r=2}}$	-0.085	-0.066
11	$\mathrm{CSL}_{r=1}$	0.76	0.80	1.00	1.00	23	$\mathrm{RI}_{\mathrm{CSL}_{r=1}}$	-0.036	-0.017
12	$\mathrm{CSL}_{r=2}$	0.76	0.77	0.96	0.96	24	$\mathrm{RI}_{\mathrm{CSL}_{r=2}}$	-0.026	-0.019

表 **6.7** 模式求解的結果

		min		Product		兩階段法	
目標		目標值	滿意度	目標值	滿意度	目標值	滿意度
收益	$p=1$	$2,479,891$	0.53	$2,537,108$	0.67	$2,502,549$	0.59
	$d=1$	$319,114$	0.53	$279,356$	0.45	$327,660$	0.54
	$d=2$	$945,991$	0.53	$1,029,761$	0.77	$987,458$	0.65
	$r=1$	$351,125$	0.53	$295,882$	0.44	$351,482$	0.53
	$r=2$	$472,870$	0.53	$575,933$	0.80	$565,329$	0.78
安全存貨水準	$p=1$	0.53	0.53	0.57	0.58	0.53	0.53
	$d=1$	0.55	0.53	0.73	0.73	0.65	0.64
	$d=2$	0.51	0.53	0.43	0.44	0.51	0.53
	$r=1$	0.52	0.53	0.57	0.58	0.52	0.53
	$r=2$	0.51	0.53	0.61	0.64	0.55	0.57
顧客服務水準	$r=1$	0.91	0.53	1.00	1.00	0.95	0.74
	$r=2$	0.87	0.53	0.96	1.00	0.96	0.97
收益韌性指標	$p=1$	$-58,681$	0.55	$-22,277$	0.83	$-34,298$	0.74
	$d=1$	$-35,626$	0.53	$-1,798$	0.98	0	1.00
	$d=2$	$-75,341$	0.53	$-52,334$	0.67	$-44,178$	0.72
	$r=1$	$-55,423$	0.53	$-9,851$	0.92	$-6,895$	0.94
	$r=2$	$-61,992$	0.56	$-27,046$	0.81	$-16,963$	0.88
安全存貨水準韌性指標	$p=1$	-0.02	0.53	-0.001	0.99	0.00	1.00
	$d=1$	-0.03	0.53	0.00	1.00	0.00	1.00
	$d=2$	-0.02	0.53	0.00	1.00	0.00	1.00
	$r=1$	-0.02	0.53	0.00	1.00	0.00	1.00
	$r=2$	-0.03	0.53	-0.001	0.98	0.00	1.00
顧客服務水準韌性指標	$r=1$	-0.01	0.53	0.00	1.00	0.00	1.00
	$r=2$	-0.01	0.53	0.00	1.00	0.00	1.00

表 **6.8** 產品單位售價與買賣雙方的滿意度

	i	p	d	r	USP	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$		i	p	d	r	USP	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$
USP^i_{dr}	1		1	1	1425	0.75	0.75	USP^i_{pd}	1	1	1		926	0.74	0.76
	1		1	2	1475	0.75	0.75		1	1	2		826	0.75	0.75
	1		2	1	1326	0.74	0.76		2	1	1		476	0.74	0.76
	1		2	2	1276	0.75	0.75		2	1	2		375	0.75	0.75
	2		1	1	725	0.75	0.75	USP^i_{rc}	1			1	1728	0.72	0.78
	2		1	2	775	0.75	0.75		1			2	1678	0.72	0.78
	2		2	1	676	0.74	0.76		2			1	1079	0.72	0.78
	2		2	2	626	0.74	0.76		2			2	1031	0.69	0.81

圖 **6.1** 收益、安全存貨水準以及顧客服務水準的雷達圖

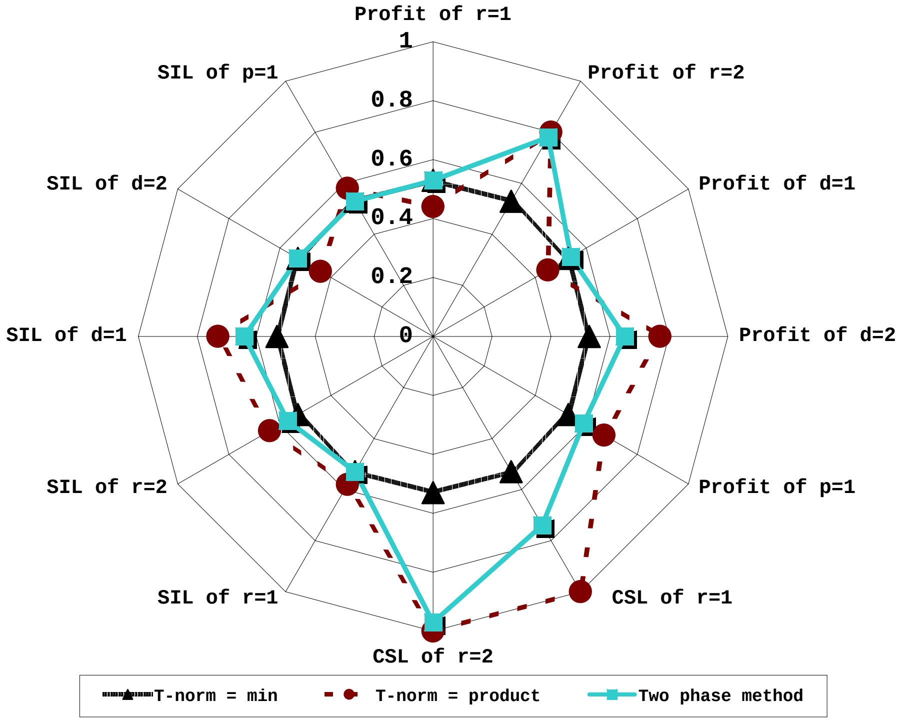


圖 **6.2** 韌性指標的雷達圖

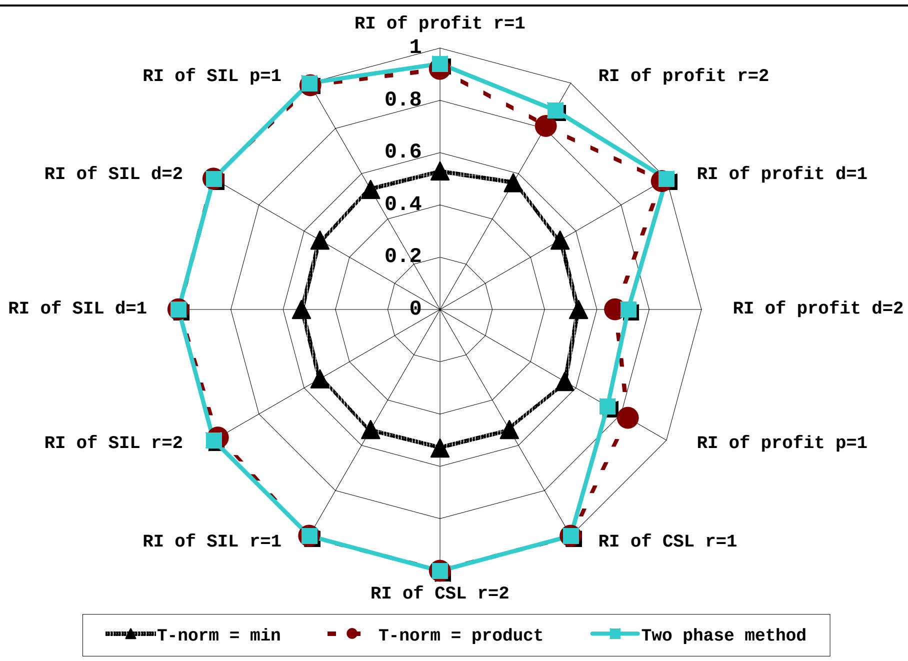


表 **6.9** 在有考量韌性指標與沒有考量兩種情況下，所有情境的目標值

		收益					安全存貨水準					顧客服務水準	
	情境	$p=1$	$d=1$	$d=2$	$r=1$	$r=2$	$p=1$	$d=1$	$d=2$	$r=1$	$r=2$	$r=1$	$r=2$
RI not included	1	2709353	353342	1300455	657240	288886	0.60	0.64	0.43	0.60	0.53	1.00	1.00
	2	2036686	413862	821158	852790	917316	0.47	0.82	0.50	0.74	0.53	1.00	1.00
	3	2806934	250369	1196849	79628	736006	0.49	0.71	0.57	0.50	0.62	0.99	1.00
	4	2447388	375178	936194	234508	756312	0.61	0.97	0.57	0.59	0.75	0.99	0.85
	5	2648390	421579	1159809	210789	-271410	0.65	0.84	0.55	0.68	0.74	1.00	1.00
	6	2760923	123027	1053518	229115	46819	0.64	0.91	0.57	0.62	0.67	1.00	1.00
	7	2387742	318640	772951	-253262	853122	0.69	0.95	0.60	0.63	0.75	1.00	0.99
	期望值	2502362	332101	1023055	366009	538010	0.58	0.84	0.53	0.62	0.65	1.00	0.96
	RI	-114353	-37930	-78733	-141041	-152013	$-.033$	$-.050$	$-.021$	$-.025$	$-.046$	$-.004$	$-.026$
RI included	1	2627463	327660	987458	396451	637799	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	2	2580353	327660	1034208	350482	595791	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	3	2502549	327660	1151319	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	4	2502549	327660	1050643	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	5	2485710	327660	817240	299611	452736	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	6	2451158	327660	765471	332659	528373	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	7	2129671	327660	987458	350482	536394	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	期望值	2502549	327660	987458	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	RI	-34298	0	-44178	-6895	-16963	0.00	0.00	0.00	0.00	0.00	0.00	0.00

表 6.8 列出產品單位售價與買賣雙方的滿意度。 表 6.9 則列出，在考量韌性指標與無考量兩種情況下，所有情境的目標值。當無考量韌性指標時，目標值在各情境中，有很大的變動。尤其零售商 $r=1$ 和 $r=2$，在某些情境中的收益相當低，甚至出現虧損。而將韌性指標納入目標函數中，則可以明顯地降低目標值的變動。

7

結論與未來展望

7.1 結論

本研究探討在產品需求與價格不確定下之供應鏈網路最適化，其中選擇以情境為基礎之方法來描述不確定的產品需求，同時運用模糊變數來描述不確定之產品價格。整合成一個「多目標混合整數非線性規劃問題」，來達成各成員間收益平均分配、提升安全存貨水準與顧客服務水準、最大化決策韌性，以及增加各成員對於產品價格的滿意度。最後使用兩階段模糊多目標最適化法，為多個互斥目標與模糊售價提供一個相互妥協的最適解。

相較於過去許多研究所使用的單目標規劃法，藉由模糊理論將各目標函數對應至其隸屬度函數來表達決策者對各目標的滿意程度，能公平反映出各目標的重要性，而兩階段模糊多目標最適化法在第一階段以 min 運算子最大化滿意度最低的目標；接著於第二階段在具備最低滿意度的保證下，以 product 或算數平均運算子盡量提升個別隸屬度函數的值，使得各成員的收益分配問題在彼此互斥的關係下得到一個相互妥協的最佳解；並可進一步考量許多單目標規劃法無法妥善考慮的問題，例如本研究模式將顧客滿意度與安全存貨度納入模式之中。

在面對產品價格不確定時，本研究分別從買方與賣方的觀點建立模糊集合和相關隸

屬度函數，來衡量雙方對於產品價格的偏好。由模擬的結果得知：成員間平均分配收益使得與供應鏈內部相關的售價，有時落於有利於買方的位置，有時則落於有利於賣方的位置；而零售商售予顧客的售價則皆落於對賣方有利的位置，此乃是整體的供應鏈要獲取最大利益之必然結果；但是，若顧客的滿意度太低，則會有流失市場之虞，而兩階段模糊最適化法，顯然可以提供最低顧客滿意度的保證。

選擇以情境為基礎之方法來描述不確定的產品需求時，必須注意：有時雖然目標的期望值符合決策者之期待，但在實際面對某些情境時，目標值卻變得很差，也就是相關決策缺乏韌性。本研究提出一個指標，下方局部平均值，來衡量決策的韌性，並將其納入目標函數中。由模擬的結果得知：將韌性指標納入目標函數中，可以明顯地降低在不同情境中目標值的變動。

7.2 未來展望

本文所討論的範圍為短期之供應鏈規劃，每個週期的大小皆相同。未來的研究方向可考慮不同大小的週期，例如：距離現在半個月內的週期以天為單位，再逐漸地以星期、月、季為一週期；最後，整個規劃時間可以長達一年或更久。透過這個方式，將短中期規劃整合成一個供應鏈模式，並進一步探討其相關特性。

本研究應用之例子，與實際供應鏈的規模相較，仍屬狹隘。需尋求更具代表性之實例，如：台灣能源供應鏈，其中包含數種不同形式的能源：煤、石油、天然氣、核能等等；不同能源原料的供應地、運送方式、運送前置時間以及儲存方式等等都會有很大的不同；售予顧客的方式也有不小的差異，例如，天然氣可直接輸送到顧客家中使用，而核能則須轉換成電能，再傳輸至終端顧客；此外，原料在運送與使用的過程中，可能會洩漏或排放有害物質，而能源有限，並不能毫無節制地使用；所以，除了考量收益或成本最小化的目標外，應該將社會、經濟、資源與環境等永續經營目標納入；從以上的描述，可以預見，能源供應鏈模式將相當複雜，具有很高的挑戰性與實用性，是很值得研究的實例。

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出席國際學術會議心得報告

供應鏈網路整合性多目標模糊決策規劃研究

計畫編號：　NSC 95－2214－E－002－001－
計畫主持人：陳誠亮
執行單位：　國立臺灣大學化學工程學系

本計劃提供主持人出席國際學術會議，研究期間主要的出席會議包括美國化工年會、電腦輔助程序操作會議等，共計三次，開會地點包括美國邁阿密、舊金山、辛辛那堤。本人共計發表與供應鍊網路相關的論文三篇，其中，一篇有關供應鏈網路整合性多目標模糊決策規劃研究的論文更獲得電腦輔助程序操作會議的最佳論文(最佳論文共計三篇)，備感榮性。

電腦輔助程序操作會議每五年舉行一次，規模雖然不大，但是大會通常會安排二十位左右的知名學者或工業界人士依規劃的主題作專題演講，除了檢討近來主要研究成果，也相當強調未來研判方向，同時，每場演講之後也很注重出席人員間的討論，因此，整體呈現的內容相當紮實，與會者多能有深刻的體會和學習，本人首次參加後的感受是很震撼，更加深了作一流研究的期許了。

美國化工年會的規模相當龐大，每年出席人數都有五千人之多，內容包羅萬象，如果不謹慎篩選規劃，很容易在會場迷路，錯失有興趣的演講。本人通常會將想聽的場次依時間記錄起來，再依序跑攤，也就是說通常並不會出席固定的議題，而是滿場換教室，可以學習到新點子，也可以觀摩不同國家人士的演講技巧，雖辛苦但是也很有趣，記得一位博士班學生跟我開會幾天後，表示以後不敢當教授，因為太辛苦了！

出席國際學術會議，一方面可以發表自己最新研究成果，另一方面也是最好的學習機會，相信自己在國際間的表現，沒有辜負國科會的要求與期望。

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Multiobjective Optimization for a Multienterprise Supply Chain Network

Cheng-Liang Chen,* Bin-Wei Wang, and Wen-Cheng Lee

Department of Chemical Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C.

The problem of a fair profit distribution for a multienterprise supply chain network is investigated in this paper. To implement this concept, we construct a multiproduct, multistage, and multiperiod production and distribution planning model to achieve multiple objectives such as maximizing the profit of each participant enterprise, the customer service level, and the safe inventory level and ensuring a fair profit distribution. A two-phase fuzzy decision-making method is proposed to attain a compromise solution among all participant companies of the supply chain. One numerical example is supplied, demonstrating that the proposed two-phase decision-making method can provide an improved compensatory solution for multiobjective optimization problems in a multienterprise supply chain network.

1. Introduction

Given industry structure in recent years, all industries are gradually becoming more global and specialized. To face global competition, companies have to pay more attention to increasing customer service in its entirety. Thus, in addition to having good internal management and controls, companies should be oriented toward maintaining good strategic partners and cooperation. A company can create the best operating efficiency by working with other companies through communication and specialization. This new type of relationship between companies has developed into a "supply chain" relationship, and the concept of supply chain management has evolved. Recently, issues concerning supply chain management in chemical industries have attracted many researchers.[1−7]

In traditional supply chain management, minimizing costs or maximizing profit as a single objective is often the focus when considering the integration of a supply chain network.[8] For example, Cohen and Lee[9] formulated the problem of making resource allocation decisions in a global supply chain system and solved a single-objective mixed-integer linear programming model with different scenarios. Tsiakis et al.[10] proposed a multiproduct, multiperiod deterministic single-objective linear programming model for a supply chain network design problem. The objective function included production, transportation, and inventory costs. By solving this model, the locations and numbers of plants, warehouses, and distribution centers can be determined under uncertainties in customer demand.

Although these strategies can create an optimal result for the entire system, they can also increase costs or decrease profits for some members in the supply chain system. For example, under the economies of scale for transporting goods, distributors will try to ship an entire shipment downstream to its customers at one time to minimize costs and protect their profit margins. However, when one focuses on minimizing costs or maximizing profit for the entire supply chain system as a whole, the best overall result could force a distributor to increase his transporting frequency, making him unable to take advantage of economies of scale in shiping his goods. This could certainly increase the costs while lowering profit margins of this particular distributor. Therefore, members would be unwilling to cooperate if an efficient decision-making process that organizes and manages the resources of all members in the supply chain, while evenly guaranteeing that costs and profits be fairly distributed, cannot be created. For this reason, Gjerdrum et al.[11] proposed a mixed-integer linear programming model for a production and distribution planning problem and solved the fair profit distribution problem by using a Nash-type model as the objective function. However, this approach could also encounter two problems in guaranteeing a fair profit distribution. First, the lower bound of each member's profit might be difficult to determine because of the inherent uncertainty. Obviously, it would be influenced by decision maker's favor and cause different solution as the case might be. Second, directly maximizing the production of profits might cause an unfair profit distribution because of the different scales of profits. Furthermore, today's consumers are demanding better customer service, whether it be in the manufacturing or service industry. A company can only benefit by constantly improving its customer service. Thus, customer service should also be taken into consideration when formulating a supply chain system. In the traditional supply chain management approach of minimizing costs or maximizing profit as a single objective, however, it is difficult to quantify customer service as a monetary amount in the objective function. To solve this problem, the model presented here uses multiple-objective optimization to formulate the production and distribution planning problem of a supply chain system. In addition to maximization of profit for the entire system, we also consider fair profit distribution for its members, customer service, and safe inventory levels as objectives. The model presented here also considers the problem in light of the economies of scale for manufacturing or shipping faced by most firms today. Binary variables are added to the model to act as policy decisions on whether to use economies of scale for manufacturing or shipping. This model is then formulated as a multiobjective mixed-integer nonlinear programming (MOMINLP) problem.

* To whom correspondence should be addressed. Fax: 886-2-2362 3040. E-mail: ccl@ccms.ntu.edu.tw.

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Many methodologies have been proposed for treating multiobjective optimization problems. Among them, the weighted-sum method, the ϵ-constraint method, and the goal-programming method are all rooted in the conversion of vector objectives into a scalar objective.[12] The resulting problem can then be solved by using any existing optimization technique. If the algorithm does not converge to a suitable solution or the decision maker (DM) does not agree with the result, the DM can adjust the related parameters used in the algorithm, such as weighting factors in the weighted-sum method. The computation can then be repeated until a satisfactory solution is obtained. This is inherently an interactive process, and the DM is constantly involved in the decision. Because the optimization of a multiobjective problem is a procedure looking for a compromise policy, the result, called a Pareto-optimal or noninferior solution, consists of an infinite number of options. Methods for finding a Pareto-optimal solution are thus filled with subjective and fuzzy properties.

To overcome the difficulty of describing fuzzy attributes, Zadeh[13] proposed the fuzzy-set concept. By using multivalued logic to replace the traditional Boolean logic, one can quantitatively elucidate unclear information or knowledge. Subsequently, Bellman and Zadeh[14] further extended the fuzzy concept to the idea of decision making under a fuzzy environment. Tanaka et al.[15] introduced the concept of fuzzy mathematical programming and demonstrated that fuzzy mathematical programming can be reduced to a conventional nonlinear programming problem. A two-phase method has also been studied to guarantee uniqueness of the optimal solution by a max−min approach.[16] In this paper, we attempt to establish a production and distribution planning model that can fairly distribute profit and also take several performance indices, such as customer service and safe inventory level, into consideration and that can then be turned into a multiobjective programming problem. Then, we proposed a modified two-phase method for solving the multiobjective programming problem, so that we can guarantee that each member of the supply chain system can strive for its own maximum profit on the basis of the minimum required profit.

In the rest of this article, the problem statement and assumptions are outlined in section 2. The formulation of production and distribution planning model is described in section 3. The procedure for grouping the vector objectives into a scalar objective using the fuzzy-set concept is described in section 4. A numerical example demonstrating the usefulness of the proposed method is given in section 5. Section 6 shows the results and provides a discussion of the illustrative numerical example. Finally, some conclusions and discussions are made in section 7.

2. Problem Description

A general supply chain is considered, as shown in Figure 1, that consists of three different level enterprises. The first-level enterprise is the retailer or market from which the products are sold to customers subject to a given lower bound of customer service. The second-level enterprise is the distribution center (DC) or warehouse, which uses different types of transportation with different capacities to deliver products from the plant side to the retailer side. The third-level enterprise is the plant or manufacturer that batch manufactures one product during one particular period. If the production line is changed over to manufacture another product, then the manufacturer encounters a fixed manufacturing cost. Also, if the production line is set up to manufacture product i but actually the production line remains idle, then the manufacturer encounters a fixed idle cost. The plant has options of manufacturing in regular time or overtime to satisfy the customer demand. To simplify the problem here, we do not consider the raw material purchasing and inventory problems for plants, and we include the purchasing cost in the manufacturing cost. Therefore, the research region of this paper is from manufacturer to customer, as indicated by the region enclosed in the dashed line in Figure 1.

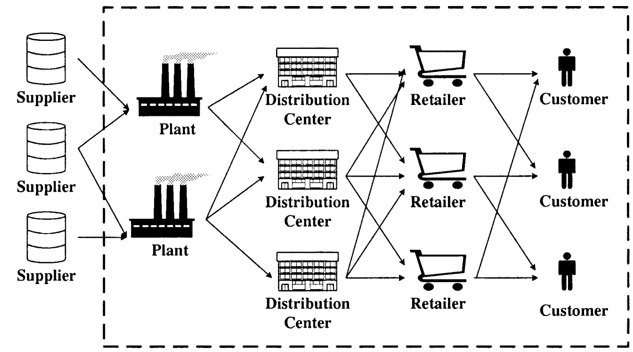


Figure 1. Research region.

In addition, the following assumptions have been made: (1) Products are independent of each other, in terms of marketing and sales price. (2) All required information is available for the entire supply chain system. (3) The customer demand is forecasted for the entire planning period. (4) The optimal decisions will be made on the basis of the forecasted customer demand. (5) Each enterprise has its own safe inventory quantity to reduce the influence of uncertainty caused by demand forecasting. (6) Each cost is different for each different location and character of each enterprise.

The overall problem can thus be stated as follows:

Given

(1) each cost parameter, such as manufacturing, inventory, etc.;

(2) manufacturing data, such as batch manufacturing quantity of regular time and overtime, overtime number constraint, etc.;

(3) transportation data, such as lead time, transportation capacity, etc.;

(4) inventory data, such as inventory capacity, safe inventory quantity, etc.; and

(5) forecasted customer demand and product sales price,

determine

(1) the production plan of each plant,

(2) the transportation plan of each distribution center,

(3) the sales quantity of each retailer,

(4) the inventory level of each enterprise, and

(5) each kind of cost.

The targets are to (1) integrate the multienterprise decisions simultaneously, so as to generate a fair profit distribution, and (2) increase the customer service level and safe inventory level as much as possible.

3. Mathematical Formulation

3.1. Indices, Sets, Parameters, and Variables. According to the assumptions listed in section 2, we can

Table 1. Indices, Sets, and Parameters

index/set	dimension	physical meaning
$r \in$ R	[R] = R	retailers
$d \in$ D	[D] = D	distribution centers
$p \in$ P	[P] = P	plants
$i \in$ I	[I] = I	products
$t \in$ T	[T] = T	periods
$k \in$ K	[K] = K	transportation capacity level, from DC to retailer
$k' \in$ K′	[K′] = K'	transportation capacity level, from plant to DC

parameter	$x \in$	physical meaning
USR_x^i	$\{pd, dr, r\}$	unit sale revenue of i, sold from p to d, etc.
UIC_x^i	$\{p, d, r\}$	unit inventory cost of i for p, d, r
UHC_x^i	$\{p, d, r\}$	unit handling cost of i for p, d, r
$\mathrm{UTC}_x^{k'}$	$\{pd\}$	k'th-level unit transportation cost, from p to d
UTC_x^k	$\{dr\}$	kth-level unit transportation cost, from d to r
$\mathrm{FTC}_x^{k'}$	$\{pd\}$	k'th-level fixed transportation cost, from p to d
FTC_x^k	$\{dr\}$	kth-level fixed transportation cost, from d to r
UMC_x^i	$\{p\}$	unit manufacturing cost of i
OMC_x^i	$\{p\}$	overtime unit manufacturing cost of i
FMC_x^i	$\{p\}$	fixed manufacturing cost for changing p to make i
FIC_x^i	$\{p\}$	fixed idle cost to keep p idle
FCD_x^i	$\{r\}$	forecasted customer demand for i
TLT_x	$\{pd, dr\}$	transportation lead time, from p to d or from d to r
SIQ_x^i	$\{p, d, r\}$	safe inventory quantity in p, d, r
MIC_x	$\{p, d, r\}$	maximum inventory capacity of p, d, r
$\mathrm{TCL}_x^{k'}$	$\{pd\}$	k'th transportation capacity level, from p to d
TCL_x^k	$\{dr\}$	kth transportation capacity level, from d to r
MITC_x	$\{d\}$	maximum input transportation capacity of d
MOTC_x	$\{d\}$	maximum output transportation capacity of d
FMQ_x^i	$\{p\}$	fixed manufacturing quantity of i
OMQ_x^i	$\{p\}$	overall fixed manufacturing quantity
MTO_x	$\{p\}$	maximum total overtime in manufacturing period

design the indices, sets, and parameters of the supply chain model, as shown in Table 1. In this table, the parameters are divided into two categories: the cost parameters, including inventory costs, transportataion costs, etc., and other parameters describing the system information, such as inventory capacities, transportation lead times, etc. Furthermore, relevant variables, including binary ones, which act as policy decisions on whether to use economies of scale for manufacturing or shipping, and other continuous variables are listed in Table 2.

3.2. Constraints and Objective Functions for Retailer *r*. All mathematical relations concerning retailer $r \in \mathscr{R}$ are itemized in Table 3, for which some details are stated below.

3.2.1. Constraints. *1. Inventory Balance.* The inventory level of product i of retailer r during period t, I_{rt}^i, is equal to the amount at period $t-1$, $I_{r,t-1}^i$, plus the amounts received from all DCs, $\sum_d S_{dr,t-\mathrm{TLT}_{dr}}^i$, less the amounts sold to customers during period t, S_{rt}^i. Notably, $S_{dr,t-\mathrm{TLT}_{dr}}^i$ is the quantity of product i shipped from distribution center d to retailer r, considering the delayed shipment caused by the transportation lead time TLT_{dr}. Also note that all inventories should be greater than the safe inventory quantities for last period. Similarly, the backlog level of product i at retailer r during period t, B_{rt}^i, is equal to the amount at period $t-1$, $B_{r,t-1}^i$, plus the amount of customer demand forecasted for period t, FCD_{rt}^i, less the amounts sold to customers during period t, S_{rt}^i. Also, the backlog at last period should be 0 for the purpose of fulfilling customer demand. Finally, all physical variables should be greater than 0.

2. Maximum Inventory Capacity. The amounts of all products at retailer r during period t, $\sum_i I_{rt}^i$, cannot exceed the maximum inventory capacity of retailer r, MIC_r.

3. Safe Inventory Quantity. By using safe inventory quantity constraints, we can make the shortage in the safe inventory level of product i at retailer r during period t, D_{rt}^i, be 0 if the inventory level I_{rt}^i is greater than the safe inventory quantity SIQ_r^i, or we can make it be the less of safe inventory quantity and inventory level if the inventory level is smaller than the safe inventory quantity. Notably, the requirement of all inventories being greater than the safe inventory quantities at the last period implies that there should be no shortage in safe inventories at $t = T$, i.e., $D_{rT}^i = 0$ for all retailers r.

Table 2. Binary Variables and Other Continuous Variables for $t \in \mathscr{T}$

binary	$x \in$	meaning when value = 1
$Y_{xt}^{k'}$	$\{pd\}$	k'th transportation capacity level, from p to d
Y_{xt}^k	$\{dr\}$	kth transportation capacity level, from d to r
α_{xt}^i	$\{p\}$	manufacture with regular-time workforce
β_{xt}^i	$\{p\}$	set up plant p to manufacture i
γ_{xt}^i	$\{p\}$	change p over to manufacture i
o_{xt}^i	$\{p\}$	manufacture with overtime workforce

real	$x \in$	physical meaning
S_{xt}^i	$\{pd, dr, r\}$	sales quantity of i, from p to d, etc.
$Q_{xt}^{k'}$	$\{pd\}$	k'th-level transportation quantity, from p to d
Q_{xt}^k	$\{dr\}$	kth-level transportation quantity, from d to r
Q_{xt}	$\{pd, dr\}$	total transportation quantity, from p to d or from d to r
I_{xt}^i	$\{p, d, r\}$	inventory level of i in p, d, r
B_{xt}^i	$\{r\}$	backlog level of i in r at end of t
D_{xt}^i	$\{p, d, r\}$	shortage in safe inventory level in p, d, r
TMC_{xt}	$\{p\}$	total manufacturing cost of p
TPC_{xt}	$\{d, r\}$	total purchase cost of d, r
TIC_{xt}	$\{p, d, r\}$	total inventory cost of p, d, r
THC_{xt}	$\{p, d, r\}$	total handling cost of p, d, r
TTC_{xt}	$\{d, pd, dr\}$	total transportation cost of d, from p to d or from d to r
PSR_{xt}	$\{p, d, r\}$	product sales revenue of p, d, r
SIL_{xt}	$\{p, d, r\}$	safe inventory level of p, d, r
CSL_{xt}	$\{d\}$	customer service level of r
Z_{xt}	$\{p, d, r\}$	net profit of p, d, r

3.2.2. Costs, Revenues, Customer Service Levels, and Safe Inventory Levels. *1. Total Purchase Cost.* The total purchase cost of retailer r during period t is equal to the sum of the unit sales revenue of product i for DC d selling to retailer r, USR_{dr}^i, multiplied by the quantity of product i sold by DC d to retailer r during period t, S_{drt}^i, for all DCs and all products.

2. Total Inventory Cost. The total inventory cost of retailer r during period t is equal to the sum of the unit inventory cost of product i for retailer r, UIC_r^i, multiplied by the product i inventory level of retailer r at the end of period t, I_{rt}^i, for all products.

Table 3. Mathematical Relations Relevant to Retailer $r \in \mathcal{R}$

	Constraints
inventory and backlog levels	$I^i_{rt} = I^i_{r,t-1} + \sum_d S^i_{dr,t-\mathrm{TLT}_{dr}} - S^i_{rt}$
	$I^i_{rT} \geq \mathrm{SIQ}^i_r$
	$B^i_{rt} = B^i_{r,t-1} + \mathrm{FCD}^i_{rt} - S^i_{rt}$
	$B^i_{rT} = 0,\ I^i_{rt},\ B^i_{rt},\ S^i_{rt} \geq 0$
maximum inventories	$\sum_i I^i_{rt} \leq \mathrm{MIC}_r$
shortage in safe inventories	$\mathrm{SIQ}^i_r - I^i_{rt} \leq D^i_{rt} \leq \mathrm{SIQ}^i_r$
	$D^i_{rt} \geq 0\ (D^i_{rT} = 0)$
	Costs
purchase cost	$\mathrm{TPC}_{rt} = \sum_d \sum_i \mathrm{USR}^i_{dr}\, S^i_{drt}$
inventory cost	$\mathrm{TIC}_{rt} = \sum_i \mathrm{UIC}^i_r\, I^i_{rt}$
handling cost	$\mathrm{THC}_{rt} = \sum_i \mathrm{UHC}^i_r (\sum_d S^i_{dr,t-\mathrm{TLT}_{dr}} + S^i_{rt})$
	Revenue
product sales	$\mathrm{PSR}_{rt} = \sum_i \mathrm{USR}^i_r\, S^i_{rt}$
	Service Level
customer service level	$\mathrm{CSL}_{rt}\,(\%) = \frac{100}{I} \sum_i \left(\frac{S^i_{rt}}{\mathrm{FCD}^i_{rt} + B^i_{r,t-1}} \right)$
	Inventory Level
safe inventory level	$\mathrm{SIL}_{rt}\,(\%) = \frac{100}{I} \sum_i \left(1 - \frac{D^i_{rt}}{\mathrm{SIQ}^i_r} \right)$
	Objective Functions
overall profit	$\max_{\mathbf{x} \in \Omega} \sum_t Z_{rt} = \mathrm{PSR}_{rt} - \mathrm{TPC}_{rt} - \mathrm{TIC}_{rt} - \mathrm{THC}_{rt}$
average customer service level	$\max_{\mathbf{x} \in \Omega} \frac{1}{T} \sum_t \mathrm{CSL}_{rt}$
average safe inventory level	$\max_{\mathbf{x} \in \Omega} \frac{1}{T} \sum_t \mathrm{SIL}_{rt}$

3. Total Handling Cost. The total handling cost of retailer r during period t is equal to the sum of the unit handling cost of product i for retailer r, UHC^i_r, multiplied by the total amount of product i handled during period t, $\sum_d S^i_{dr,t-\mathrm{TLT}_{dr}} + S^i_{rt}$, for all products.

4. Product Sales Revenue. The product sales revenue of retailer r during period t is equal to the sum of the unit sales revenue of product i for retailer r, USR^i_r, multiplied by the quantity of product i sold by retailer r to customers during period t, S^i_{rt}, for all products.

5. Customer Service Level. Considering all products, the customer service level of retailer r during period t is defined as the average percentage ratio of actual sales quantity of product i from retailer r to customer during period t, S^i_{rt}, to the total demand quantity. The total demand quantity is the sum of the forecasted customer demand for product i from retailer r during period t, FCD^i_{rt}, and the backlog level of product i of retailer r at the end of period $t-1$, $B^i_{r,t-1}$.

6. Safe Inventory Level. The safe inventory level of retailer r during period t is defined as the average percentage of 1 minus the ratio of the shortage in the safe inventory level of product i for retailer r during period t, D^i_{rT}, to the safe inventory level of product i for retailer r, SIQ^i_r, for all products.

Table 4. Mathematical Relations Relevant to Distribution Center $d \in \mathcal{D}$

	Constraints
inventory balance	$I^i_{dt} = I^i_{d,t-1} + \sum_p S^i_{pd,t-\mathrm{TLT}_{pd}} - \sum_r S^i_{drt}$
	$I^i_{dT} \geq \mathrm{SIQ}^i_d,\ I^i_{dt},\ S^i_{drt} \geq 0$
maximum inventories	$\sum_i I^i_{dt} \leq \mathrm{MIC}_d$
shortage in safe inventories	$\mathrm{SIQ}^i_d - I^i_{dt} \leq \mathrm{D}^i_{dt} \leq \mathrm{SIQ}^i_d$
	$D^i_{dt} \geq 0\ (D^i_{dT} = 0)$
output transportation	$Q_{drt} = \sum_k Q^k_{drt} = \sum_i S^i_{drt}$
	$\mathrm{TCL}^{k-1}_{dr}\, Y^k_{drt} < Q^k_{drt} \leq \mathrm{TCL}^k_{dr}\, Y^k_{drt}$
	$\sum_k Y^k_{drt} \leq 1$
	$\sum_r \sum_k \mathrm{TCL}^k_{dr}\, Y^k_{drt} \leq \mathrm{MOTC}_d$
input transportation	$Q_{pdt} = \sum_{k'} Q^{k'}_{pdt} = \sum_i S^i_{pdt}$
	$\mathrm{TCL}^{k'-1}_{pd}\, Y^{k'}_{pdt} < Q^{k'}_{pdt} \leq \mathrm{TCL}^{k'}_{pd}\, Y^{k'}_{pdt}$
	$\sum_{k'} Y^{k'}_{pdt} \leq 1$
	$\sum_p \sum_{k'} \mathrm{TCL}^{k'}_{pd}\, Y^{k'}_{pdt} \leq \mathrm{MITC}_d$
	Costs
purchase cost	$\mathrm{TPC}_{dt} = \sum_p \sum_i \mathrm{USR}^i_{pd}\, S^i_{pdt}$
inventory cost	$\mathrm{TIC}_{dt} = \sum_i \mathrm{UIC}^i_d\, I^i_{dt}$
handling cost	$\mathrm{THC}_{dt} = \sum_i \mathrm{UHC}^i_d (\sum_p S^i_{pd,t-\mathrm{TLT}_{pd}} + \sum_r S^i_{drt})$
transportation cost	$\mathrm{TTC}_{dt} = \sum_k \sum_r (\mathrm{FTC}^k_{dr}\, Y^k_{drt} + \mathrm{UTC}^k_{dr}\, Q^k_{drt}) + \sum_{k'}^{k} \sum_p^{r} (\mathrm{FTC}^{k'}_{pd} \mathrm{Y}^{k'}_{pdt} + \mathrm{UTC}^{k'}_{pd} \mathrm{Q}^{k'}_{pdt})$
	Revenue
product sales	$\mathrm{PSR}_{dt} = \sum_r \sum_i \mathrm{USR}^i_{dr}\, S^i_{drt}$
	Inventory Level
safe inventory level	$\mathrm{SIL}_{dt}\,(\%) = \frac{100}{I} \sum_i \left(1 - \frac{D^i_{dt}}{\mathrm{SIQ}^i_d} \right)$
	Objective Functions
overall profit	$\max_{\mathbf{x} \in \Omega} \sum_t \mathrm{Z}_{dt} = \mathrm{PSR}_{dt} - \mathrm{TPC}_{dt} - \mathrm{TIC}_{dt} - \mathrm{THC}_{dt} - \mathrm{TTC}_{dt}$
average safe inventory level	$\max_{\mathbf{x} \in \Omega} \frac{1}{T} \sum_t \mathrm{SIL}_{dt}$

3.2.3. Objectives over T Periods. Some conflicting objectives, including the overall profit, the average customer service level, and the average safe inventory level, are considered simultaneously, as stated in Table 3. Therein, the overall profit is equal to the sum of the sales revenue less each kind of cost. The customer service level and the safe inventory level are average values for all products over the whole forecasting period.

3.3. Constraints and Objective Functions for Distribution Center d and Plant p. The consider-

Table 5. Mathematical Relations Relevant to Plant $p \in \mathscr{P}$

	Constraints
inventory balance	$I^i_{pt} = I^i_{p,t-1} + \mathrm{FMQ}^i_p\, \alpha^i_{p,t-1} + \mathrm{OMQ}^i_p\, o^i_{p,t-1} - \sum_d S^i_{pdt}$
	$I^i_{pT} \geq \mathrm{SIQ}^i_p,\ I^i_{pt},\ S^i_{pdt} \geq 0$
maximum inventories	$\sum_i I^i_{pt} \leq \mathrm{MIC}_p$
shortage in safe inventories	$\mathrm{SIQ}^i_p - I^i_{pt} \leq D^i_{pt} \leq \mathrm{SIQ}^i_p$
	$D^i_{dp} \geq 0\ (D^i_{pT} = 0)$
manufacturing	$\sum_i \beta^i_{pt} = 1 \qquad \alpha^i_{pt} \leq \beta^i_{pt}$
	$\gamma^i_{pt} \geq \beta^i_{pt} - \beta^i_{p,t-1} \qquad o^i_{pt} \leq \alpha^i_{pt}$
	$\sum_i \sum_t o^i_{pt} \leq \mathrm{MTO}_p$
	$\sum_i \sum_n o^i_{p,t-n+1} \leq N - 1$
	Costs
manufacturing cost	$\mathrm{TMC}_{pt} = \sum_i [\mathrm{FMC}^i_p\, \gamma^i_{pt} + \mathrm{FIC}^i_p(\beta^i_{pt} - \alpha^i_{pt}) + \mathrm{UMC}^i_p \mathrm{FMQ}^i_p\, \alpha^i_{pt} + \mathrm{OMC}^i_p \mathrm{OMQ}^i_p\, o^i_{pt}]$
inventory cost	$\mathrm{TIC}_{pt} = \sum_i \mathrm{UIC}^i_p\, I^i_{pt}$
handling cost	$\mathrm{THC}_{pt} = \sum_i \mathrm{UIC}^i_p(\mathrm{FMQ}^i_p\, \alpha^i_{p,t-1} + \mathrm{OMQ}^i_p\, o^i_{p,t-1} + \sum_d S^i_{pdt})$
	Revenue
product sales	$\mathrm{PSR}_{pt} = \sum_d \sum_i \mathrm{USR}^i_{pd}\, S^i_{pdt}$
	Inventory Level
safe inventory level	$\mathrm{SIL}_{pt}\,(\%) = \dfrac{100}{I} \sum_i \left(1 - \dfrac{D^i_{pt}}{\mathrm{SIQ}^i_p}\right)$
	Objective Functions
overall profit	$\max_{\mathbf{x} \in \Omega} \sum_t Z_{pt} = \mathrm{PSR}_{pt} - \mathrm{TMC}_{pt} - \mathrm{TIC}_{pt} - \mathrm{THC}_{pt}$
average safe inventory level	$\max_{\mathbf{x} \in \Omega} \dfrac{1}{T} \sum_t \mathrm{SIL}_{pt}$

ations for the distribution centers and plants are similar to those for the retailers, so we will not repeat the descriptions. The relevant mathematical formulations are listed in Tables 4 and 5, respectively. Therein, some output constraints exist for DC d to transport product i at different economic scales to retailers. The quantity of each product i shipped to retailer r during period t, $\sum_i S^i_{drt}$, is translated into a total quantity shipped to retailer r, $Q_{drt} = \sum_k Q^k_{drt}$. There are upper/lower bounds for each type of transportation. DC d can choose only one mode of transportation to retailer r during period t, and DC d cannot exceed its maximum transportation energy to transport products to all retailers. Similar constraints for transportation from plants to distribution centers also exist. The transportation cost is the sum of the input and output transportation costs. For instance, with output transportation quantity $Q_{drt} = Q^k_{drt} \in [\mathrm{TCL}^{k-1}_{drt}, \mathrm{TCL}^{k-1}_{drt}]$, the output transportation cost from d to r during period t is a composite of the transportation-level-dependent fixed cost, FTC^k_{dr}, and a transportation-quantity-dependent carrying cost,

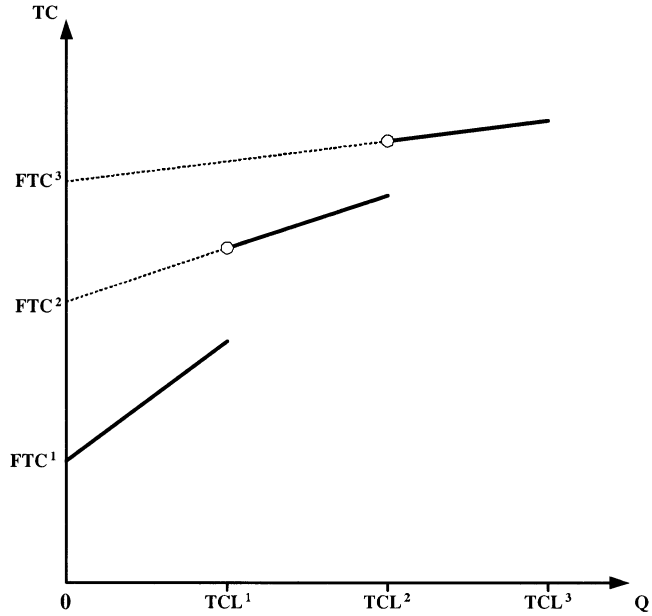


Figure 2. Piecewise linear relationship (solid lines) between transportation cost, TC, and shipment quantity, Q.

$\mathrm{UTC}^k_{dr} Q_{drt}$. This would cause a piecewise linear output transportation cost from d to r, TTC_{drt}, as a function of the distribution center's output shipment quantity, TC_{drt}, as shown in Figure 2, where the subscripts have been omitted. This relation applies for input transportation costs and shipment quantities.

Notably, we pose six constraints on manufacturing, as shown in Table 5. First, the plant must be set up to manufacture product i (only one of the variables β^i_{pt} can have value 1). The second constraint, $\alpha^i_{pt} \leq \beta^i_{pt}$, restricts the plant to manufacture product i in regular time only after it has been set up to manufacture product i. Third, when $\beta^i_{pt} - \beta^i_{p,t-1} = 1$, the plant can change over to manufacture product i during period t. Fourth, the plant is able to manufacture product i in overtime only when regular time production is not sufficient. The fifth constraint implies that the total number of overtime periods should be less than the maximum allowable number of overtime periods, $\mathrm{MTO_p}$; the last restriction also says that the number of continuous overtime periods should be less than N. The manufacturing cost is the sum of the fixed manufacturing and idle costs, plus the regular and overtime manufacturing costs. The equation for manufacturing cost can help explain the meanings of α^i_{pt}, β^i_{pt}, γ^i_{pt}, and o^i_{pt}. For example, the γ^i_{pt} value (to measure whether the production plan is going to be changed to produce product i) will be either 0 (if $\beta^i_{pt} - \beta^i_{p,t-1} = 0$, continue to produce or to not produce product i) or 1 (if $\beta^i_{pt} - \beta^i_{p,t-1} = 1$, change over to start producing product i).

3.4. Integration of Production and Distribution Models. We integrate three different levels of enterprises to establish a mixed-integer nonlinear programming model. Then, we can solve this model using the fuzzy approach, which is discussed in section 4. The numbers of objectives, constraints, and variables are summarized as follows: (1) The number of objective functions is $3R + 2D + 2P$; (2) the numbers of constraints are (a) for retailers, $(2I + 2T + 7I \times T) \times R$, (b) for DCs, $[I \times D + (3 + 2R + K \times R + 2P + K' \times P + 5I) \times T] \times D$, and (c) for plants: $(2 + I + 2T + 8I \times T) \times P$; and (3) the numbers of variables are (a)

$(K \times D \times R + K' \times P \times D + 4I \times P) \times T$ binary variables and (b) $(K \times D \times R + K' \times P \times D + 3I \times R + 2I \times D + 2I \times P) \times T$ continuous variables.

4. Fuzzy Approach for Multiobjective Optimization

Consider the multiobjective mixed-integer nonlinear programming problem defined below

$$\max_{\mathbf{x}\in\Omega} (J_1(\mathbf{x}), ..., J_S(\mathbf{x})) \tag{1}$$

where $\mathbf{x}$ is the variable vector and Ω denotes the feasible searching space. The objective functions $J_i(\mathbf{x})$ usually conflict with one another in practice. It is thus impossible for every objective function to attain its own optimum, J_s, $s \in \mathcal{S} = [1, ..., S]$, simultaneously. The optimization of one objective implies the sacrifice of other targets. Therefore, the decision maker (DM) must make some compromise among these goals. In contrast to the optimality used in single-objective optimization problems, Pareto optimality characterizes the solutions of multiobjective optimization problems.[12]

Several methods for solving multiobjective optimization problems can be found in the literature. Among them, the weighted-sum method is used most often. On the basis of a subjective understanding of each objective, the DM can weigh these objectives and assemble them into a scalar form. However, as the possible ways of combining weighting factors are numerous, this method becomes tedious, and the solution might still be invalid. Moreover, it is difficult for the DM to assign a set of incompatible objectives, such as cost, economic efficiency, and service level, without knowledge of the possible levels of attainment for these objectives. The physical meaning of the final scalar objective function is thus usually vague.

One method of relaxing parallel comparisons of objectives with different units is to scale each of the objectives directly onto the range [0, 1] or some other interval by suitable factors. Then, one can optimize the weighted sum of the scalar functions or a product of them, such as the Nash-type function. However, we adopt the fuzzy-set concept[13] in the following because it can provide a clearer theoretical analysis. By considering the uncertain property of human thinking, it is quite natural to assume that the DM has a fuzzy goal, $\mathcal{J}_s$, to describe the objective J_s in an interval $[J_s^*, J_s^-]$. The sth maximum objective is quite satisfied if the objective value $J_s \geq J_s^*$, and it is unacceptable if $J_s \leq J_s^-$. A strictly monotonically increasing membership function, $\mu_{\mathcal{J}_s}(\mathbf{x}) \in [0, 1]$, can be used to characterize such a transition from objective value to degree of satisfaction

$$\mu_{\mathcal{J}_s}(\mathbf{x}) = \begin{cases} 1 & \text{for } J_s \geq J_s^* \\ \mathbb{F}(J_s, J_s^-, J_s^*) & \text{for } J_s^- \leq J_s \leq J_s^*,\ s \in \mathcal{S} \\ 0 & \text{for } J_s \leq J_s^- \end{cases} \tag{2}$$

where $\mathbb{F}(J_s, J_s^-, J_s^*)$ is a monotonically increasing membership function for which a value of 1 denotes absolutely satisfactory and a value of 0 means unacceptable. The original multiobjective optimization problem is now equivalent to looking for a suitable decision that can provide the maximum overall degree of satisfaction for the multiple fuzzy objectives

$$\max_{\mathbf{x}\in\Omega} (\mu_{\mathcal{J}_1}(\mathbf{x}), ..., \mu_{\mathcal{J}_s}(\mathbf{x})) \tag{3}$$

Under circumstances of incompatible objective, a DM must make a compromise decision that provides a maximum degree of satisfaction for all of the conflicting objectives. The new optimization problem, eq 3, can be interpreted as the synthetic notation of a conjunction statement (maximize jointly all objectives). The result of this aggregation, $\mathcal{D}$, can be viewed as a fuzzy intersection of all fuzzy goals $\mathcal{J}_s$, $s \in \mathcal{S}$, and is still a fuzzy set

$$\mathcal{D} = \mathcal{J}_1 \cap \mathcal{J}_2 \cap \cdots \cap \mathcal{J}_s \tag{4}$$

The final degree of satisfaction resulting from a certain variable set, $\mu_{\mathcal{D}}(\mathbf{x})$ can be determined by aggregating the degree of satisfaction for all objectives, $\mu_{\mathcal{J}_s}(\mathbf{x})$, $s \in \mathcal{S}$, via a specific t-norm, $\mathbb{T}$

$$\mu_{\mathcal{D}}(\mathbf{x}) = \mathbb{T}(\mu_{\mathcal{J}_1}(\mathbf{x}), \mu_{\mathcal{J}_2}(\mathbf{x}), ..., \mu_{\mathcal{J}_s}(\mathbf{x})) \tag{5}$$

As the firing level for each policy is determined by the above procedure, the best solution $\mathbf{x^*}$ with the maximum firing level, $\mu_{\mathcal{D}}(\mathbf{x^*})$, can be selected

$$\mu_{\mathcal{D}}(\mathbf{x^*}) = \max_{\mathbf{x}\in\Omega} \mu_{\mathcal{D}}(\mathbf{x}) = \max_{\mathbf{x}\in\Omega} \mathbb{T}(\mu_{\mathcal{J}_1}(\mathbf{x}), \mu_{\mathcal{J}_2}(\mathbf{x}), ..., \mu_{\mathcal{J}_s}(\mathbf{x})) \tag{6}$$

Now the original problem, eq 1, has been modified into the new multiobjective problem, eq 3. Using the t-norm, this new problem is converted into a single-objective problem, eq 6. Several t-norms can be chosen for $\mathbb{T}$, for which the two most popular selections are shown below[17]

$$\mathbb{T}(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, ..., \mu_{\mathcal{J}_s}) = \begin{cases} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, ..., \mu_{\mathcal{J}_s}) & \mathbb{T} = \text{minimum} \\ \mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times \cdots \times \mu_{\mathcal{J}_s} & \mathbb{T} = \text{product} \end{cases} \tag{7}$$

Selecting the product of scaled objective functions can guarantee a compensatory solution, but the drawback is that product operator might cause an unbalanced solution between all objectives by the inherent character of product. This also conflicts with the original purpose of obtaining a compromise solution for multiobjective programming. The minimum operator represents the worst situation. However, the minimum operator might result in a noncompensatory solution.[16] We thus propose a modified two-phase method by combining the advantages of these two t-norms. The minimum operator is used first in phase I to maximize the satisfaction of the worst situation; then the product operator is applied in phase II to maximize the overall satisfaction with guaranteed minimal fulfillment for all fuzzy objectives as additional constraints. Notably, we have substituted the average operator in the original two-phase method[16] with the product for phase II, because the average is not a t-norm and its physical meaning is vague. Such a modification can provide the best achievable performance, as demonstrated in section 6. The merit of the proposed method is that we can not only obtain the unique optimal solution by using the product operator but also guarantee each objective to go after their own maximum on the basis of the least degree of satisfaction as the lower-bound constraint. Thus, now we can summarize the procedure of the fuzzy satisfying approach for the multiobjective optimization problem, eq 1.

Step 1. Determine the ideal solution and the anti-ideal solution by directly maximizing and minimizing each objective function, respectively

$$\max J_s = J_s^* \quad \text{(ideal solution of } J_s\text{, totally acceptable value)} \tag{8}$$

$$\min J_s = J_s^- \quad \text{(anti-ideal solution of } J_s\text{, unacceptable value)} \tag{9}$$

Notably, if an objective function being maximized is minimized, its value could sometimes be negative or zero. In such a case one can also choose a meaningful expected lower-bound as the anti-ideal solution of its objective.

Step 2. Define membership functions for those fuzzy objectives. To simplify treatment of the problem, we adopt a linear function for $\mathbb{F}$, although optimal fuzzy membership functions exist for specific problems. It is noted that the use of a linear membership function results in simple scaling of all objective values onto the interval [0, 1]

$$\mu_{\mathcal{J}_s} = \begin{cases} 1 & J_s \geq J_s^* \\ \dfrac{J_s - J_s^-}{J_s^* - J_s^-} & J_s^- \leq J_s \leq J_s^*, \forall\, s \in \mathcal{S} \\ 0 & J_s \leq J_s^- \end{cases} \tag{10}$$

Step 3 (Phase I). Obtain the maximum degree of satisfaction for the worst situation, $\mu_{\min}$, by the minimum operator

$$\max_{\mathbf{x}\in\Omega} \mu_{\mathcal{D}} = \max_{\mathbf{x}\in\Omega} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, ..., \mu_{\mathcal{J}_s}) = \mu_{\min} \tag{11}$$

Step 4 (Phase II). Maximize the overall satisfaction of the problem by using the product operator with guaranteed minimal fulfillment for all objectives

$$\max_{\mathbf{x}\in\Omega} \mu_{\mathcal{D}} = \max_{\mathbf{x}\in\Omega^+}(\mu_{\mathcal{J}_1} \times \mu_{\mathcal{J}_2} \times \cdots \times \mu_{\mathcal{J}_s}) \tag{12}$$

where

$$\Omega^+ = \Omega \cap \{\mu_{\mathcal{J}_s} \geq \mu_{\min}, \forall\, s \in \mathcal{S}\} \tag{13}$$

5. Numerical Example

Considering a supply chain consisting of one plant, two distribution centers, two retailers, and two products. The first distribution center is a smaller-scale but faster-delivery-service distributor. This means that the first DC can rapidly respond to suddenly increasing customer demand to maintain a retailer's customer service level, but it also implies higher operating costs. The second DC, on the other hand, is a large-scale but slower-delivery-service distributor. This means it can use economies of scale for transporting goods to lower its operating costs, but on the other hand, it cannot provide prompt delivery. We assume that the transportation lead time between each level for the second DC is 1 week. Thus, the distribution channels between plants and retailers are complementary, with faster, smaller shipments and slower, larger shipments. In addition, to simplify the problem, we neglect the fluctuating rate of cost parameters. The whole planning horizon is 10 periods (weeks) based on a forecasted customer demand with a normal distribution with a mean and standard deviation.

Other indices and sets are $[\mathcal{N}] = 5$, $[\mathcal{R}] = 3$, and $[\mathcal{K}'] = 2$. We assume values of all parameters as listed in Tables 6 and 7. By way of parameter design, there are only two effective selections for the smaller but faster distributor ($d = 1$), although the allowable number of output transportation levels is $[\mathcal{R}] = 3$. To solve this mixed-integer nonlinear programming problem for the supply chain model, the generalized algebraic modeling system (GAMS),[18] a well-known high-level modeling system for mathematical programming problems, is used as the solution environment. The MINLP solver used is SBB, which employs a standard branch-and-bound strategy, and the NLP solver is CONOPT. We used a personal computer with an Intel Pentium III 866 CPU for all computational runs with a tolerance of optimality of 5%.

Table 6. Cost Parameters of Illustrative Example

unit sales revenue					unit transportation cost					fixed transportation cost				
i	*p*	*d*	*r*	$	*k*	*p*	*d*	*r*	$	*k*	*p*	*d*	*r*	$
USR^{ir}					UTC_d^{kr}					FTC_d^{kr}				
1			1	1700	1		1	1	45	1		1	1	7000
1			2	1700	2		1	1	27	2		1	1	10 000
2			1	1700	3		1	1	27	3		1	1	10 000
2			2	1700	1		1	2	50	1		1	2	7000
USR_d^{ir}					2		1	2	30	2		1	2	10 000
1		1	1	1600	3		1	2	30	3		1	2	10 000
1		1	2	1600	1		2	1	45	1		2	1	3000
1		2	1	1250	2		2	1	30	2		2	1	4600
1		2	2	1200	3		2	1	18	3		2	1	7200
2		1	1	1600	1		2	2	35	1		2	2	2500
2		1	2	1600	2		2	2	25	2		2	2	4000
2		2	1	1250	3		2	2	15	3		2	2	6000
2		2	2	1200										
USR_{pd}^{i}					$UTC_{pd}^{k'}$					$FTC_{pd}^{k'}$				
1	1	1		900	1	1	1		60	1	1	1		10 000
1	1	2		800	2	1	1		40	2	1	1		16 000
2	1	1		900	1	1	2		25	1	1	2		12 000
2	1	2		800	2	1	2		15	2	1	2		15 000

unit inventory cost					unit handling cost					unit manufacturing cost		
i	*p*	*d*	*r*	$	*i*	*p*	*d*	*r*	$	*i*	*p*	$
UIC_r^i					UHC_r^i					UMC_p^i		
1			1	50	1			1	15	1	1	80
1			2	50	1			2	15	2	1	40
2			1	50	2			1	15	OMC_p^i		
2			2	50	2			2	15	1	1	120
UIC_d^i					UHC_d^i					2	1	60
1		1		60	1		1		20	fixed manufacturing/ idle cost		
1		2		20	1		2		10	FMC_p^i		
2		1		60	2		1		20	1	1	32 000
2		2		20	2		2		10	2	1	64 000
UIC_p^i					UHC_p^i					FIC_p^i		
1	1			30	1	1			10	1	1	3200
2	1			30	2	1			10	2	1	6400

Table 7. Other Parameters of Illustrative Example

transportation lead time (p d r)		safe inventory quantity (i p d r)		transportation capacity level (k p d r)	
TLT_{dr}		SIQ_r^i		TCL_{dr}^k	
1 1	0	1 1	100	1 1 1	50
1 2	0	1 2	100	2 1 1	100
2 1	1	2 1	100	3 1 1	100
2 2	1	2 2	100	1 1 2	50
TLT_{pd}		SIQ_d^i		2 1 2	100
1 1	0	1 1	100	3 1 2	100
1 2	1	1 2	600	1 2 1	150
maximum		2 1	100	2 2 1	300
inventory capacity		2 2	600	3 2 1	600
MIC_r		SIQ_p^i		1 2 2	150
1	400	1 1	400	2 2 2	300
2	400	2 1	400	3 2 2	600
MIC_d		fixed manuf quantity		$TCL_{pd}^{k'}$	
1	800	FMQ_p^i		1 1 1	100
2	6000	1 1	800	2 1 1	200
		2 1	800	1 1 2	600
MIC_p		OMQ_p^i		2 1 2	1000
1	3200	1 1 1	200		
total overtime #		2 1 1	200		
MTO_p		max input/output transportation capacities			
1	5	$MITC_d$		$MOTC_d$	
		1	200	1	200
		2	1200	2	1200

Table 8. Ideal and Anti-Ideal Solutions of Each Objective

objectives	p	d	r	ideal solution	anti-ideal solution
profit			1	1, 378, 004	−142, 710
			2	1, 570, 641	92, 130
		1		944, 700	−365, 523
		2		2, 856, 482	224, 354
service level	1			5, 305, 600	2, 964, 022
safe inventory level			1	0.99	0.73
			2	0.99	0.73
			1	0.94	0.00
			2	0.95	0.00
		1		1.00	0.00
		2		0.97	0.00
	1			0.98	0.00

6. Results and Discussion

According to the problem description, mathematical formulation, and parameter design provided above, we solved the multiobjective mixed-integer nonlinear programming problem for a production and distribution planning problem by using the fuzzy procedure discussed in section 4.

Step 1. Obtain the ideal and anti-ideal solutions by directly maximizing and minimizing each objective function, respectively; the results are reported in Table 8. As we have mentioned previously, one can also subjectively select ideal and anti-ideal solutions for each objective if meaningful upper and lower bounds can be expected. Alternatively, the DM can also adjust these values according to subjective judgment if not satisfied with the final result. Without loss of generality, we adopt the computed ideal and anti-ideal solutions directly without any adaptation.

Step 2. Establish each linear membership function and the overall degree of satisfaction $\mu_{\mathscr{D}}$ as described in the preceding section.

Step 3 (Phase I). Obtain the least degree of satisfaction for all objectives, $\mu_{\min}$, by the minimum operator. For this example, the result is $\mu_{\min} = 0.66$.

Step 4 (Phase II). reoptimize the problem with new constraints of maximized satisfaction for the worst situation. The results are shown in the following figures and discussed below. In these figures, the results obtained by using only the minimum or product t-norms and results obtained using a Nash-type objective and a single profit-based objective are also provided. In the latter two cases, the service levels and safe inventory levels have been ignored.

As shown in Figure 3, by selecting the minimum as the t-norm, we can obtain more balanced satisfaction among all objectives, with an overall degree of satisfaction of around 0.66. By using the product operator to guarantee a unique solution, however, the results are unbalanced, with the lowest degree of satisfaction for the profit and safe inventory level of distributor $d = 2$ and the profit of plant $p = 1$. On the other hand, higher performance objectives or goals are given a very high emphasis. Obviously, this is not desirable for a compromise solution. To overcome the drawbacks of a single-phase method, the proposed modified two-phase method can combine the advantages of these two t-norms. The minimum operator is used in phase I to find the maximum satisfaction for the worst situation, and the product operator is applied in phase II with a guaranteed satisfaction level for all fuzzy objectives. The results of the original two-phase method, where the average operator is applied in phase II optimization, are also provided for comparison. To summarize, the resulting satisfaction levels for all fuzzy objectives are greater than 0.66, which is the maximized worst fulfillment obtained by phase I, and the modified two-phase method can provide the best achievable performance, as depicted in Figure 4.

We can also compare these results to the single-objective programming method of maximizing the overall profit summed over all participants, the most common method in the traditional approach to supply chain planning in which only profit-related terms are considered, because it is difficult to quantify customer service and other nonmonetary goals into monetary amounts in the objective function. We can also project the result caused by single-objective programming on the membership functions, as shown in Figure 5. Obviously, the satisfaction levels are extremely unbalanced, because the objective function is taking only the sum of the overall profit into consideration. We can also compare the results of the two-phase approach to the use of a Nash-type model as the objective function.[11] The lower bound on the profit of each member might be difficult to determine because of the inherent uncertainty, so we use the lower bound on the membership function in the fuzzy approach instead. As the single-objective programming, we can also project the result caused by Nash-type model on the satisfaction levels, as shown in Figure 5. The satisfaction levels are extremely unbalanced, because the objective function is taking only profits into consideration. The results of modified two-phase method are also shown for comparison.

By the computation results of the modified two-phase method, we can also obtain all decision variables, such as the production schedule, transportation plan, etc., to achieve the goal of fair profit distribution. For example, the transportation quantities from DCs to retailers, Q_{drt}^k, are showed in Figure 6.

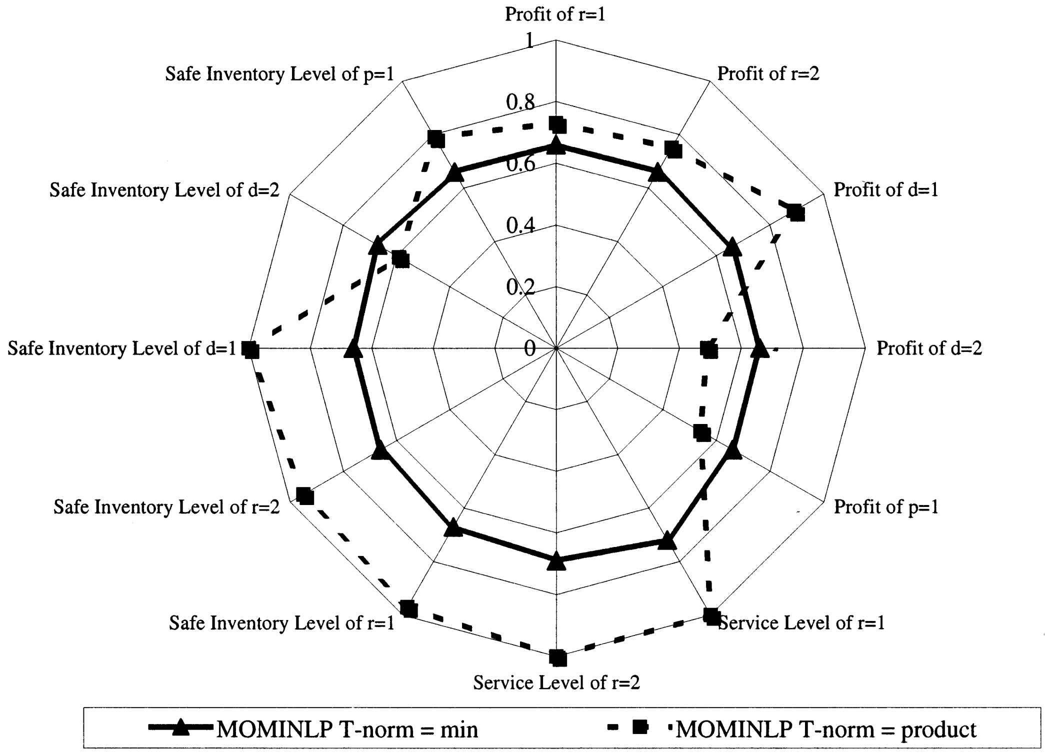


Figure 3. Comparison of satisfaction level of each objective using single-phase optimization by selecting minimum or product as t-norm.

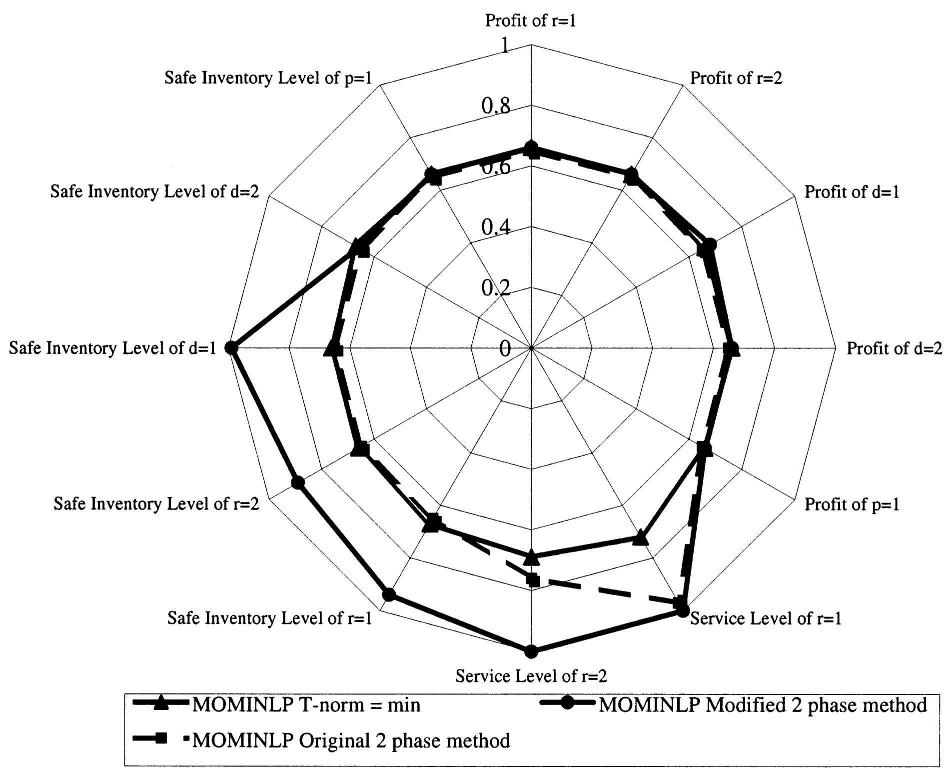


Figure 4. Comparison of satisfaction level of each objective by single-phase minimum operator and original and modified two-phase methods.

It can be seen that the DCs will select the proper economical transportation capacity level, such as 150, 300, and 600 products from DC $d = 2$ to retailer $r = 1$ in Figure 6c, to transport products. This is caused by the noncontinuous piecewise linear transportation cost function, which is composed of fixed and variable transportation costs for different levels of capacities. Analyses of other variables are omitted due to space limitations and can be found elsewhere.[19]

7. Conclusion

In this paper, we investigate the problem of a fair profit distribution for a typical supply chain network. The range is from manufacturing plant to customer site, including factories, distribution centers or warehouses, and retailers or markets.

To implement this concept, we construct a multiproduct, multistage, and multiperiod production and distri-

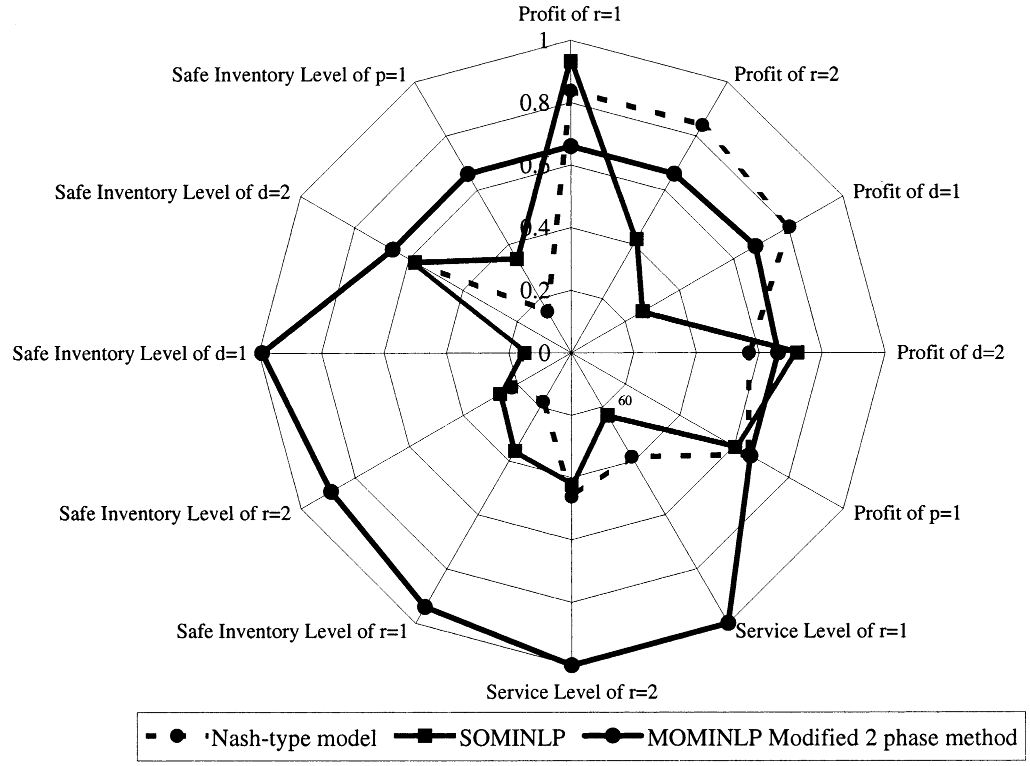
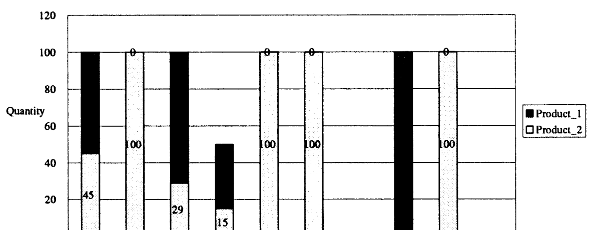


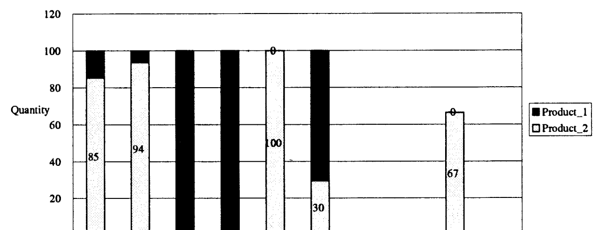
Figure 5. Comparison of satisfaction level of each objective by single-objective programming method, Nash-type method, and modified two-phase method



	1	2	3	4	5	6	7	8	9	10
■ Product_1	55	0	71	35	0	0	0	100	0	0
□ Product_2	45	100	29	15	100	100	0	0	100	0

Time

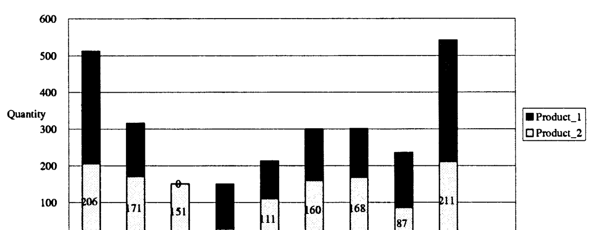
(a) *from* $d = 1$ *to* $r = 1$



	1	2	3	4	5	6	7	8	9	10
■ Product_1	15	6	100	100	0	71	0	0	0	0
□ Product_2	85	94	0	0	100	30	0	0	67	0

Time

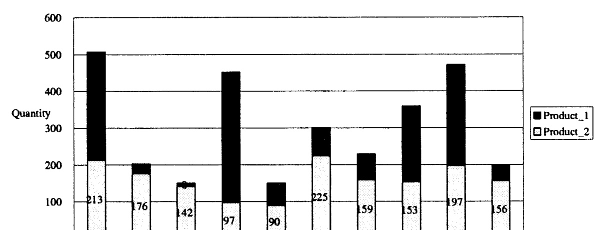
(b) *from* $d = 1$ *to* $r = 2$



	1	2	3	4	5	6	7	8	9	10
■ Product_1	306	145	0	121	102	140	133	149	330	0
□ Product_2	206	171	151	29	111	160	168	87	211	0

Time

(c) *from* $d = 2$ *to* $r = 1$



	1	2	3	4	5	6	7	8	9	10
■ Product_1	294	27	8	355	60	77	70	206	275	40
□ Product_2	213	176	142	97	90	225	159	153	197	156

Time

(d) *from* $d = 2$ *to* $r = 2$

Figure 6. Plans for transportation from DCs to retailers.

bution planning model to achieve objectives such as maximizing the profit of each participant enterprise, maximizing the customer service level, maximizing the safe inventory level, and ensuring a fair profit distribution. The model is then formulated as a multiobjective mixed-integer nonlinear programming (MOMINLP) problem.

The fuzzy-set theory is used to attain a compromise solution among all participant companies of the supply chain. Therein, each objective function is viewed as a fuzzy goal. The ideal and anti-ideal solutions are determined by maximizing and minimizing each individual objective function, respectively. A linearly increasing membership function is used to denote the degree of satisfaction of each objective by using the ideal and anti-ideal solutions as upper and lower bounds, respectively. The final decision is interpreted as the fuzzy aggregation of multiple objectives, and the best compromise solution can be found by maximizing the overall degree of satisfaction for the decision. Two popular t-norms, the product and the minimum, are studied for implementing the fuzzy intersection. It is found that using the product operator might cause an unbalanced solution among all objectives, whereas using the minimum operator might result in noncompensatory solutions. We proposed a modified two-phase method by combining the advantages of these two t-norms to reach a fair profit distribution solution. The minimum operator is used in phase I to find the maximum satisfaction for the worst situation, and the product operator is then applied in phase II with a guaranteed minimal degree of fulfillment for all fuzzy objectives. One case study is discussed, demonstrating that the proposed two-phase decision-making method can provide an improved compensatory solution for multiobjective problems in a supply chain network.

Acknowledgment

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Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices

Cheng-Liang Chen*, Wen-Cheng Lee

Department of Chemical Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC

Abstract

A multi-product, multi-stage, and multi-period scheduling model is proposed in this paper to deal with multiple incommensurable goals for a multi-echelon supply chain network with uncertain market demands and product prices. The uncertain market demands are modeled as a number of discrete scenarios with known probabilities, and the fuzzy sets are used for describing the sellers' and buyers' incompatible preference on product prices. The supply chain scheduling model is constructed as a mixed-integer nonlinear programming problem to satisfy several conflict objectives, such as fair profit distribution among all participants, safe inventory levels, maximum customer service levels, and robustness of decision to uncertain product demands, therein the compromised preference levels on product prices from the sellers and buyers point of view are simultaneously taken into account. The inclusion of robustness measures as part of objectives can significantly reduce the variability of objective values to product demand uncertainties. For purpose that a compensatory solution among all participants of the supply chain can be achieved, a two-phase fuzzy decision-making method is presented and, by means of application of it to a numerical example, proved effective in providing a compromised solution in an uncertain multi-echelon supply chain network.

Keywords: Supply chain management; Uncertainty; Robustness; Multiple objectives; Mixed-integer nonlinear programming; Fuzzy optimization

1. Introduction

Industries around the world are now all rushing the territory of globalization and specialization. Cooperating with good strategic partners is the sure way to tackle the potential problems arising from competition. Companies can achieve the optimum operating efficiency by working with other companies through communication and specialization, which evolve a new type of relationship, the supply chain relationship, among these companies and further foster a new concept in management: the supply chain management concept. A great variety of companies, those in chemical industry included, can also take advantage of this novel management scheme. Therefore, many researchers in process systems engineering (PSE) society devote themselves to this interesting field (Applequist, Pekny, & Reklaitis, 2000; Bose & Pekny, 2000; Chen, Wang, & Lee, 2003; Garcia-Flores, Wang, & Goltz, 2000; Gupta & Maranas, 2000; Gupta, Maranas, & McDonaldet, 2000; Perea-Lopez, Grossmann, & Ydstie, 2000; Pinto, Joly, & Moro, 2000; Zhou, Cheng, & Hua, 2000; to name a few).

In traditional supply chain management, the focus of the integration of supply chain network is usually on single objective, minimum cost or maximum profit. For example, Gjerdrum, Shah, and Papageorgiouet (2001) proposed a mixed-integer linear programming model for a production and distribution planning problem and solve the fair profit distribution problem by using the Nash-type model as the single objective function. However, there are no design tasks that are single objective problems. The design/planning/scheduling projects are usually involving trade-offs among different incompatible goals (Cheng, Subrahmanian, & Westerberg, 2003). Recently, a multi-objective production and distribution-scheduling scheme for a supply chain system is formulated by Chen et al. (2003). In this method, in addition to maximizing profit for the entire system, fair profit distribution among all members, customer service levels, and safe inventory levels are taken into account simultaneously. All the problem parameters are deterministically known in the model. In practice, however, this is rarely the case as it is usually difficult to foretell prices of chemicals, market demands, and availabilities of raw materials, etc., in a precise fashion (Liu & Sahinidis, 1997).

* Corresponding author. +886-2-23636194; fax: +886-2-23623040.
E-mail address: CCL@ntu.edu.tw (C.-L. Chen).

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A number of works have devoted to studying supply chain management under uncertain environments. For example, Gupta and Maranas (2000), Gupta et al. (2003) incorporate the uncertain demand via a normal probability function and propose a two-stage solution framework. A generalization to handle multi-period and multi-customer problems is recently proposed (Gupta & Maranas, 2003). Tsiakis et al. (2001) use scenario planning approach to describe demand uncertainties. Therein a number of demand scenarios with assigned non-zero probabilities is used as discrete stochastic demand quantities. All scenarios are simultaneously taken into account in the supply chain network design. However, the robustness of decision to uncertain product demands is not considered in these studies. Due to the potential of dealing with linguistic expressions and uncertain issues (Zadeh, 1965; Petrovic, Roy, & Petrovic, 1998) use fuzzy sets to handle uncertain demands and external raw material problems, and further considering uncertain supply deliveries in a later work (Petrovic, Roy, & Petrovic, 1999). Giannoccaro, Pontrandolfo, and Scozzi (2003) also apply fuzzy sets theory to model the uncertainties associated with both market demand and inventory costs. The product price, despite with their obvious negotiable and uncertain characteristics in real businesses, seems seldom to be taken into account as a source of uncertainty in previous works. Instead, the product prices at selling points are usually treated as determined parameters.

In this paper, we incorporate two kinds of uncertainties including the market demands and product prices. The scenario-based approach will be adopted for modeling the uncertain market demands, and the product prices will be taken as fuzzy variables where the incompatible preference on prices for different members are handled simultaneously. The whole supply chain scheduling model would turn into a mixed-integer nonlinear programming (MINLP) problem ultimately. The compromised solution for ensuring fair profit distribution, safe inventory levels, maximum customer service levels, decision robustness to uncertain product demands, and simultaneously considering incompatible preference of product prices for all participants will be determined by applying the fuzzy multi-objective optimization method.

In the rest of this article, the problem statement and assumptions are outlined in Section 2. The considered uncertain issues in supply chain scheduling are described in Section 3. The formulation of a production and distribution-scheduling model is set out in Section 4. The procedure for grouping the scenario-dependent multiple conflict objectives and uncertain fuzzy product prices into a scalar one using the fuzzy sets concept is presented in Section 5. The contents of a numerical example, used to demonstrate the usefulness of the proposed method, are given in Section 6. Finally, some concluding remarks are drawn in Section 7.

2. Problem description

A general supply chain that consists of three different levels of enterprises is considered and showed in Fig. 1 (Chen et al., 2003): the first level enterprise is retailer or market from which the products are sold to customer under the conditions subject to a given low bound of customer service; the second level enterprise is distribution center (DC) or warehouse using different type of transport capacity to deliver products from plant side to retailer side; and the third level enterprise is plant or manufacturer that batch-manufactures one product at one period. The fixed manufacture/idle costs are also employed: on one hand, if the production line is changed over to manufacture another product, manufacture cost would be remained fixed; on the other hand, if the production line is set up to manufacture one specific product but actually is idle, the idle cost, also fixed. Furthermore, the plant has options of manufacturing in regular time or overtime to satisfy the customer demand. To simplify the problem here, we do not consider the problem of purchase and inventory of the raw material in plants nor incorporate

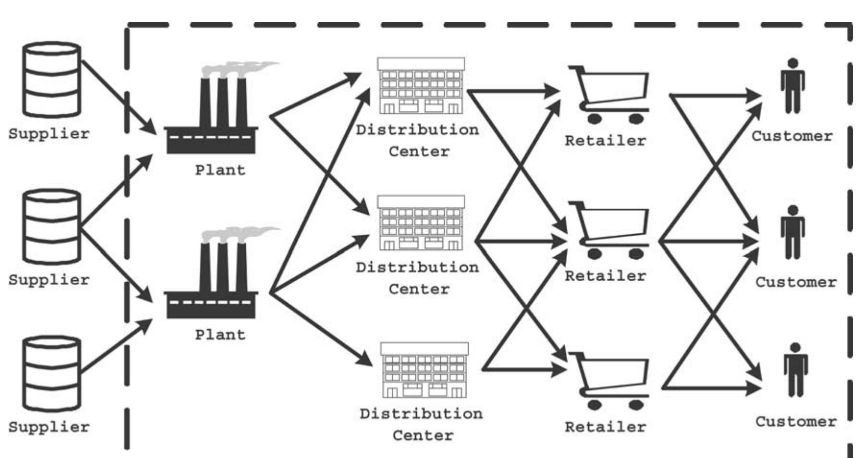

Fig. 1. Research region.

the purchasing cost into manufacturing cost. The research region of this paper, therefore, is from manufacturer to customer, like the dash line region showed in Fig. 1. And the following assumptions have been made:

1. Products are independent to each other, related to marketing and sales price.
2. Each enterprise has its own safe inventory quantity to reduce the influence of uncertain product demand.
3. Several scenarios of product demands with known probabilities are forecasted over the entire scheduling periods.
4. The buyer's acceptability for product price can be quite different from the provider's.

The overall problem can thus be stated as follows:

- Given:
  1. Manufacture data, such as batch manufacturing quantity of regular time and overtime, overtime number constraint, etc.
  2. Transportation data, such as lead time, transport capacity, etc.
  3. Inventory data, such as inventory capacity, safe inventory quantity, etc.
  4. Each cost parameter, such as manufacturing, inventory, etc.
  5. The buyers' and providers' acceptable levels for product prices.
  6. Several scenarios of forecasted product demands with known probabilities.
- Determine:
  1. Production plan of each plant.
  2. Transportation plan of each DC.
  3. Sales quantity and compromised product price of each participant.
  4. Inventory level of each enterprise.
  5. All kinds of cost.
- The target is to integrate the multi-echelon decisions simultaneously to:
  1. Guarantee a fair profit distribution among all participants.
  2. Elevate the customer service levels, the safe inventory levels, the product-prices satisfaction levels, and the robustness of all considered objectives to product demand uncertainties as much as possible.

3. Uncertainties in the supply chain scheduling

In the market, the participants of a supply chain not only face the uncertainties of product demands and raw material supplies but also faces the uncertainties of commodity prices and costs (Liu & Sahinidis, 1997). The first concern in incorporating uncertainties into supply chain modeling and optimization is the determination of suitable representation of the uncertain parameters (Gupta & Maranas, 2003). Three distinct methods are frequently mentioned for representing uncertainty (Liu & Sahinidis, 1997; Gupta & Maranas, 2003): first, the distribution-based approach, where the normal distribution with specified mean and standard deviation is widely invoked for modeling uncertain demands and/or parameters; second, the fuzzy-based approach, therein the forecast parameters are considered as fuzzy numbers with accompanied membership functions; and third, the scenario-based approach, in which several discrete scenarios with associated probability levels are used to describe expected occurrence of particular outcomes. We will address issues of demand uncertainty and uncertain product prices in the following.

To simplify the subsequent mathematical calculations, we will adopt the discrete scenario-based approach for modeling uncertain product demands. For applying the discrete cases representation for modeling uncertain demands, several possible outcomes with known probabilities, PPD_s, $s \in \mathcal{S}$ where $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s = 1$, should be determined at first. Then all variables will become scenario dependent, and the expected value of any variable will be the weighted average of those scenario-dependent values. That is, for any variable v, we have to solve for several scenario-dependent values, v_s, $s \in \mathcal{S}$, and the expected value of v can be taken as $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s v_s$. In such a case the deterministic supply chain model can be easily extended to cope with uncertain demand conditions, as shown in the next section.

Due to the obvious negotiable and uncertain characteristics of products' prices at various selling sites in real businesses, the final product prices are usually result of compromised considerations. When contemplating the competitive positions hold between sellers and buyers in settling sales/purchase prices for a specific product, the preference of the price would be very different from each one's point of view. For example, the retailer would be fully satisfied if the selling price to customers is higher than an expected high value, say $(\mathrm{USP})_S^1$; on the other hand, it would be totally unacceptable for a price less than a lower minimum $(\mathrm{USP})_S^0$; and the degree-of-acceptability will increase in accordance with the increase of price between these two bounds. To describe such a transition from numerical price value to linguistic preference expression, it is quite suitable to set up a fuzzy set, $\mathcal{SP}$, with some kinds of monotonic increasing membership function, $\mu_{\mathcal{SP}}(\mathrm{USP})$ where $\mu_{\mathcal{SP}}(\mathrm{USP} \le (\mathrm{USP})_S^0) = 0$, $\mu_{\mathcal{SP}}(\mathrm{USP} \ge (\mathrm{USP})_S^1) = 1$, and $\mu_{\mathcal{SP}}((\mathrm{USP})_S^0 < \mathrm{USP} < (\mathrm{USP})_S^1) = \mathbb{F}_{\mathrm{inc}}(\mathrm{USP}; (\mathrm{USP})_S^0, (\mathrm{USP})_S^1) \in [0, 1]$, to measure the seller's preference for product price. The buyer side, on the other hand, has its own fuzzy preference of purchase price, $\mathcal{BP}$, and corresponding monotonic decreasing membership function, $\mu_{\mathcal{BP}}(\mathrm{USP})$ where $\mu_{\mathcal{BP}}(\mathrm{USP} \le (\mathrm{USP})_B^1) = 1$, $\mu_{\mathcal{BP}}(\mathrm{USP} \ge (\mathrm{USP})_B^0) = 0$, and $\mu_{\mathcal{BP}}((\mathrm{USP})_B^1 < \mathrm{USP} < (\mathrm{USP})_B^0) = \mathbb{F}_{\mathrm{dec}}(\mathrm{USP}; (\mathrm{USP})_B^1, (\mathrm{USP})_B^0) \in [0, 1]$. The determination of membership functions are usually based on decision maker's subjectivity. It has been shown that use of linear membership functions can provide similar solution quality to that using more complicated nonlinear membership functions (Delgado, Herrera, & Verdegay, 1993; Sakawa, 1993; Liu & Sahinidis, 1997). Thus, we will assume

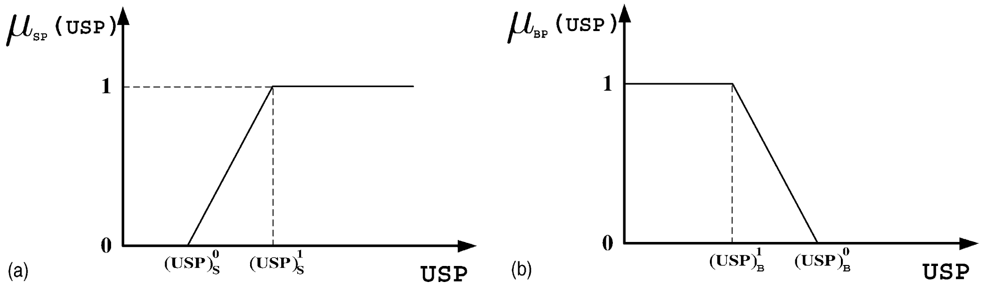

Fig. 2. Membership functions for seller's (a) and buyer's (b) fuzzy product prices.

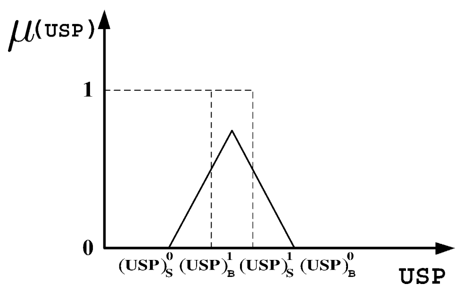

Fig. 3. Typical membership functions for fuzzy product prices when simultaneously considering the seller's and buyer's viewpoints.

constant rate of increased/decreased membership satisfaction and will adopt linear membership functions, as shown below and Fig. 2.

$$\mu_{\mathcal{SP}}(\text{USP}) = \begin{cases} 0 & \text{for USP} \le (\text{USP})_S^0 \\ \dfrac{\text{USP} - (\text{USP})_S^0}{(\text{USP})_S^1 - (\text{USP})_S^0} & \text{for } (\text{USP})_S^0 \le \text{USP} \le (\text{USP})_S^1 \\ 1 & \text{for USP} \ge (\text{USP})_S^1 \end{cases}$$

$$\mu_{\mathcal{BP}}(\text{USP}) = \begin{cases} 1 & \text{for USP} \le (\text{USP})_B^1 \\ \dfrac{(\text{USP})_B^0 - \text{USP}}{(\text{USP})_B^0 - (\text{USP})_B^1} & \text{for } (\text{USP})_B^1 \le \text{USP} \le (\text{USP})_B^0 \\ 0 & \text{for USP} \ge (\text{USP})_B^0 \end{cases} \quad (1)$$

The final product price is determined by a compromising procedure taken place between these conflicting fuzzy preferences. Some typical final membership functions of the fuzzy product price—incorporating both the seller's and buyer's—are depicted in Fig. 3.

4. Supply chain modeling with demand uncertainty

A general supply chain that consists of three different levels of enterprises is considered here: the first level enterprise is the retailer from which the products are sold to customers; the second level enterprise is the distribution center (DC) or warehouse using different type of transport capacity to deliver products from plant side to retailer side; the third level enterprise is the plant or the manufacturer that batch-manufactures one product at one period. In the following, we develop an integrated multi-echelon supply chain model for optimal decisions (Chen et al., 2003). The scenario-based representation for uncertain product demands is considered in the modeling.

4.1. Indices, sets, parameters, and variables

The indices, sets and parameters, designed to model the supply chain network with product demand uncertainty are shown in the nomenclature. Therein, parameters are divided into two categories: the cost parameters, including inventory cost and transport cost; and other parameters describing the system information, such as inventory capacity, transport lead time, etc. Two kinds of scenario-dependent variables are used: the binary variables that act as policy decisions to use economies of scale for manufacturing or transportation, and continuous variables that include manufacturing quantities and product prices.

4.2. Manufacture constraints

Six constraints on manufacturing are set up for all products and plants over concerned periods.

$$\sum_{\forall i \in \mathcal{I}} \beta_{pts}^i = 1 \quad (2)$$

$$o_{pts}^i \le \alpha_{pts}^i \le \beta_{pts}^i \quad (3)$$

$$\gamma_{pts}^i \ge \beta_{pts}^i - \beta_{p,t-1,s}^i \quad (4)$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{\forall t \in \mathcal{T}} o_{pts}^i \le \text{MTO}_p \quad (5)$$

$$\sum_{\forall i \in \mathcal{I}} \sum_{\forall n \in \mathcal{N}} o_{p,t-n+1,s}^i \le N - 1 \quad (6)$$

where $i \in \mathcal{I}$, $p \in \mathcal{P}$, $t \in \mathcal{T}$, $s \in \mathcal{S}$.

Eq. (2) denotes that the plant can be setup for manufacturing one product. Eq. (3) states that the plant is able to manufacture a product in regular time only after the plant has been setup to produce it, and the plant is able to manufacture the product in overtime only when the regular time production is insufficient. In Eq. (4), $\gamma^i_{pts} = 1$ only if $\beta^i_{pts} - \beta^i_{p,t-1,s} = 1$, thus the plant can be changed to manufacture product i at period t. Eq. (5) implies total number of overtime periods is less than the maximal allowable overtime periods, MTO_p. And Eq. (6) says the number of continuous overtime periods should be less than a specified value N. Notably, these constraints are scenario dependent.

4.3. Transportation constraints

The transportation constraints at considered periods, $t \in \mathcal{T}$, in different economic scales are given below.

$$\mathrm{TCL}^{k'-1}_{pd} Y^{k'}_{pdts} < \mathrm{TQ}^{k'}_{pdts} \le \mathrm{TCL}^{k'}_{pd} Y^{k'}_{pdts} \tag{7}$$

$$\mathrm{TCL}^{k-1}_{dr} Y^{k}_{drts} < \mathrm{TQ}^{k}_{drts} \le \mathrm{TCL}^{k}_{dr} Y^{k}_{drts} \tag{8}$$

$$\sum_{\forall k' \in \mathcal{K}'} Y^{k'}_{pdts} \le 1, \qquad \sum_{\forall k \in \mathcal{K}} Y^{k}_{drts} \le 1 \tag{9}$$

$$\mathrm{TQ}_{pdts} = \sum_{\forall k' \in \mathcal{K}'} \mathrm{TQ}^{k'}_{pdts} = \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}^{i}_{pdts} \tag{10}$$

$$\mathrm{TQ}_{drts} = \sum_{\forall k \in \mathcal{K}} \mathrm{TQ}^{k}_{drts} = \sum_{\forall i \in \mathcal{I}} \mathrm{SQ}^{i}_{drts} \tag{11}$$

$$\sum_{\forall p \in \mathcal{P}} \mathrm{TQ}_{pdts} \le \mathrm{MITC}_d \tag{12}$$

$$\sum_{\forall r \in \mathcal{R}} \mathrm{TQ}_{drts} \le \mathrm{MOTC}_d \tag{13}$$

$$\forall d \in \mathcal{D}, \quad p \in \mathcal{P}, \quad r \in \mathcal{R}, \quad k' \in \mathcal{K}',$$
$$k \in \mathcal{K}, \quad t \in \mathcal{T}, \quad s \in \mathcal{S}$$

Eqs. (7)–(9) imply that several transport-capacity levels with various unit transport costs can be used, as depicted in Fig. 4 for a three-level case, and at most one transport capacity can be chosen at each period. In Eqs. (10) and (11), the transport quantities of each product from plants to DCs or from DCs to retailers at each period are respectively translated into total transport quantities, and Eqs. (12) and (13) are constraints on these total transport quantities.

4.4. Inventory constraints

All relevant inventory constraints in all plants, DCs, and retailers can be summarized as follows:

$$I^i_{rts} = I^i_{r,t-1,s} + \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}^i_{dr,t-\mathrm{TLT}_{dr},s} - \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}^i_{rcts} \tag{14}$$

$$I^i_{dts} = I^i_{d,t-1,s} + \sum_{\forall p \in \mathcal{P}} \mathrm{SQ}^i_{pd,t-\mathrm{TLT}_{pd},s} - \sum_{\forall r \in \mathcal{R}} \mathrm{SQ}^i_{drts} \tag{15}$$

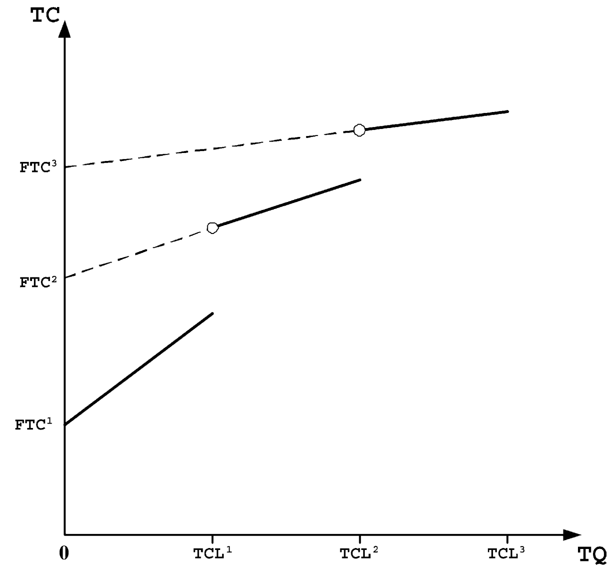

Fig. 4. Piecewise linear relation (solid lines) between transport cost (TC) and shipment quantity (TQ).

$$I^i_{pts} = I^i_{p,t-1,s} + \mathrm{FMQ}^i_p \alpha^i_{p,t-1,s} + \mathrm{OMQ}^i_p o^i_{p,t-1,s} - \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}^i_{pdts} \tag{16}$$

$$B^i_{rts} = B^i_{r,t-1,s} + \mathrm{FCD}^i_{rts} - \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}^i_{rcts}, \quad B^i_{rTs} = 0 \tag{17}$$

$$\sum_{\forall i \in \mathcal{I}} I^i_{*ts} \le \mathrm{MIC}_* \tag{18}$$

$$\mathrm{SIQ}^i_* - I^i_{*ts} \le D^i_{*ts} \tag{19}$$

$$I^i_{*ts}, \mathrm{SQ}^i_{*ts}, B^i_{*ts}, D^i_{*ts} \ge 0 \tag{20}$$

where $* \in \{p, d, r\}$, $p \in \mathcal{P}$, $d \in \mathcal{D}$, $r \in \mathcal{R}$, $i \in \mathcal{I}$, $t \in \mathcal{T}$, $s \in \mathcal{S}$.

Here, Eq. (14) states that inventory level of one product of a retailer at each period equals the amounts at previous period plus the amounts received from all DCs and less the amounts sold to customers. Similar constraints apply for DCs and plants, as shown in Eqs. (15) and (16). Eqs. (14) and (15) also consider delayed transport quantity caused by transport lead time. Eq. (17) means that backlog level of one product equals the amounts at previous period and added to the amounts of forecasting customer demand, less the amounts sold to customer; and the backlog at the last period should be zero for fulfilling expected customer demand. Eq. (18) says that the amounts of all products can not exceed the maximal inventory capacity. By using safe inventory quantity constraints, we can make the short safe inventory level of a product to be zero if inventory level is greater than safe inventory quantity, or to be the difference of safe inventory quantity and inventory level if inventory level is smaller than safe inventory quantity, as shown in Eq. (19).

4.5. Costs and revenues

The plants' manufacturing costs, purchasing costs for DCs, retailers and customers, all inventory and handling costs, and the transportation costs are listed in the following for all $p \in \mathcal{P}$, $d \in \mathcal{D}$, $r \in \mathcal{R}$, $t \in \mathcal{T}$, and $s \in \mathcal{S}$.

$$\mathrm{TMC}_{pts} = \sum_{\forall i \in \mathcal{I}} [\mathrm{FMC}_p^i \gamma_{pts}^i + \mathrm{FIC}_p^i (\beta_{pts}^i - \alpha_{pts}^i) + \mathrm{UMC}_p^i \mathrm{FMQ}_p^i \alpha_{pts}^i + \mathrm{OMC}_p^i \mathrm{OMQ}_p^i o_{pts}^i] \quad (21)$$

$$\mathrm{TPC}_{dts} = \sum_{\forall p \in \mathcal{P}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{pds}^i \mathrm{SQ}_{pdts}^i,$$
$$\mathrm{TPC}_{rts} = \sum_{\forall d \in \mathcal{D}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{drs}^i \mathrm{SQ}_{drts}^i \quad (22)$$

$$\mathrm{TIC}_{*ts} = \sum_{\forall i \in \mathcal{I}} \mathrm{UIC}_*^i I_{*ts}^i \quad * \in \{p, d, r\} \quad (23)$$

$$\mathrm{THC}_{pts} = \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_p^i \times \left(\mathrm{FMQ}_p^i \alpha_{p,t-1,s}^i + \mathrm{OMQ}_p^i o_{p,t-1,s}^i + \sum_{\forall d \in \mathcal{D}} \mathrm{SQ}_{pdts}^i \right) \quad (24)$$

$$\mathrm{THC}_{dts} = \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_d^i \left(\sum_{\forall p \in \mathcal{P}} \mathrm{SQ}_{pd,t-\mathrm{TLT}_{pd},s}^i + \sum_{\forall r \in \mathcal{R}} \mathrm{SQ}_{drts}^i \right) \quad (25)$$

$$\mathrm{THC}_{rts} = \sum_{\forall i \in \mathcal{I}} \mathrm{UHC}_r^i \left(\sum_{\forall d \in \mathcal{D}} \mathrm{SQ}_{dr,t-\mathrm{TLT}_{dr},s}^i + \sum_{\forall c \in \mathcal{C}} \mathrm{SQ}_{rcts}^i \right) \quad (26)$$

$$\mathrm{TTC}_{pts} = \sum_{\forall k' \in \mathcal{K}'} \sum_{\forall p \in \mathcal{P}} (\mathrm{FTC}_{pd}^{k'} Y_{pdts}^{k'} + \mathrm{UTC}_{pd}^{k'} \mathrm{TQ}_{pdts}^{k'}) \quad (27)$$

$$\mathrm{TTC}_{dts} = \sum_{\forall k \in \mathcal{K}} \sum_{\forall r \in \mathcal{R}} (\mathrm{FTC}_{dr}^{k} Y_{drts}^{k} + \mathrm{UTC}_{dr}^{k} \mathrm{TQ}_{drts}^{k}) \quad (28)$$

$$\mathrm{PSP}_{pts} = \sum_{\forall d \in \mathcal{D}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{pds}^i \mathrm{SQ}_{pdts}^i,$$
$$\mathrm{PSP}_{dts} = \sum_{\forall r \in \mathcal{R}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{drs}^i \mathrm{SQ}_{drts}^i,$$
$$\mathrm{PSP}_{rts} = \sum_{\forall c \in \mathcal{C}} \sum_{\forall i \in \mathcal{I}} \mathrm{USP}_{rcs}^i \mathrm{SQ}_{rcts}^i \quad (29)$$

In Eq. (21), the manufacturing cost is a composite obtained by fixed manufacture and idle cost plus regular and overtime manufacturing costs. Here, the γ_{pts}^i value (measured if we are going to change production plan to produce product i) will be either zero (if $\beta_{pts}^i - \beta_{p,t-1,s}^i = 0$, continuing to produce or not to produce product i) or 1 (if $\beta_{pts}^i - \beta_{p,t-1,s}^i = 1$, changeover to start producing product i). Eq. (22) gives the purchasing costs for DCs and retailers; Eq. (23) is the inventory cost, and Eqs. (24) and (26) are handling costs for plants, DCs, and retailers, respectively; Eqs. (27) and (28) are transport costs for plant and DC, respectively. Here, the transport cost is a composite of transport level-dependent fixed cost and a transport quantity-dependent carrying cost. This would cause a discontinuous piecewise linear transport cost, as illustrated in Fig. 4 with skipped subscripts. Notably, the discontinuities in the transport cost make the model more general than the continuous one proposed by Tsiakis et al. (2001). Finally, Eq. (29) is product sales for all plants, DCs, and retailers.

4.6. Multiple objectives

The conflict objectives such as each participant's profit, the average customer service level, and the average safe inventory level are considered simultaneously, as stated in the following.

Objective 1: *to simultaneously maximize participants' expected profits for* $p \in \mathcal{P}$, $d \in \mathcal{D}$, *and* $r \in \mathcal{R}$.

Instead of directly maximizing the overall profit of the integrated supply chain network, we intend to fairly distribute the profit to all members within scheduling periods. The profits of all participants to be maximized are considered separately, where the profit at period t is equal to the product sales less all kinds of costs.

$$Z_* = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s Z_{*s}, \quad * \in \{p, d, r\} \quad (30)$$

where

$$Z_{ps} = \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{pts} - \mathrm{TMC}_{pts} - \mathrm{TTC}_{pts} - \mathrm{TIC}_{pts} - \mathrm{THC}_{pts}) \quad \forall p \in \mathcal{P}, s \in \mathcal{S}$$

$$Z_{ds} = \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{dts} - \mathrm{TPC}_{dts} - \mathrm{TTC}_{dts} - \mathrm{TIC}_{dts} - \mathrm{THC}_{dts}) \quad \forall d \in \mathcal{D}, s \in \mathcal{S}$$

$$Z_{rs} = \sum_{\forall t \in \mathcal{T}} (\mathrm{PSP}_{rts} - \mathrm{TPC}_{rts} - \mathrm{THC}_{rts} - \mathrm{TIC}_{rts}) \quad \forall r \in \mathcal{R}, s \in \mathcal{S}.$$

Objective 2: *to maximize average safe inventory levels for* $p \in \mathcal{P}$, $d \in \mathcal{D}$, $r \in \mathcal{R}$.

The safe inventory level of retailer r at period t for scenario s is defined as the expected average percentage of 1 less the ratio of short safe inventory level of product i of retailer r at period t, D_{rts}^i, over the safe inventory quantity of product i of retailer r, SIQ_r^i, for all products. Similar definitions are also applied to plants and DCs. All participants' safe inventory levels are concerned as objectives for simultaneous optimization.

$$\mathrm{SIL}_* = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{SIL}_{*s}, \quad * \in \{p, d, r\} \tag{31}$$

where

$$\mathrm{SIL}_{*s}\,(\%) = \frac{100}{IT} \sum_{\forall t \in \mathcal{T}} \sum_{\forall i \in \mathcal{I}} \left(1 - \frac{D_{*ts}^i}{\mathrm{SIQ}_*^i}\right), \quad \forall s \in \mathcal{S}$$

Objective 3: *to maximize average customer service levels for $r \in \mathcal{R}$.*

Under the condition of taking all products into consideration, the customer service level of retailer r at period t is defined as the expected average percentage ratio of actual sales quantity of product i from retailer r to customers at period t, $\sum_{\forall c \in \mathcal{C}} \mathrm{SQ}_{rcts}^i$, over the expected total demand quantity. The expected total demand quantity is the sum of backlog level of product i for retailer r at the end of period $t-1$, $B_{r,t-1,s}^i$, and forecasting customer demand of product i to retailer r at period t, $\sum_{\forall c \in \mathcal{C}} \mathrm{FCD}_{rcts}^i$.

$$\mathrm{CSL}_r = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{CSL}_{rs}, \quad \forall r \in \mathcal{R} \tag{32}$$

where

$$\mathrm{CSL}_{rs}\,(\%) = \frac{100}{IT} \sum_{\forall t \in \mathcal{T}} \sum_{\forall i \in \mathcal{I}} \times \left(\frac{\sum_{\forall c \in \mathcal{C}} \mathrm{SQ}_{rcts}^i}{B_{r,t-1,s}^i + \sum_{\forall c \in \mathcal{C}} \mathrm{FCD}_{rcts}^i}\right), \quad \forall s \in \mathcal{S}.$$

Objective 4: *to maximize robustness of selected objectives to demand uncertainties.*

It has been mentioned that all variables are scenarios dependent when the explicit scenario-based approach is applied to the uncertain product demand. However, the profit realization might be unacceptably low for certain scenarios with especially low probabilities (Suh & Lee, 2001). It is thus significant to reduce the variability of above-mentioned objective values for any realization of scenarios. An important issue in enforcing robustness to uncertainties is the choice of variability metric (Ahmed & Sahinidis, 1998). For those objectives to be maximized as mentioned previously, the decision-maker usually does not care if the objective value is greater than the expected one. We thus propose the lower partial mean as the measure of robustness, where only objective values less than the expectation are penalized and are weighted by probabilities of related scenarios.

$$\mathrm{RI}_{m'} = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \min\{0, J_{m's} - J_{m'}\}, \quad \forall m' \in \mathcal{M}' \tag{33}$$

Here, $\mathcal{M}'$ is the index set of objectives in Eqs. (30)–(32) with dimension $[\mathcal{M}'] = M' = 2P + 2D + 3R$.

In summary, the feasible searching space, $\boldsymbol{\Omega}$, are composite of all constraints mentioned above. The multiple objectives $J_m(\boldsymbol{x}), m \in \mathcal{M}$, where $\mathcal{M}$ is the index set of all objectives including the robustness indices with $[\mathcal{M}] = M = 2M'$, and the decision vector $\boldsymbol{x}$ are shown below. Notably, further to the scenario-dependent product prices, the decision vector $\boldsymbol{x}$ includes all production, transportation, sales quantities and inventory levels during considered periods.

$$\begin{aligned}\max_{\boldsymbol{x} \in \boldsymbol{\Omega}} &(J_1(\boldsymbol{x}), \dots, J_M(\boldsymbol{x})) \\ &= (Z_p, Z_d, Z_r; \mathrm{SIL}_p, \mathrm{SIL}_d, \mathrm{SIL}_r; \mathrm{CSL}_r; \mathrm{RI}_{m'}; \\ &\quad \forall p \in \mathcal{P}, d \in \mathcal{D}, r \in \mathcal{R}, m' \in \mathcal{M}')\end{aligned} \tag{34}$$

$$\begin{aligned}\boldsymbol{x} = \{&\alpha_{pts}^i, \beta_{pts}^i, \gamma_{pts}^i, o_{pts}^i; \mathrm{SQ}_{*ts}^i; \mathrm{USP}_{*s}^i; \mathrm{TQ}_{pdts}^{k'}, \mathrm{TQ}_{drts}^k, \\ &Y_{pdts}^{k'}, Y_{drts}^k; I_{pts}^i, I_{dts}^i, I_{rts}^i; B_{rts}^i; D_{pts}^i, D_{dts}^i, D_{rts}^i; \\ &* \in \{pd, dr, rc\}; i \in \mathcal{I}, p \in \mathcal{P}, d \in \mathcal{D}, r \in \mathcal{R}, \\ &c \in \mathcal{C}, k' \in \mathcal{K}', k \in \mathcal{K}, t \in \mathcal{T}, s \in \mathcal{S}\}\end{aligned} \tag{35}$$

5. Supply chain optimization with uncertain demands and prices

By considering the uncertain property of human thinking, it is quite intuitive to assume that the DM has a fuzzy goal, $\mathcal{J}_m$, to describe the maximizing objective J_m with an acceptable interval $[J_m^0, J_m^1]$. It would be quite satisfactory as the objective value is greater than J_m^1, and unacceptable as the profit is less than J_m^0, the minimum acceptable objective value such that the company would like to enter to negotiation for a fair deal in the multi-enterprise network. A strictly monotonic increasing membership function, $\mu_{\mathcal{J}_m}(J_m(\boldsymbol{x})) \in [0, 1]$, can be used to characterize such a transition from numerical objective value $J_m(\boldsymbol{x})$ to degree-of-satisfaction for $\mathcal{J}_m$. Without loss of generality, we will adopt the linear membership function since it has been proved in providing qualified solutions for many applications (Liu & Sahinidis, 1997).

$$\mu_{\mathcal{J}_m}(J_m(\boldsymbol{x})) = \begin{cases} 1; & \text{for } J_m(\boldsymbol{x}) \geq J_m^1 \\ \dfrac{J_m(\boldsymbol{x}) - J_m^0}{J_m^1 - J_m^0}; & \text{for } J_m^0 \leq J_m(\boldsymbol{x}) \leq J_m^1 \quad \forall m \in \mathcal{M} \\ 0; & \text{for } J_m^0 \geq J_m(\boldsymbol{x}) \end{cases} \tag{36}$$

Here, $\boldsymbol{x}$ denotes the argument vector as shown in Eq. (35). The effective range of the membership function, $[J_m^0, J_m^1]$, can sometimes be subjectively defined by company's decision makers. Some procedures can also follow for providing reasonable limiting values for the objective. For those objectives such as profits and inventory levels and customer service levels, $J_{m'}$, $m' \in \mathcal{M}'$, one can use the most optimistic expectation as the upper limit, $\bar{J}^1_{m'} = J_{m'}(\boldsymbol{x}^*_{m'})$, where $\boldsymbol{x}^*_{m'}$ is the optimal solution of the single objective maximizing problem, $\max_{\boldsymbol{x}\in\boldsymbol{\Omega}} J_{m'}(\boldsymbol{x})$. And choose the most pessimistic expectation, $\underline{J}^0_{m'}$, as the lower limiting value (Zimmermann, 1978; Sakawa, 1993), where

$$\underline{J}^0_{m'} = \min\{J_{m'}(\boldsymbol{x}^*_i),\ i \in \mathcal{M}'\}, \quad \forall m' \in \mathcal{M}' \tag{37}$$

As for objectives measuring robustness to uncertainties, the reasonable upper limit is zero (i.e., absolute robustness), $\bar{J}^1_{M'+m'} = 0$, and the lower limiting value can be found similar to Eq. (37).

$$\underline{J}^0_{M'+m'} = \min\{J_{M'+m'}(\boldsymbol{x}^*_i),\ i \in \mathcal{M}'\}, \quad \forall m' \in \mathcal{M}' \tag{38}$$

One can thus subjectively determine the effective range for membership functions with the restriction of $\underline{J}^0_m \le J^0_m < J^1_m \le \bar{J}^1_m$. The original multi-objective optimization problem is now equivalent to look for a suitable decision vector that can provide the maximal degree-of-satisfaction for the aggregated fuzzy objectives, $\mathcal{J}_1 \cap \ldots \cap \mathcal{J}_M$. When simultaneously considering the incompatible fuzzy preference on product prices from sellers and buyers viewpoints, the final fuzzy decision, $\mathcal{FD}$, can be interpreted as the fuzzy intersection between all fuzzy objectives and fuzzy product prices.

$$\mathcal{FD} = \mathcal{J}_m \cap \mathcal{SP}^i_{pd} \cap \mathcal{SP}^i_{dr} \cap \mathcal{SP}^i_{rc} \cap \mathcal{BP}^i_{pd} \cap \mathcal{BP}^i_{dr} \cap \mathcal{BP}^i_{rc}$$
$$\forall m \in \mathcal{M},\ i \in \mathcal{I},\ p \in \mathcal{P},\ d \in \mathcal{D},\ r \in \mathcal{R},\ c \in \mathcal{C} \tag{39}$$

Noted that the expected product prices, $\mathrm{USP}^i_* = \sum_{\forall s\in\mathcal{S}} \mathrm{PPD}_s \mathrm{USP}^i_{*s}$, $* \in \{pd, dr, rc\}$, should be used in evaluating the degree-of-acceptability of various fuzzy preferences. The final overall satisfactory level, $\mu_{\mathcal{FD}}(\boldsymbol{x})$, can be determined by aggregating the degree-of-satisfaction for all objectives, $\mu_{\mathcal{J}_m}(J_m(\boldsymbol{x}))$, and sellers' and buyers' preference on product prices, $\mu_{\mathcal{SP}^i_*}(\mathrm{USP}^i_*)$ and $\mu_{\mathcal{BP}^i_*}(\mathrm{USP}^i_*)$, via specific t-norm, $\mathbb{T}$.

$$\mu_{\mathcal{FD}}(\boldsymbol{x}) = \mathbb{T}(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pd}},\mu_{\mathcal{SP}^i_{dr}},\mu_{\mathcal{SP}^i_{rc}};$$
$$\mu_{\mathcal{BP}^i_{pd}},\mu_{\mathcal{BP}^i_{dr}},\mu_{\mathcal{BP}^i_{rc}} \mid \forall m, i, p, d, r, c) \tag{40}$$

The best solution $\boldsymbol{x}^*$ with the maximal firing level, $\mu_{\mathcal{FD}}(\boldsymbol{x}^*)$, should be selected.

$$\mu_{\mathcal{FD}}(\boldsymbol{x}^*) = \max_{\boldsymbol{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{FD}}(\boldsymbol{x}) \tag{41}$$

Several t-norms can be chosen for $\mathbb{T}$, therein two most popular selections are shown below (Klir & Yuan, 1995).

$$\mathbb{T}(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pd}},\mu_{\mathcal{SP}^i_{dr}},\mu_{\mathcal{SP}^i_{rc}};\mu_{\mathcal{BP}^i_{pd}},\mu_{\mathcal{BP}^i_{dr}},\mu_{\mathcal{BP}^i_{rc}}) \tag{42}$$

$$= \begin{cases} \min(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pd}},\mu_{\mathcal{SP}^i_{dr}},\mu_{\mathcal{SP}^i_{rc}}; \\ \quad \mu_{\mathcal{BP}^i_{pd}},\mu_{\mathcal{BP}^i_{dr}},\mu_{\mathcal{BP}^i_{rc}}), & \mathbb{T} = \text{minimum} \\ \mu_{\mathcal{J}_m} \times \mu_{\mathcal{SP}^i_{pd}} \times \mu_{\mathcal{SP}^i_{dr}} \times \mu_{\mathcal{SP}^i_{rc}} \\ \quad \times \mu_{\mathcal{BP}^i_{pd}} \times \mu_{\mathcal{BP}^i_{dr}} \times \mu_{\mathcal{BP}^i_{rc}}, & \mathbb{T} = \text{product} \end{cases} \tag{43}$$

The minimum operator concerns the worst situation only, and the product operator results in a Nash-type objective. Maximizing the single worst scenario may end in a non-compensatory solution, and maximizing the Nash-type objective can guarantee a compensatory solution (Li & Lee, 1993). But the drawback is that product operator may cause an unbalanced solution between all fuzzy terms by the inherent character of product. We thus propose a two-phase method to combine advantages of these two operators, as summarized in the following (Chen et al., 2003).

Step 1. Determining membership function for each fuzzy objective based on expected upper/lower bounds for the objective value, as shown in Eq. (36), where

$$\underline{J}^0_m \le J^0_m \le J^1_m \le \bar{J}^1_m, \quad \forall m \in \mathcal{M}.$$

Step 2 (Phase I). Considering all fuzzy objectives and fuzzy product prices and using the minimum operator, maximizing the degree of satisfaction for the worst situation.

$$\max_{\boldsymbol{x}\in\boldsymbol{\Omega}} \mu_{\mathcal{FD}} = \max_{\boldsymbol{x}\in\boldsymbol{\Omega}} \min(\mu_{\mathcal{J}_m};\mu_{\mathcal{SP}^i_{pd}},\mu_{\mathcal{SP}^i_{dr}},\mu_{\mathcal{SP}^i_{rc}};$$
$$\mu_{\mathcal{BP}^i_{pd}},\mu_{\mathcal{BP}^i_{dr}},\mu_{\mathcal{BP}^i_{rc}}) \equiv \mu_{\min} \tag{44}$$

Step 3 (Phase II). Applying the product operator, maximizing the overall Nash-type satisfactory level with guaranteed minimal fulfillment for all fuzzy objectives and sales preferences.

Table 1
Scenarios ($s = 1, 2, 3, 4, 5, 6$ and 7) of forecasting product demands and probabilities of illustrative example

i	r	t	FCD^i_{rts}						
			0.15[a]	0.2[a]	0.12[a]	0.24[a]	0.09[a]	0.13[a]	0.07[a]
1	1	1	160	160	160	160	160	160	160
1	1	2	170	170	170	160	150	150	150
1	1	3	180	180	180	160	140	140	140
1	1	4	190	180	170	160	150	140	130
1	1	5	200	180	160	160	160	140	120
1	2	1	180	180	180	180	180	180	180
1	2	2	200	200	180	200	160	160	160
1	2	3	220	220	180	220	140	140	140
1	2	4	220	240	180	200	140	120	160
1	2	5	220	260	180	180	140	100	180
2	1	1	240	240	240	240	240	240	240
2	1	2	240	270	210	210	270	270	210
2	1	3	240	300	180	180	300	300	180
2	1	4	240	270	210	150	330	300	180
2	1	5	240	240	240	120	360	300	180
2	2	1	280	280	280	280	280	280	280
2	2	2	320	240	320	320	240	240	280
2	2	3	360	200	360	360	200	200	280
2	2	4	320	200	400	360	160	240	280
2	2	5	280	200	400	360	120	280	280

[a] PPD_s.

$$\max_{\boldsymbol{x}\in\boldsymbol{\Omega}^{+}} \mu_{\mathcal{FD}}(\boldsymbol{x}) = \max_{\boldsymbol{x}\in\boldsymbol{\Omega}^{+}} (\mu_{\mathcal{J}_m} \times \mu_{\mathcal{SP}^i_{pd}} \times \mu_{\mathcal{SP}^i_{dr}} \times \mu_{\mathcal{SP}^i_{rc}} \times \mu_{\mathcal{BP}^i_{pd}} \times \mu_{\mathcal{BP}^i_{dr}} \times \mu_{\mathcal{BP}^i_{rc}}) \tag{45}$$

where

$$\Omega^{+} = \Omega \cap \{\mu_{\mathcal{J}_m}, \mu_{\mathcal{SP}^i_{*}}, \mu_{\mathcal{BP}^i_{*}} \geq \mu_{\min} | * \in \{pd, dr, rc\}; \forall m, i, p, d, r, c\} \tag{46}$$

6. Numerical example

Considering a small-scale but typical supply chain consists of one plant, two DCs, two retailers, and two products. The first DC, a smaller scale but faster delivery service distributor, can rapidly respond to the suddenly increasing customer demand to keep retailer's customer service level, but this also implies a higher operational cost; the second one, a large scale but slower delivery service distributor, on the other hand, can use the economies of scale to transport goods at lower operational cost, but the prompt delivery is not available, however. We assume one period of transport lead time between each level for the second DC. So, the distribution channel between plants to retailers is complementary with the faster, smaller shipment and slower, larger shipment. And in order to simplify the problem, we neglect the fluctuating rate for cost parameters. The whole scheduling horizon is five periods. The product demand scenarios and the assigned probabilities are shown in Table 1 for the case study. Other indices and sets are $[\mathcal{N}] = 3$, $[\mathcal{K}] = 3$, and $[\mathcal{K}'] = 3$. Values of all cost parameters are listed in Tables 2 and 3, and other parameters, Table 4. Notably, Table 3 gives the required parameters for defining fuzzy product prices

Table 2
Cost parameters of illustrative example

Unit Inventory Cost						Unit Transport Cost						Fix Transport Cost					
	i	p	d	r	$		k	p	d	r	$		k	p	d	r	$
	1			1	50		1		1	1	60		1		1	1	1800
UIC^i_r	1			2	40		2		1	1	45		2		1	1	2700
	2			1	30		3		1	1	33		3		1	1	3200
	2			2	24		1		1	2	50		1		1	2	1500
	1		1		45		2		1	2	37		2		1	2	2200
UIC^i_d	1		2		20	UTC^k_{dr}	3		1	2	27	FTC^k_{dr}	3		1	2	2600
	2		1		27		1		2	1	25		1		2	1	3000
	2		2		12		2		2	1	18		2		2	1	5250
UIC^i_p	1	1			15		3		2	1	14		3		2	1	6750
	2	1			9		1		2	2	30		1		2	2	2000
Unit Handling Cost							2		2	2	22		2		2	2	3500
	1			1	15		3		2	2	16		3		2	2	4500
UHC^i_r	1			2	12		1	1	1		40		1	1	1		2000
	2			1	9		2	1	1		30		2	1	1		3000
	2			2	7	$\mathrm{UTC}^{k'}_{pd}$	3	1	1		20	$\mathrm{FTC}^{k'}_{pd}$	3	1	1		3500
	1		1		12		1	1	2		20		1	1	2		3200
UHC^i_d	1		2		6		2	1	2		15		2	1	2		5600
	2		1		7		3	1	2		10		3	1	2		7200
	2		2		4	Unit Manuf. Cost						Fix Manuf/Idle Cost					
UHC^i_p	1	1			5		i	p			$		i	p			$
	2	1			3	UMC^i_p	1	1			60	FMC^i_p	1	1			48000
							2	1			30		2	1			36000
						OMC^i_p	1	1			90	FIC^i_p	1	1			4800
							2	1			45		2	1			3600

Table 3
Parameters for defining fuzzy product prices in illustrative example

•	i	p	d	r	Seller		Buyer	
					$(\bullet)^0_S$	$(\bullet)^1_S$	$(\bullet)^1_B$	$(\bullet)^0_B$
USP^i_{dr}	1		1	1	1350	1450	1400	1500
	1		1	2	1400	1500	1450	1550
	1		2	1	1250	1350	1300	1400
	1		2	2	1200	1300	1250	1350
	2		1	1	650	750	700	800
	2		1	2	700	800	750	850
	2		2	1	600	700	650	750
	2		2	2	550	650	600	700
USP^i_{pd}	1	1	1		850	950	900	1000
	1	1	2		750	850	800	900
	2	1	1		400	500	450	550
	2	1	2		300	400	350	450
USP^i_{rc}	1			1	1650	1750	1700	1800
	1			2	1600	1700	1650	1750
	2			1	1000	1100	1050	1150
	2			2	950	1050	1000	1100

Table 4
Other parameters of illustrative example

Trans. Lead Time					Safe Inven Quant						Trans. Cap. Level					
	p	d	r			i	p	d	r			k	p	d	r	
		1	1	0		1			1	150		1		1	1	60
TLT_{dr}		1	2	0	SIQ^i_r	1			2	150		2		1	1	120
		2	1	1		2			1	250		3		1	1	180
		2	2	1		2			2	250		1		1	2	60
TLT_{pd}	1	1		0		1		1		200		2		1	2	120
	1	2		1	SIQ^i_d	1		2		300	TCL^k_{dr}	3		1	2	180
Max Inventory Cap						2		1		300		1		2	1	220
	p	d	r			2		2		500		2		2	1	440
MIC_r			1	600	SIQ^i_p	1	1			400		3		2	1	660
			2	800		2	1			600		1		2	2	220
MIC_d		1		1000	Fix Manuf Quantity							2		2	2	440
		2		4000		i	p					3		2	2	660
MIC_p	1			2500	FMQ^i_p	1	1			1200		1	1	1		100
Total Overtime #						2	1			1500		2	1	1		200
	p				OMQ^i_p	1	1			300	$\mathrm{TCL}^{k'}_{pd}$	3	1	1		300
MTO_p	1			3		2	1			400		1	1	2		400
												2	1	2		800
												3	1	2		1200
					Max Input/Output Transport Capacities											
								d						d		
					MITC_d			1		300	MOTC_d			1		300
								2		1200				2		1200

Table 5
Parameters for defining membership functions for objectives

m	J_m	$\underline{J}_m^0$	J_m^0	J_m^1	$\bar{J}_m^1$
1	$Z_{p=1}$	2, 273, 758	2, 273, 758	2, 664, 123	4, 623, 672
2	$Z_{d=1}$	−290, 481	37, 429	570, 869	1, 104, 309
3	$Z_{d=2}$	−467, 993	762, 862	1, 109, 662	3, 155, 891
4	$Z_{r=1}$	−797, 333	28, 323	639, 630	1, 345, 449
5	$Z_{r=2}$	−755, 271	276, 206	648, 639	1, 553, 022
6	$\mathrm{SIL}_{p=1}$	0.09	0.09	0.92	0.92
7	$\mathrm{SIL}_{d=1}$	0.07	0.07	0.97	0.97
8	$\mathrm{SIL}_{d=2}$	0.02	0.02	0.95	0.95
9	$\mathrm{SIL}_{r=1}$	0.06	0.06	0.94	0.94
10	$\mathrm{SIL}_{r=2}$	0.04	0.04	0.93	0.93
11	$\mathrm{CSL}_{r=1}$	0.80	0.80	1.00	1.00
12	$\mathrm{CSL}_{r=2}$	0.77	0.77	0.96	0.96
13	$\mathrm{RI}_{Z_{p=1}}$	−204, 289	−129, 519		
14	$\mathrm{RI}_{Z_{d=1}}$	−101, 687	−75, 487		
15	$\mathrm{RI}_{Z_{d=2}}$	−193, 525	−159, 639		
16	$\mathrm{RI}_{Z_{r=1}}$	−200, 097	−117, 435		
17	$\mathrm{RI}_{Z_{r=2}}$	−244, 216	−139, 514		
18	$\mathrm{RI}_{\mathrm{SIL}_{p=1}}$	−0.066	−0.048		
19	$\mathrm{RI}_{\mathrm{SIL}_{d=1}}$	−0.073	−0.060		
20	$\mathrm{RI}_{\mathrm{SIL}_{d=2}}$	−0.057	−0.039		
21	$\mathrm{RI}_{\mathrm{SIL}_{r=1}}$	−0.086	−0.034		
22	$\mathrm{RI}_{\mathrm{SIL}_{r=2}}$	−0.085	−0.066		
23	$\mathrm{RI}_{\mathrm{CSL}_{r=1}}$	−0.036	−0.017		
24	$\mathrm{RI}_{\mathrm{CSL}_{r=2}}$	−0.026	−0.019		

Table 6
The compromised product prices of the illustrative example

	i	p	d	r	USP	$\mu_{\mathcal{BP}}$	$\mu_{\mathcal{SP}}$
USP^i_{dr}	1		1	1	1425	0.75	0.75
	1		1	2	1475	0.75	0.75
	1		2	1	1326	0.74	0.76
	1		2	2	1276	0.75	0.75
	2		1	1	725	0.75	0.75
	2		1	2	775	0.75	0.75
	2		2	1	676	0.74	0.76
	2		2	2	626	0.74	0.76
USP^i_{pd}	1	1	1		926	0.74	0.76
	1	1	2		826	0.75	0.75
	2	1	1		476	0.74	0.76
	2	1	2		375	0.75	0.75
USP^i_{rc}	1			1	1728	0.72	0.78
	1			2	1678	0.72	0.78
	2			1	1079	0.72	0.78
	2			2	1031	0.69	0.81

for sellers and buyers, respectively. Membership functions shown in Fig. 3 are respectively adopted for all aggregated fuzzy product prices.

The problem includes 5702 equations, 4079 continuous variables, and 910 binary variables. To solve this mixed-integer nonlinear programming problem for the supply chain model, the Generalized Algebraic Modeling System (GAMS, Brooke et al., 1998), a well-known high-level modeling system for mathematical programming problems, is used as the solution environment. The MINLP solver used is DICOPT and the NLP solver, CONOPT.

According to the problem description, mathematical formulation, and parameter design mentioned previously, we solve the multi-objective mixed-integer non-linear programming problem for a production and distribution scheduling by using the fuzzy procedure discussed in Section 5.

Step 1. Select suitable ranges for defining membership functions. Relevant lower/upper limits, $\underline{J}_m^0$ and $\bar{J}_m^1$, and selected effective ranges, $[J_m^0, J_m^1]$, for membership functions are shown in Table 5. As mentioned previously, one can subjectively select values for J_m^0 and J_m^1 for each objective if meaningful lower/upper bounds can be expected.

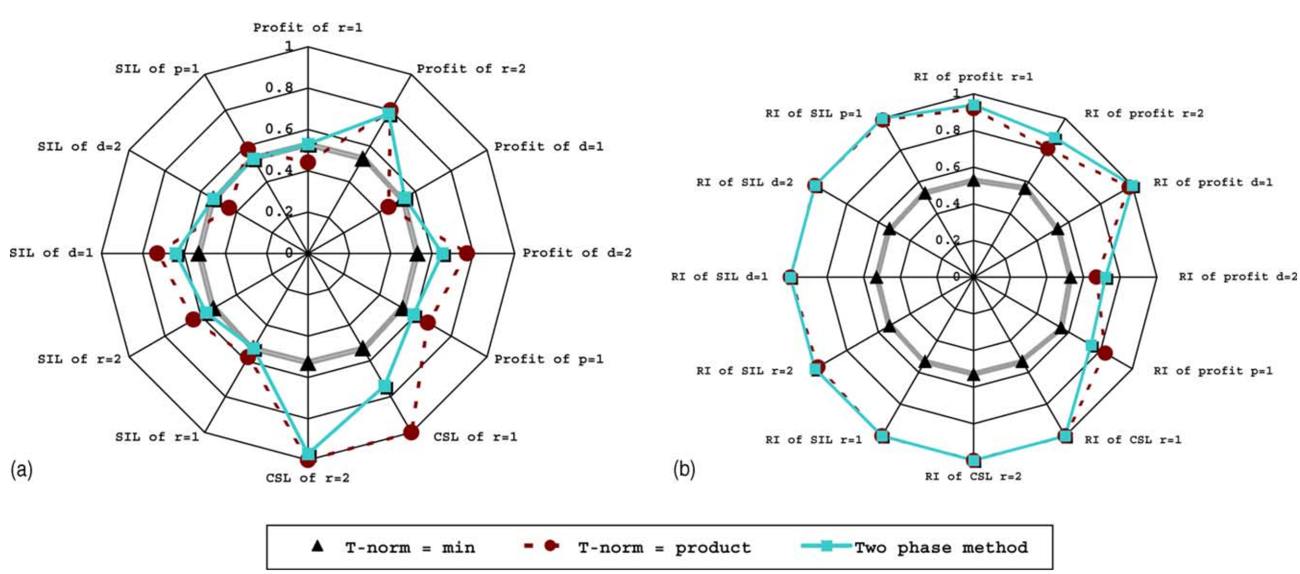

Fig. 5. Radar plots by using minimum or product t-norms (single-phase optimization) and proposed two-phase optimization method. (a) Objectives such as profits, inventory levels, and service levels; (b) robustness measures.

Table 7
Variability of scenario-dependent objective values

	Scenario	Profit					Safe inventory level					Service level	
		$p=1$	$d=1$	$d=2$	$r=1$	$r=2$	$p=1$	$d=1$	$d=2$	$r=1$	$r=2$	$r=1$	$r=2$
RI not included	1	2709353	353342	1300455	657240	288886	0.60	0.64	0.43	0.60	0.53	1.00	1.00
	2	2036686	413862	821158	852790	917316	0.47	0.82	0.50	0.74	0.53	1.00	1.00
	3	2806934	250369	1196849	79628	736006	0.49	0.71	0.57	0.50	0.62	0.99	1.00
	4	2447388	375178	936194	234508	756312	0.61	0.97	0.57	0.59	0.75	0.99	0.85
	5	2648390	421579	1159809	210789	−271410	0.65	0.84	0.55	0.68	0.74	1.00	1.00
	6	2760923	123027	1053518	229115	46819	0.64	0.91	0.57	0.62	0.67	1.00	1.00
	7	2387742	318640	772951	−253262	853122	0.69	0.95	0.60	0.63	0.75	1.00	0.99
Expected		2502362	332101	1023055	366009	538010	0.58	0.84	0.53	0.62	0.65	1.00	0.96
RI		−114353	−37930	−78733	−141041	−152013	−0.033	−0.050	−0.021	−0.025	−0.046	−0.004	−0.026
RI included	1	2627463	327660	987458	396451	637799	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	2	2580353	327660	1034208	350482	595791	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	3	2502549	327660	1151319	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	4	2502549	327660	1050643	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	5	2485710	327660	817240	299611	452736	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	6	2451158	327660	765471	332659	528373	0.53	0.65	0.51	0.52	0.55	0.95	0.96
	7	2129671	327660	987458	350482	536394	0.53	0.65	0.51	0.52	0.55	0.95	0.96
Expected		2502549	327660	987458	350482	565329	0.53	0.65	0.51	0.52	0.55	0.95	0.96
RI		−34298	0	−44178	−6895	−16963	0.00	0.00	0.00	0.00	0.00	0.00	0.00

We thus directly use $[\underline{J}_m^0, \bar{J}_m^1]$ as the effective range for defining fuzzy objectives such as inventory levels and customer service levels. Due to the wide variability of scenario-dependent profits, it is suggested using the lowest positive profit as the lower bound, and the second largest value as the upper bound. For emphasizing robustness measures, we suggest adopting the second lower value as the lower bound, and the zero as the upper bound.

Step 2 (Phase I). To maximize the degree of satisfaction for the worst objective by using the minimum operator. The result is $\mu_{\min} = 0.53$.

Step 3 (Phase II). Re-optimize the problem with new constraints of guaranteed minimum satisfaction for all fuzzy objectives and fuzzy product prices. The results will be shown and discussed in the following.

The radar plots for profits, safe inventory levels, customer service levels, and the robustness measures are shown in Fig. 5, and the resulting compromised sales prices are listed in Table 6.

Form the results obtained by selecting minimum as t-norm, we can get a more balanced satisfaction among all objectives where the degrees of satisfaction are all around 0.53. By using product operator to guarantee a unique solution, however, the results are unbalanced with lower degree of satisfaction for profits of $r = 1$ and $d = 1$, and the safe inventory level of $d = 2$. On the other hand, the high profit of $r = 2$ and service levels of $r = 1$ and $r = 2$ are given very high emphasis. Obviously this is not desirable for obtaining a compromise solution. Overcoming the drawbacks of the single phase method, the proposed two-phase method can incorporate advantages of these two t-norms. The minimum operator is used in phase I to find the maximal satisfaction for worst situation, and the product operator is applied in phase II to maximize the overall satisfaction with guaranteed minimal fulfillment for all fuzzy objectives and fuzzy product prices.

Resulting objective values for all scenarios either considering robustness measures or not are listed in Table 7. It can be found that the variability of scenario-dependent objective values is quite high if the robustness measures are not included as objectives. In such a case, some profit realizations are unacceptably low for certain scenarios especially for retailers $r = 1$ and $r = 2$. When simultaneously considering the robustness measures as objectives, i.e., objective values less than the expectation are penalized, the variability of scenario-related objective values is significantly reduced.

7. Conclusion

This paper investigates the simultaneous optimization of multiple conflict objectives and the uncertain product prices problem in a typical supply chain network with market demand uncertainties. The demand uncertainty is modeled as discrete scenarios with given probabilities for different expected outcomes, and the uncertain product prices are described as fuzzy variables. The problem is formulated as a MINLP model to achieve fair profit distribution among whole network's participants, safe inventory levels, maximum customer service levels, maximum robustness to demand uncertainties, and to guarantee maximum acceptability levels of sellers' and buyers' preference on product prices. Considering the robustness measures as part of multiple objectives can significantly reduce the variability of other objective values to product demand uncertainties. To find the degree of satisfaction of the multiple objectives, the linear increasing membership function is used; the final decision is acquired by fuzzy aggregation of the fuzzy goals and the fuzzy product prices, and the best compromised solution can be derived by maximizing the overall degree of satisfaction for the decision. The implementation of the proposed fuzzy decision-making method, as one can see in the case study, demonstrates that the method can provide a compensatory solution for the multiple conflict objectives and the fuzzy product prices problem in a supply chain network with demand uncertainties.

Nomenclature

Index/set	*Dimension*	*Physical meaning*
$c \in \mathcal{C}$	$[\mathcal{C}] = C$	customers
$d \in \mathcal{D}$	$[\mathcal{D}] = D$	distribution centers
$i \in \mathcal{I}$	$[\mathcal{I}] = I$	products
$k \in \mathcal{K}$	$[\mathcal{K}] = K$	transport capacity level, DC to retailer
$k' \in \mathcal{K}'$	$[\mathcal{K}'] = K'$	transport capacity level, plant to DC
$m \in \mathcal{M}$	$[\mathcal{M}] = M$	all objectives
$m' \in \mathcal{M}'$	$[\mathcal{M}'] = M'$	objectives 1–3
$n \in \mathcal{N}$	$[\mathcal{N}] = N$	counter for overtime manufacturing
$p \in \mathcal{P}$	$[\mathcal{P}] = P$	plants
$r \in \mathcal{R}$	$[\mathcal{R}] = R$	retailers
$t \in \mathcal{T}$	$[\mathcal{T}] = T$	periods
$s \in \mathcal{S}$	$[\mathcal{S}] = S$	scenarios

Parameters	$* \in$	*Physical meaning*
FCD^{i}_{*ts}	$\{r\}$	forecast customer demand of i
FIC^{i}_{*}	$\{p\}$	fix idle cost to keep p idle
FMC^{i}_{*}	$\{p\}$	fix manufacture cost changed to make i
FMQ^{i}_{*}	$\{p\}$	fix manufacture quantity of i
FTC^{k}_{*}	$\{dr\}$	kth level fix transport cost, d to r
$\mathrm{FTC}^{k'}_{*}$	$\{pd\}$	k'th level fix transport cost, p to d
MIC_{*}	$\{p, d, r\}$	maximum inventory capacity of p, d, r
MITC_{*}	$\{d\}$	maximum input transport capacity of d
MOTC_{*}	$\{d\}$	maximum output transport capacity of d
MTO_{*}	$\{p\}$	maximum total overtime manufacture period
OMC^{i}_{*}	$\{p\}$	overtime unit manufacture cost of i
OMQ^{i}_{*}	$\{p\}$	overall fix manufacture quantity
PPD_{*}	$\{s\}$	probability for scenario s
SIQ^{i}_{*}	$\{p, d, r\}$	safe inventory quantity in p, d, r
$\mathrm{SQL}^{i\vee}_{*}$	$\{p, d\}$	sales quantity levels of i, $(*, \vee) \in \{(p, \ell'), (d, \ell)\}$
UHC^{i}_{*}	$\{p, d, r\}$	unit handling cost of i for p, d, r
UIC^{i}_{*}	$\{p, d, r\}$	unit inventory cost of i for p, d, r
UMC^{i}_{*}	$\{p\}$	unit manufacture cost of i
$(\mathrm{USP}^{i}_{*})^{\bullet}_{+}$	$\{pd, dr, rc\}$	parameters for defining piecewise unit sale prices, $+ \in \{S, B\}$, $\bullet \in \{0, 1\}$
UTC^{k}_{*}	$\{dr\}$	kth level unit transport cost, d to r
$\mathrm{UTC}^{k'}_{*}$	$\{pd\}$	k'th level unit transport cost, p to d
TCL^{k}_{*}	$\{dr\}$	kth transport capacity level, d to r
$\mathrm{TCL}^{k'}_{*}$	$\{pd\}$	k'th transport capacity level, p to d
TLT_{*}	$\{pd, dr\}$	transport lead time, p to d (d to r)

Binary variables	$* \in$	*Meaning when having value of* 1
Y^{k}_{*ts}	$\{dr\}$	kth transport capacity level, d to r
$Y^{k'}_{*ts}$	$\{pd\}$	k'th transport capacity level, p to d
α^{i}_{*ts}	$\{p\}$	manufacture with regular time workforce
β^{i}_{*ts}	$\{p\}$	setup plant p to manufacture i

γ^i_{*ts}	$\{p\}$	p changeover to manufacture i
o^i_{*ts}	$\{p\}$	manufacture with overtime workforce
Real variables	$* \in$	*Physical meaning*
B^i_{*ts}	$\{r\}$	backlog level of i in r at end of t
D^i_{*ts}	$\{p, d, r\}$	short safe inventory level in p, d, r
I^i_{*ts}	$\{p, d, r\}$	inventory level of i in p, d, r
J_*	$\{m\}$	objectives
PSP_{*ts}	$\{p, d, r\}$	product sales of p, d, r
RI_*	$\{m'\}$	robustness index of objectives
SQ^i_{*ts}	$\{pd, dr, rc\}$	sales quantity of i from p to d, d to r, r to c
TIC_{*ts}	$\{p, d, r\}$	total inventory cost of p, d, r
THC_{*ts}	$\{p, d, r\}$	total handling cost of p, d, r
TMC_{*ts}	$\{p\}$	total manufacture cost of p
TPC_{*ts}	$\{d, r\}$	total purchase cost of d, r
TQ^k_{*ts}	$\{dr\}$	kth level transport quantity, d to r
$\mathrm{TQ}^{k'}_{*ts}$	$\{pd\}$	k'th level transport quantity, p to d
TQ_{*ts}	$\{pd, dr\}$	total transport quantity, p to d or d to r
TTC_{*ts}	$\{d; pd, dr\}$	total transport cost of d; p to d or d to r
USP^i_{*s}	$\{pd, dr, rc\}$	unit product price of i, p to d, d to r, and r to c
SIL_{*t}	$\{p, d, r\}$	expected safe inventory level of p, d, r
CSL_{*t}	$\{r\}$	expected customer service level of r
Z_{*t}	$\{p, d, r\}$	expected net profit of p, d, r
Fuzzy variables	$* \in$	*Physical meaning*
$\mathcal{BP}^i_*$	$\{pd, dr, rc\}$	fuzzy sets to measure buyer's preference for product price
$\mathcal{FD}$		fuzzy set for final decision
$\mathcal{J}_m$		fuzzy set for objective m, $m \in \mathcal{M}$
$\mathcal{SP}^i_*$	$\{pd, dr, rc\}$	fuzzy sets to measure seller's preference for product price

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Multi-criteria fuzzy optimization for locating warehouses and distribution centers in a supply chain network

Cheng-Liang Chen [1,*], Tzu-Wei Yuan[2], Wen-Cheng Lee[3]

Department of Chemical Engineering, National Taiwan University, Taipei 10617, Taiwan

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Abstract

This study considers the planning of a multi-product, multi-period, and multi-echelon supply chain network that consists of several existing plants at fixed places, some warehouses and distribution centers at undetermined locations, and a number of given customer zones. Unsure market demands are taken into account and modeled as a number of discrete scenarios with known probabilities. The supply chain planning model is constructed as a multi-objective mixed-integer linear program (MILP) to satisfy several conflict objectives, such as minimizing the total cost, raising the decision robustness in various product demand scenarios, lifting the local incentives, and reducing the total transport time. For the purpose of creating a compensatory solution among all participants of the supply chain, a two-phase fuzzy decision-making method is presented and, by means of application of it to a numerical example, is proven effective in providing a compromised solution in an uncertain multi-echelon supply chain network.

Keywords: Supply chain management; Uncertainty; Multiple objectives; Mixed-integer linear program (MILP); Fuzzy decision making

1. Introduction

The supply chain is an integrated process wherein a number of business entities (suppliers, manufacturers, distributors and retailers) work together in an effort to acquire raw materials, convert them into specified final products and deliver these final products to retailers (Beamon, 1998). The supply chain further fosters a new concept in management: the concept of supply chain management.

Over the past decade the world has changed from a marketplace with some large independent markets to an extremely integrated global market. The increase in competitive pressures in the global marketplace coupled with the rapid advances in information technology have brought supply chain planning into the forefront of the business practices of most manufacturing and service organizations (Gupta and Maranas, 2003). A great variety of companies, those in chemical industry included, can also benefit from this novel management scheme. Therefore, many researchers in the process systems engineering (PSE) society devote themselves to this interesting field (Applequist *et al*., 2000; Bose and Pekny, 2000; Chen *et al*., 2003; Cheng *et al*., 2003; Garcia-Flores *et al*., 2000; Gupta and Maranas, 2000; Gupta *et al*., 2000; Perea-Lopez *et al*., 2000; Pinto *et al*., 2000; Zhou *et al*., 2000, etc.).

Traditionally, the integration of supply chain networks is usually based on deterministic parameters. In practice, however, this is rarely the case as it is usually difficult to foretell prices of chemicals, market demands, availabilities of raw materials, etc., in a precise fashion (Liu and Sahinidis, 1997). A number of works are devoted to studying supply chain management under uncertain environments. For example, Gupta and Maranas (2000) incorporate uncertain demand via a normal probability function and propose a two-stage solution framework. A generalization to handle multi-period and multi-customer problems was recently proposed by Gupta and Maranas (2003). Tsiakis *et al*. (2001) use a scenario planning approach to describe demand uncertainties. Therein a number of demand scenarios with assigned non-zero probabilities is used as discrete stochastic demand quantities. All scenarios are simultaneously taken into account in the supply chain network design. However, the robustness of decision for uncertain product demands is not considered in these studies. In this paper, one of the major concerns is market demand uncertainty. The scenario-based approach will be adopted for modeling the uncertain market demands.

* Corresponding author. Tel.: +886 2 23636194; fax: +886 2 23623040.
E-mail address: CCL@ntu.edu.tw (C.-L. Chen).
[1] 陳誠亮
[2] 袁子偉
[3] 李文誠

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The location of manufacturing and warehousing facilities has received considerable attention from academics and practitioners alike over the past four decades. Location models have been developed to answer questions such as how many facilities to establish, where to locate them, and how to distribute the products to the customers in order to satisfy demand and minimize total cost (Melachrinoudis *et al*., 2000). However, when making location decisions, in addition to the total cost, one should also consider some other conditions such as the influence of local incentives and transport time.

In this article, the mid-term planning problem of locating warehouses and distribution centers in a supply chain network will be addressed, where multiple conflict objectives will be considered simultaneously including minimizing the total cost, raising the decision robustness to various product demand scenarios, lifting the local incentives, and reducing the total transport time. This problem can be further formulated as a multi-objective mixed-integer linear program. So the two-phase fuzzy optimization solution strategy proposed by Chen and Lee (2004a,b) can be adopted directly.

In the rest of this article, the problem statement and assumptions are outlined in Section 2. The considered uncertain issues in supply chain planning are also described. The formulation of a production and distribution–planning model is set out in Section 3. The procedure for grouping the scenario-dependent multiple conflict objectives into a scalar objective using the fuzzy sets concept is presented in Section 4. The contents of a numerical example, used to demonstrate the usefulness of the proposed method, are given in Section 5. Finally, some concluding remarks are given in Section 6.

Index/set	Dimension	Physical meaning
$c \in \mathcal{C}$	$[\mathcal{C}] = C$	Customer zones
$d \in \mathcal{D}$	$[\mathcal{D}] = D$	Distribution centers
$i \in \mathcal{I}$	$[\mathcal{I}] = I$	Products
$k \in \mathcal{K}$	$[\mathcal{K}] = K$	Transport capacity level
$m \in \mathcal{M}$	$[\mathcal{M}] = M$	All objectives
$n \in \mathcal{N}$	$[\mathcal{N}] = N$	Resources
$p \in \mathcal{P}$	$[\mathcal{P}] = P$	Plants
$s \in \mathcal{S}$	$[\mathcal{S}] = S$	Scenarios
$t \in \mathcal{T}$	$[\mathcal{T}] = T$	Periods
$w \in \mathcal{W}$	$[\mathcal{W}] = W$	Warehouses

Parameters	$* \in$	Physical meaning
FCD^{i}_{*ts}	$\{c\}$	Forecasting customer demand of i for customer c
FTC^{k}_{*}	$\{pw, wd, dc\}$	kth level fix transport cost, p to w, w to d, d to c
LI_{*}	$\{w, d\}$	Local incentive of w, d
PPD_{s}		Probability of product scenario s
PQ^{*}_{ips}	{max, min}	Maximum, minimum manufacturing quantity of product i
$Q^{\max}_{*s}$	$\{pw, wd, dc\}$	Maximum transport quantity of p to w, w to d, d to c
$Q^{\min}_{*s}$	$\{pw, wd, dc\}$	Minimum transport quantity of p to w, w to d, d to c
R_{*nts}	$\{p\}$	Total resource n at p
SQ^{+}_{*}	$\{w, d\}$	Maximum, minimum capacity of w, d, $+ \in$ {max, min}
TCL^{k}_{*}	$\{pw, wd, dc\}$	kth transport capacity level, p to w, w to d, d to c
TT_{*}	$\{pw, wd, dc\}$	Transport time of p to w, w to d, d to c
UEC_{*}	$\{w, d\}$	Unit establishing cost of w, d
UHC^{i}_{*}	$\{w, d\}$	Unit handling cost of product i for w, d
UPC^{i}_{*}	$\{p\}$	Unit production cost of product i for plant p
UTC^{k}_{*}	$\{pw, wd, dc\}$	kth level unit transport cost, p to w, w to d, d to c
α^{i}_{*}	$\{w\}$	Coefficient relating the capacity of d to flow of product i handled
β^{i}_{*}	$\{d\}$	Coefficient relating the capacity of w to flow of product i handled
ρ^{i}_{*nts}	$\{p\}$	Coefficient for resource m used in plant p for product i

Real var.	$* \in$	Physical meaning
J_{*}	$\{m\}$	Objectives
OTT		Total transportation time
PQ^{i}_{*ts}	$\{p\}$	Manufacture quantity of i
Q^{i}_{*ts}	$\{pw, wd, dc\}$	Total transport quantity, p to w, w to d, d to c
SQ_{*}	$\{w, d\}$	Capacity of w, d
TCO		Total cost
TEC		Total establishment cost of all warehouses and distribution centers
THC_{ts}		Total handling cost of scenario s in period t
TLI, LD		Total local incentive and an overall index on distribution centers
TPC_{ts}		Total production cost of scenario s in period t
TTC_{ts}		Total transportation cost for scenario s in period t

TTC_{*ts}	$\{pw, wd, dc\}$	Total transportation cost of * for scenario s in period t
TTQ^{k}_{*ts}	$\{pw, wd, dc\}$	kth level transport quantity, p to w, w to d, d to c
$\mu_{\mathcal{J}\mathrm{m}}(J_\mathrm{m}(x))$		The membership function of fuzzy objective $\mathcal{J}_\mathrm{m}$

Binary var.	*∈	Meaning when having value of 1
X_*	$\{pw, wd, dc\}$	A link between p and w, w and d, d and c exists
Y_*	$\{w, d\}$	Warehouse w or distribution center d is to be established
Z^{k}_{*ts}	$\{pw, wd, dc\}$	kth transport capacity level, p to w, w to d, d to c

Fuzzy var.		Physical meaning
$\mathcal{FD}$		Fuzzy set for final decision
$\mathcal{J}_\mathrm{m}$		Fuzzy set for objective m

2. Problem description for locating warehouses and distribution centers in a supply chain network

The researchers consider a typical multi-product, multi-echelon and multi-period supply chain network originally studied by Tsiakis *et al.* (2001). The revised supply chain network consists of several existing multi-product plants at fixed places, some candidate warehouses and distribution centers at specific but undermined locations, and a number of known customer zones, as showed in Fig. 1. In this mid-term supply chain-planning problem, each customer zone places demands for one or more products. The candidate warehouses and distribution centers are described by the upper and lower bounds on their handling capacity. The establishment of warehouses and distribution centers will result in a fixed infrastructure cost. Operational costs include those associated with production, handling of material at warehouses and distribution centers, and transportation. The numbers and the locations of selected warehouses and distribution centers are left to be determined for establishment of a cost–effective supply chain network. The following assumptions are made for subsequent modeling and optimization: the whole system is operated steadily; therefore, there is no stock accumulation or depletion, and inventory can be ignored; the production capacity of each plant is related linearly to resources; the capacities of warehouses and distribution centers are related linearly to the materials that they handle; the transportation costs are piecewise linear functions of the actual flow of the product from the source stage to the destination podium; several scenarios of product demands with known probabilities are forecast over the entire planning periods. The overall problem can thus be stated as follows. Given are the manufacturing data, such as product capacity and resource constraints; the basic data for candidate warehouses and distribution centers, such as capacities and local incentives; the transportation data, such as transport time and transport capacity; all cost parameters, such as manufacturing and handling costs; and several scenarios of forecasted product demands with known probabilities. The authors are going to determine the production plan of each plant; the number, location, and the capacity of warehouses and distribution centers to be set up; the transportation plan of each warehouse and distribution center; and all types of costs. The target is to integrate the multi-echelon decisions simultaneously to minimize the total cost and the transport time, and to elevate local incentives and the robustness of all considered design objectives to product demand uncertainties as much as possible.

In the market, the participants of a supply chain not only faces the uncertainties of product demands and raw material supplies but also faces the uncertainties of commodity prices and costs (Liu and Sahinidis, 1997). The authors will also

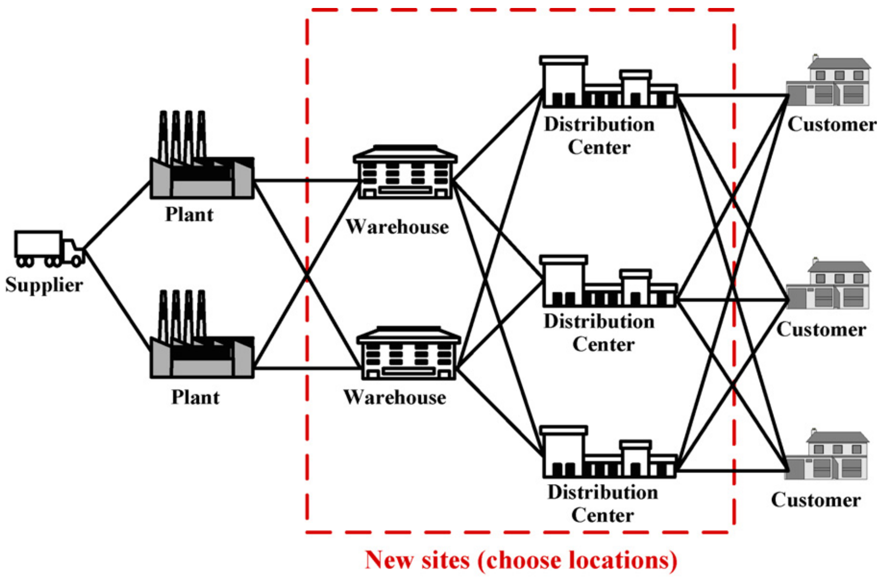

Fig. 1. The studied supply chain network.

address issues of demand uncertainty in the mid-term planning problem. The first concern in incorporating uncertainties into supply chain modeling and optimization is the determination of suitable representation of the uncertain parameters (Gupta and Maranas, 2003). Several distinct methods are frequently mentioned for representing uncertainty. For example, the fuzzy-based approach (Giannoccaro *et al.*, 2003; Liu and Sahinidis, 1997; Petrovic *et al.*, 1998, 1999), wherein the forecast parameters are considered as fuzzy numbers with accompanied membership functions; the scenario-based approach (Gupta and Maranas, 2003), in which several discrete scenarios with associated probability levels are used to describe expected occurrence of particular outcomes. To simplify the subsequent mathematical calculations, the discrete scenario-based approach for modeling uncertain mid-term product demands is adopted. Previous experience concerning uncertain product demands in short-term supply chain management problems (Chen and Lee, 2004a,b) gives strong support for applying the scenario-based approach. The mid-term planning problem considering multiple conflict objectives, including uncertain product demands, will be addressed in this article.

For applying the discrete cases representation for modeling uncertain demands, several possible outcomes for demand forecasting, $\mathrm{FCD}_s, s \in \mathcal{S}$, with known probabilities, PPD_s, should be determined at first with the restriction of $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s = 1$. Then, all variables will become scenario-dependent, and the expected value of any variable will be the weighted average of those scenario-dependent values. That is, for any variable v, one has to solve for several scenario-dependent values, $v_s, s \in \mathcal{S}$, and the expected value of v can be taken as $\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s v_s$. In such a case the deterministic supply chain model can be easily extended to cope with the uncertain demand conditions (Chen and Lee, 2004a,b).

3. Supply chain modeling with demand uncertainty

A general supply chain that consists of three different levels of enterprises is considered. The first level enterprise is the retailer from which the products are sold to customers. The second level enterprise is the distribution center (DC) and/or warehouse using different types of transport capacity to deliver products from the plant side to the retailer side. The third level enterprise is the plant or the manufacturer that batch-manufactures one product over one period. In the following, the integrated multi-echelon supply chain model of Tsiakis *et al.* (2001) is extended for optimal decisions. The scenario-based representation for uncertain product demands is considered in the modeling. The indices, sets and parameters designed for modeling the supply chain network with product demand uncertainty are given in the nomenclature. Therein, parameters are divided into two categories: the cost parameters, including product cost, handling cost and transport cost; and other parameters describing the system information, such as handling and transport capacity or forecasting customer demand. Two kinds of variables are used: the binary variables that act as policy decisions to establish warehouses and distribution centers, along with using economies of scale for manufacturing or transportation, and the continuous variables that include manufacturing quantities, handling capacity and transport quantities.

3.1. Network structure constraints

All relevant network structural constraints between all plants, warehouses, DCs and customer zones can be summarized as follows.

$$X_{pw} \le Y_w, \qquad X_{wd} \le Y_w \tag{1}$$

$$X_{wd} \le Y_d, \qquad X_{dc} \le Y_d \tag{2}$$

$$\sum_{\forall w \in \mathcal{W}} X_{wd} = Y_d, \qquad \sum_{\forall d \in \mathcal{D}} X_{dc} = 1 \tag{3}$$

$$\forall\, p \in \mathcal{P}, w \in \mathcal{W}, d \in \mathcal{D}, c \in \mathcal{C}$$

Eq. (1) denotes that a link between a plant p and a warehouse w or between a warehouse w and a DC d can exist only if warehouse w exists. Similar constraints can apply to the link between DCs and customer zones, as shown in Eq. (2). To simplify the problem, it is assumed that a DC can only be served by a single warehouse, and a customer zone can only be served by a single DC, as shown in Eq. (3).

3.2. Transport constraints

The transportation constraints at considered periods, $t \in \mathcal{T}$, in different economic scales are given below.

$$\mathrm{TCL}_*^{k-1} Z_{*ts}^k < \mathrm{TTO}_{*ts}^k \le \mathrm{TCL}_*^k Z_{*ts}^k \tag{4}$$

$$\sum_{\forall k \in \mathcal{K}} Z_{*ts}^k \le 1 \tag{5}$$

$$\sum_{\forall i \in \mathcal{I}} Q_{*ts}^i = \sum_{\forall k \in \mathcal{K}} Q_{*ts}^k \tag{6}$$

$$Q_{*s}^{\min} X_* \le \sum_{\forall i \in \mathcal{I}} Q_{*ts}^i \le Q_{*s}^{\max} X_* \tag{7}$$

$$Q_{*ts}^i \ge 0 \tag{8}$$

where $* \in \{pw, wd, dc\}$,
$\forall\, p \in \mathcal{P}, w \in \mathcal{W}, d \in \mathcal{D}, c \in \mathcal{C}, i \in \mathcal{I}, t \in \mathcal{T}, s \in \mathcal{S}$

Eqs. (4) and (5) imply that several transport capacity levels with various unit transport costs can be used, as depicted in Fig. 2 for a three-level case, and at most one transport capacity can be chosen at each period. In Eq. (6), the transport quantities from plants to warehouses, from warehouses to DCs, or from DCs to customer zones at each period are respectively translated into total transport quantities. Eq. (7) says that the total transport quantities have lower/upper bonds, for all the existing links.

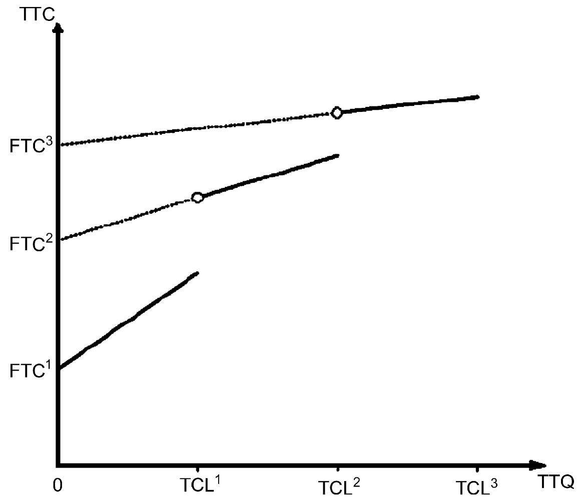

Fig. 2. Piecewise linear relation (solid lines) between transport cost, TTC, and shipment quantity, TTQ.

3.3. Material balances constraints

For mid-term design, it is assumed that the operation is in a constant state. Therefore, there is no stock accumulation or depletion. All material balance constraints can thus be summarized as follows.

$$\mathrm{PQ}^i_{pts} = \sum_{\forall w\in\mathcal{W}} Q^i_{pwts} \tag{9}$$

$$\sum_{\forall p\in\mathcal{P}} Q^i_{pwts} = \sum_{\forall d\in\mathcal{D}} Q^i_{wdts} \tag{10}$$

$$\sum_{\forall w\in\mathcal{W}} Q^i_{wdts} = \sum_{\forall c\in\mathcal{C}} Q^i_{dcts} \tag{11}$$

$$\sum_{\forall d\in\mathcal{D}} Q^i_{dcts} = \mathrm{FCD}^i_{cts} \tag{12}$$

$$\mathrm{PQ}^t_{ips} \geq 0, \quad \forall\, p\in\mathcal{P}, i\in\mathcal{I}, t\in\mathcal{T}, s\in\mathcal{S} \tag{13}$$

Eq. (9) says that the production of a product i by a plant p must be equal to the total flow of the product i to all warehouses. Eq. (10) states that the total flow of a product i from all plants to a warehouse w must be equal to the total flow of the product i from the warehouse w to all DCs.

Similarly, Eq. (11) means that the total flow of a product i from all warehouses to a DC d must equal to the total flow of a product i from the DC d to all customer zones. Eq. (10) denotes that the total flow of a product i from all DCs to a customer zone c must equal to the forecast customer demands.

3.4. Production resource constraints

An important issue in designing the network is the ability of the plants to satisfy the demands of customers. The production of each product at any plant thus has some limitations as follows.

$$\mathrm{PQ}^{\min}_{ips} \leq \mathrm{PQ}^i_{pts} \leq \mathrm{PQ}^{\max}_{ips} \tag{14}$$

$$\sum_{\forall i\in\mathcal{I}} \rho^i_{pnts}\mathrm{PQ}^i_{pts} \leq R_{pnts}, \quad \forall\, p\in\mathcal{P}, n\in\mathcal{N}, i\in\mathcal{I}, t\in\mathcal{T}, s\in\mathcal{S} \tag{15}$$

Here, Eq. (14) states that each plant has its own maximum and minimum product capacities. Many plants may apply the same resources (equipment, utilities, manpower, etc.) to produce different products at different production stages. The limitations of resource utilization can be seen in Eq. (15).

3.5. Capacity constraints

All capacity constraints for warehouses and DCs are listed in the following.

$$\mathrm{SQ}^{\min}_w Y_w \leq \mathrm{SQ}_w \leq \mathrm{SQ}^{\max}_w Y_w \tag{16}$$

$$\mathrm{SQ}^{\min}_d Y_d \leq \mathrm{SQ}_d \leq \mathrm{SQ}^{\max}_d Y_d \tag{17}$$

$$\mathrm{SQ}_w \geq \sum_{\forall i\in\mathcal{I}}\sum_{\forall d\in\mathcal{D}} \alpha^i_w Q^i_{wdts} \tag{18}$$

$$\mathrm{SQ}_d \geq \sum_{\forall i\in\mathcal{I}}\sum_{\forall c\in\mathcal{C}} \beta^i_d Q^i_{dcts}, \quad \forall\, w\in\mathcal{W}, d\in\mathcal{D}, c\in\mathcal{C}, i\in\mathcal{I}, t\in\mathcal{T}, s\in\mathcal{S} \tag{19}$$

Eq. (16) means that the capacity of a warehouse w has its lower bounds $\mathrm{SQ}^{\min}_w$ and upper bounds $\mathrm{SQ}^{\max}_w$, if the warehouse is established. Similar constraints apply to the capacities of the distribution centers, as shown in Eq. (17). It is assumed that the capacities of the warehouses and the distribution centers are related linearly to the materials that they handle, as expressed in Eqs. (18) and (19).

3.6. Costs

The establishment costs of warehouses and distribution centers, production costs, all material handling costs, and transportation costs are given below.

$$\mathrm{TEC} = \sum_{\forall w\in\mathcal{W}} \mathrm{UEC}_w Y_w + \sum_{\forall d\in\mathcal{D}} \mathrm{UEC}_d Y_d \tag{20}$$

$$\mathrm{TPC}_{ts} = \sum_{\forall i\in\mathcal{I}}\sum_{\forall p\in\mathcal{P}} \mathrm{UPC}^i_p \mathrm{PQ}^i_{pts} \tag{21}$$

$$\mathrm{THC}_{ts} = \sum_{\forall i\in\mathcal{I}}\sum_{\forall w\in\mathcal{W}} \mathrm{UHC}^i_w\left(\sum_{\forall p\in\mathcal{P}} Q^i_{pwts}\right) + \sum_{\forall i\in\mathcal{I}}\sum_{\forall d\in\mathcal{D}} \mathrm{UHC}^i_d\left(\sum_{\forall w\in\mathcal{W}} Q^i_{wdts}\right) \tag{22}$$

$$\mathrm{TTC}_{*ts} = \sum_{\forall k\in\mathcal{K}} (\mathrm{FTC}^k_* Z^k_{*ts} + \mathrm{UTC}^k_* \mathrm{TTQ}^k_{*ts}) \tag{23}$$

$$\mathrm{TTC}_{ts} = \sum_{\forall p \in \mathcal{P}} \sum_{\forall w \in \mathcal{W}} \mathrm{TTC}^{t}_{pws} + \sum_{\forall w \in \mathcal{W}} \sum_{\forall d \in \mathcal{D}} \mathrm{TTC}^{t}_{wds} + \sum_{\forall d \in \mathcal{D}} \sum_{\forall c \in \mathcal{D}} \mathrm{TTC}^{t}_{dcs}, \qquad (24)$$

where $* \in \{pw, wd, dc\}, \forall p \in \mathcal{P}, w \in \mathcal{W}, \in \mathcal{D}, c \in \mathcal{C}, i \in \mathcal{I}, t \in \mathcal{T}, s \in \mathcal{S}$

Eq. (20) gives the establishment costs of warehouses and distribution centers at candidate locations. In Eq. (21), the total production costs are the summations of the production quantity of product i multiply the unit production cost UPC_{ip}. Eq. (22) states that the total material handling costs can be expressed as a linear function of each product being handled at warehouses and distribution centers. Eq. (23) denotes transport costs for the plant and DC, respectively. Here, the transport cost is a composite of transport level-dependent fixed cost and a transport quantity-dependent carrying cost. This would cause a discontinuous piecewise linear transport cost, as illustrated in Fig. 2 with skipped subscripts. Finally, Eq. (24) is the total transportation cost (Gjerdrum *et al.*, 2001).

3.7. Multiple objectives for optimal planning

Several conflicting objectives such as minimizing the total cost, maximizing the robustness of selected objectives to demand uncertainties, maximizing the local incentives, and minimizing the total transport time can be considered simultaneously for the supply chain network design, as stated in the following.

3.7.1. Objective 1: minimizing the total cost

The total cost is a summation of the total establishment costs, the total production costs, the total handling costs, and the total transportation costs, such as

$$\min_{x \in \Omega'} \mathrm{TCO} = \mathrm{TEC} + \sum_{\forall t \in \mathcal{T}} \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s(\mathrm{TPC}_{ts} + \mathrm{THC}_{ts} + \mathrm{TTC}_{ts})$$

Where Ω' is the feasible searching space which is a composite of all constraints, Eqs. (1)–(24), and x denotes the decision vector

$$x = \{Y_w, Y_d, X_*; Q^{i}_{*ts}\mathrm{TTQ}^{k}_{*ts}, Z^{k}_{*ts}; \mathrm{PQ}^{i}_{ips}, \mathrm{SQ}_w, \mathrm{SQ}_d; * \in \{pw, wd, dc\}; \forall i \in \mathcal{I}, p \in \mathcal{P}, w \in \mathcal{W}, d \in \mathcal{D}, c \in \mathcal{C}, k \in \mathcal{K}, t \in \mathcal{T}, s \in \mathcal{S}\}$$

3.7.2. Objective 2: maximizing the robustness to various scenarios

It has been mentioned that all operating variables are scenario-dependent when the explicit scenario-based approach is applied to model the uncertain product demands. However, the total cost realization might be unacceptably high for certain scenarios with especially low probabilities (Suh and Lee, 2001). It is thus significant to reduce the variability of objective values J_s for any realization of scenarios. An important issue in enforcing the robustness to uncertainties is the choice of a variability metric (Ahmed and Sahinidis, 1998). For the total cost to be minimized, the decision maker usually does not care if the objective value J_s is lower than the expected mean value J. Thus, the upper partial mean (UPM) is used as the measure of robustness where only costs above the expectation are penalized and are weighted by probabilities of related scenarios, PPD_s.

$$\mathrm{UPM} = \sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \max\{0, J_s - J\}$$

As the upper partial mean decreases, the robustness of total cost will increase, thus one can define the robustness index (RI) as below, where the nonlinear objective function is further reformulated to equivalent linear form with additional constraint, Eq. (25).

$$\max_{x \in \Omega''} \mathrm{RI} = -\mathrm{UPM} = -\sum_{\forall s \in \mathcal{S}} \mathrm{PPD}_s \mathrm{UPM}_s$$

where

$$\mathrm{UPM}_s \geq 0, \qquad \mathrm{UPM}_s \geq J_s - J, \quad \forall s \in \mathcal{S} \qquad (25)$$

Notably, there is an additional constraint in the new feasible searching space, $\Omega'' = \Omega' \cap \{\text{Eq. (25)}\}$.

3.7.3. Objective 3: maximizing the local incentives

When dealing with the location–allocation problem, there are many factors worth being considered, such as traffic facilities, labor quality, tax breaks, laws, etc. More traffic facilities such as highways, railroads, harbors, airports, etc., will decrease transport risks. Higher labor quality will have higher work efficiency. A meaningful local incentive can be defined by first identifying all important factors which cause great impact on the location–allocation problem, and second, giving weight to each factor according to its importance, and subjectively scoring the factors of each candidate location. The weighted average of these scores can be defined as the local incentive of each candidate location. Although the target is to maximize the average local incentive of all chosen locations, it will cause the nonlinear term as shown below.

$$\max_{x \in \Omega'} \mathrm{TLI} = \frac{\sum_{\forall w \in \mathcal{W}} \mathrm{LI}_w Y_w}{\sum_{\forall w \in \mathcal{W}} Y_w} + \frac{\sum_{\forall d \in \mathcal{D}} \mathrm{LI}_d Y_d}{\sum_{\forall d \in \mathcal{D}} Y_d}$$

Thus the following model will be applied to simplify the solution procedure.

$$\max_{x \in \Omega'} \mathrm{TLI} = \min\{\mathrm{LI}_w + U(1 - Y_w) | \forall w \in \mathcal{W}\} + \min\{\mathrm{LI}_d + U(1 - Y_d) | \forall d \in \mathcal{D}\}$$

The model raises the minimum local incentives of the warehouses and the distribution centers as high as possible, where U is a large positive value. For those candidate locations of warehouses or distribution centers that are not chosen, their local incentives will be ignored. The above nonlinear objective can be re-formulated as the following linear form.

$$\max_{x \in \Omega'''} \text{TLI}$$

where $\Omega''' = \Omega' \cap \{\text{Eq. (26)}\}$.

$$\begin{aligned} &\text{TLI} \le \text{LI}_w + U(1 - Y_w) + \text{LD} \quad && \forall w \in \mathcal{W} \\ &\text{LD} \le \text{LI}_d + U(1 - Y_d) && \forall d \in \mathcal{D} \end{aligned} \tag{26}$$

3.7.4. *Objective 4: minimizing the total transport time*

Decreasing the transport time cannot only reduce the inventory levels, but can also increase the customer service levels. So, reduction of transport time is an important topic when coping with allocation–location problems. One can set the total transport time as the objective to be minimized, as shown below.

$$\min_{x \in \Omega'} \text{OTT} = \sum_{\forall p \in \mathcal{P}} \sum_{\forall w \in \mathcal{W}} \text{TT}_{pw} X_{pw} + \sum_{\forall w \in \mathcal{W}} \sum_{\forall d \in \mathcal{D}} \text{TT}_{wd} X_{wd} + \sum_{\forall d \in \mathcal{D}} \sum_{\forall c \in \mathcal{C}} \text{TT}_{dc} X_{dc}$$

In summary, the mid-term supply chain-planning model can be constructed as a multi-objective mixed-integer linear program (MILP). Notably, all objectives expressed below are set to a maximum for simplifying the discussion. The feasible searching space Ω is a composite of all constraints, Eqs. (1)–(26)

$$\max_{x \in \Omega} (J_1(x), \ldots, J_M(x)) = (-\text{TCO}, \text{RI}, \text{TLI}, -\text{OTT}) \tag{27}$$

4. Supply chain optimization with uncertain demands

The conventional approaches for solving the multi-objective optimization problems are usually searching for efficient (Pareto-optimal) solutions that can best attain the prioritized objectives. Users, on the whole, have to provide a subjective account of each objective. The fuzzy optimization approach, on the other hand, can supply a single, yet unprejudiced final decision as stated in the following.

By considering the uncertain property of human thinking, it is quite intuitive to assume that the decision maker has a fuzzy goal, $\mathcal{J}_m$, to describe a maximizing objective J_m with an acceptable interval $[J_m^0, J_m^1]$. It would be quite satisfactory as the objective value is greater than J_m^1, and unacceptable as the profit is less than J_m^0, the minimum acceptable objective value such that the company would like to enter to negotiation for a fair deal in the multi-enterprise network. A strictly monotonic increasing membership function, $\mu_{\mathcal{J}m}(J_m(x)) \in [0, 1]$, can be used to characterize such a transition from maximizing a numerical

Table 1
Scenarios of forecasting product demands and probabilities of an illustrative example

FCD^i_{cts}

i	*c*	*t*	*s*			*i*	*c*	*t*	*s*			*i*	*c*	*t*	*s*			*i*	*c*	*t*	*s*		
			1	2	3				1	2	3				1	2	3				1	2	3
1	1	1	10	18	28	2	3	1	105	145	105	3	5	1	32	72	82	4	7	1	40	80	88
1	1	2	8	18	30	2	3	2	82	143	125	3	5	2	22	73	92	4	7	2	35	82	92
1	1	3	5	19	46	2	3	3	55	143	145	3	5	3	12	72	98	4	7	3	24	82	98
1	2	1	0	0	0	2	4	1	0	0	0	3	6	1	0	0	0	4	8	1	35	49	55
1	2	2	0	0	0	2	4	2	0	0	0	3	6	2	0	0	0	4	8	2	31	50	75
1	2	3	0	0	0	2	4	3	0	0	0	3	6	3	0	0	0	4	8	3	25	49	81
1	3	1	0	0	0	2	5	1	0	0	0	3	7	1	0	0	0	5	1	1	0	0	0
1	3	2	0	0	0	2	5	2	0	0	0	3	7	2	0	0	0	5	1	2	0	0	0
1	3	3	0	0	0	2	5	3	0	0	0	3	7	3	0	0	0	5	1	3	0	0	0
1	4	1	9	13	15	2	6	1	0	0	0	3	8	1	0	0	0	5	2	1	51	70	76
1	4	2	5	15	17	2	6	2	0	0	0	3	8	2	0	0	0	5	2	2	41	71	86
1	4	3	4	17	20	2	6	3	0	0	0	3	8	3	0	0	0	5	2	3	23	72	96
1	5	1	0	0	0	2	7	1	9	14	17	4	1	1	226	276	283	5	3	1	0	0	0
1	5	2	0	0	0	2	7	2	8	14	27	4	1	2	180	277	293	5	3	2	0	0	0
1	5	3	0	0	0	2	7	3	8	16	37	4	1	3	150	277	316	5	3	3	0	0	0
1	6	1	45	50	60	2	8	1	0	0	0	4	2	1	103	173	203	5	4	1	0	0	0
1	6	2	40	51	70	2	8	2	0	0	0	4	2	2	80	174	223	5	4	2	0	0	0
1	6	3	32	52	80	2	8	3	0	0	0	4	2	3	50	174	233	5	4	3	0	0	0
1	7	1	0	0	0	3	1	1	0	0	0	4	3	1	80	236	266	5	5	1	0	0	0
1	7	2	0	0	0	3	1	2	0	0	0	4	3	2	54	231	282	5	5	2	0	0	0
1	7	3	0	0	0	3	1	3	0	0	0	4	3	3	38	231	298	5	5	3	0	0	0
1	8	1	0	0	0	3	2	1	55	105	155	4	4	1	0	0	0	5	6	1	0	0	0
1	8	2	0	0	0	3	2	2	40	101	125	4	4	2	0	0	0	5	6	2	0	0	0
1	8	3	0	0	0	3	2	3	20	100	215	4	4	3	0	0	0	5	6	3	0	0	0
2	1	1	0	0	0	3	3	1	0	0	50	4	5	1	0	0	0	5	7	1	0	0	0
2	1	2	0	0	0	3	3	2	0	0	71	4	5	2	0	0	0	5	7	2	0	0	0
2	1	3	0	0	0	3	3	3	0	0	83	4	5	3	0	0	0	5	7	3	0	0	0
2	2	1	199	399	499	3	4	1	126	141	150	4	6	1	0	0	0	5	8	1	0	0	0
2	2	2	150	398	519	3	4	2	100	142	161	4	6	2	0	0	0	5	8	2	0	0	0
2	2	3	120	397	549	3	4	3	76	144	182	4	6	3	0	0	0	5	8	3	0	0	0

objective value $J_m(x)$ to degree-of-satisfaction for $\mathcal{J}_m$ (Zadeh, 1965). It is noted that the design performance of the fuzzy method completely depends on the membership function. Different membership functions will have different outcomes. For practical consideration, a reasonable unprejudiced procedure is expected for providing reasonable limiting values for the objective. Without loss of generality, the authors first adopt the linear membership function since it has been proven in providing qualified solutions for many applications (Liu and Sahinidis, 1997).

$$\mu_{\mathcal{J}_m}(x) = \begin{cases} 1; & \text{for} \quad J_m(x) \geq J_m^1 \\ \dfrac{J_m(x) - J_m^0}{J_m^1 - J_m^0} & \text{for} \quad J_m^0 \leq J_m(x) \leq J_m^1 \quad \forall m \in \mathcal{M} \\ 0; & \text{for} \quad J_m^0 \geq J_m(x) \end{cases} \tag{28}$$

Here, x denotes the argument vector. The effective range of the membership function $[J_m^0, J_m^1]$, can be determined dispassionately as follows. For those objectives, $J_m, m \in \mathcal{M}$, one can use the most optimistic expectation as the upper limit, $\overline{J_m^1} = J_m(x_m^*)$, where x_m^* is the optimal solution of the single objective maximizing problem, $\max_{x \in \Omega} J_m(x)$, and choose the most pessimistic expectation, $\underline{J_m^0}$, as the lower limiting value (Zimmermann, 1978; Sakawa, 1993), where

$$\underline{J_m^0} = \min\{J_m(x_i^*), i \in \mathcal{M}\}, \quad \forall m \in \mathcal{M} \tag{29}$$

One can, thus, impersonally determine the effective range of membership functions with the restriction of $\underline{J_m^0} \leq J_m^0 < J_m^1 \leq \overline{J_m^1}$. The original multi-objective optimization problem is now equivalent to looking for a suitable decision vector that can provide the maximal degree-of-satisfaction for the aggregated fuzzy objectives, $\mathcal{J}_1(x) \cap \ldots \cap \mathcal{J}_m(x)$. When simultaneously considering all fuzzy objectives, the final fuzzy decision, $\mathcal{FD}(x)$, can be interpreted as the fuzzy intersection between all fuzzy objectives.

$$\mathcal{FD}(x) = \mathcal{J}_1(x) \cap \ldots \cap \mathcal{J}_M(x) \tag{30}$$

The final overall satisfactory level, $\mu_{\mathcal{FD}}(x)$, can be determined by aggregating the degree-of-satisfaction for all

Table 2
Fixed transport costs of an illustrative example

FTC_{pw}^k, FTC_{wd}^k

k	p	w	d	\$	k	p	w	d	\$	k	p	w	d	\$	k	p	w	d	\$
1	1	1		100	1		1	2	700	1		2	4	550	1		3	6	1250
2	1	1		200	2		1	2	1400	2		2	4	1100	2		3	6	2500
3	1	1		300	3		1	2	2100	3		2	4	1650	3		3	6	3750
4	1	1		400	4		1	2	2800	4		2	4	2200	4		3	6	5000
1	1	2		700	1		1	3	700	1		2	5	1300	1		3	7	800
2	1	2		1400	2		1	3	1400	2		2	5	2600	2		3	7	1600
3	1	2		2100	3		1	3	2100	3		2	5	3900	3		3	7	2400
4	1	2		2800	4		1	3	2800	4		2	5	5200	4		3	7	3200
1	1	3		700	1		1	4	200	1		2	6	800	1		4	1	250
2	1	3		1400	2		1	4	400	2		2	6	1600	2		4	1	500
3	1	3		2100	3		1	4	600	3		2	6	2400	3		4	1	750
4	1	3		2800	4		1	4	800	4		2	6	3200	4		4	1	1000
1	1	4		300	1		1	5	600	1		2	7	800	1		4	2	600
2	1	4		600	2		1	5	1200	2		2	7	1600	2		4	2	1200
3	1	4		900	3		1	5	1800	3		2	7	2400	3		4	2	1800
4	1	4		1200	4		1	5	2400	4		2	7	3200	4		4	2	2400
1	2	1		800	1		1	6	300	1		3	1	900	1		4	3	500
2	2	1		1600	2		1	6	600	2		3	1	1800	2		4	3	1000
3	2	1		2400	3		1	6	900	3		3	1	2700	3		4	3	1500
4	2	1		3200	4		1	6	1200	4		3	1	3600	4		4	3	2000
1	2	2		100	1		1	7	150	1		3	2	950	1		4	4	100
2	2	2		200	2		1	7	300	2		3	2	1900	2		4	4	200
3	2	2		300	3		1	7	450	3		3	2	2850	3		4	4	300
4	2	2		400	4		1	7	600	4		3	2	3800	4		4	4	400
1	2	3		900	1		2	1	700	1		3	3	100	1		4	5	800
2	2	3		1800	2		2	1	1400	2		3	3	200	2		4	5	1600
3	2	3		2700	3		2	1	2100	3		3	3	300	3		4	5	2400
4	2	3		3600	4		2	1	2800	4		3	3	400	4		4	5	3200
1	2	4		600	1		2	2	100	1		3	4	600	1		4	6	550
2	2	4		1200	2		2	2	200	2		3	4	1200	2		4	6	1100
3	2	4		1800	3		2	2	300	3		3	4	1800	3		4	6	1650
4	2	4		2400	4		2	2	400	4		3	4	2400	4		4	6	2200
1		1	1	100	1		2	3	750	1		3	5	1200	1		4	7	300
2		1	1	200	2		2	3	1500	2		3	5	2400	2		4	7	600
3		1	1	300	3		2	3	2250	3		3	5	3600	3		4	7	900
4		1	1	400	4		2	3	3000	4		3	5	4800	4		4	7	1200

objectives, $\mu_{\mathcal{J}_m}(x)$, via specific t-norm, T.

$$\mu_{\mathcal{FD}}(x) = T(\mu_{\mathcal{J}_1}(x), \ldots, \mu_{\mathcal{J}_m}(x)) \tag{31}$$

The best solution x^* with the maximal firing level, $\mu_{\mathcal{FD}}(x^*)$, should be selected.

$$\mu_{\mathcal{FD}}(x^*) = \max_{x \in \Omega} \mu_{\mathcal{FD}}(x) \tag{32}$$

Several t-norms can be chosen for T, wherein the three most popular selections are shown below (Klir and Yuan, 1995).

$$T(\mu_{\mathcal{J}_1}(x), \ldots, \mu_{\mathcal{J}_M}(x)) \tag{33}$$

$$= \begin{cases} \min(\mu_{\mathcal{J}_1}(x), \ldots, \mu_{J_M}(x)) & T = \text{minimum} \\ \mu_{\mathcal{J}_1}(x) \times \ldots \times \mu_{J_M}(x) & T = \text{product} \\ \dfrac{1}{M}(\mu_{\mathcal{J}_1}(x) + \ldots + \mu_{J_M}(x)) & T = \text{"average"} \end{cases} \tag{34}$$

Therein the minimum t-norm concerns the worst scenario only, but it may result in a non-compensatory solution (Li and Lee, 1993). On the other hand, both the product t-norm and the average operator can provide a compensatory result; however, they may cause an unbalanced solution between all fuzzy terms due to their inherent character. In order to avoid numerical difficulties caused by a highly nonlinear property of product t-norm, Chen and Lee (2004a,b) adopt the average operator, although it is not a t-norm. The successful application experience of combining the advantages of minimum and average operators for calculating the satisfactory level of fuzzy decisions in a short-term supply chain problem (Chen and Lee, 2004a,b) is thus applied to solving multi-objective mid-term planning problems.

Step 1. Determining the membership function for each fuzzy objective based on the expected upper/lower bounds for the objective value, as shown in Eq. (28), where $\underline{J_m^0} \le J_m^0 \le J_m^1 \le \overline{J_m^1}, \forall m \in \mathcal{M}$.

Step 2. (Phase I) Considering all fuzzy objectives and using the minimum operator, maximizing the degree of satisfaction for the worst situation.

$$\max_{x \in \Omega} \mu_{\mathcal{FD}} = \max_{x \in \Omega} \min(\mu_{\mathcal{J}_1}, \mu_{\mathcal{J}_2}, \ldots, \mu_{\mathcal{J}_M}) \equiv \mu_{\min} \tag{35}$$

Step 3. (Phase II) Applying the average operator, maximizing the overall satisfactory level with guaranteed minimal fulfillment for all fuzzy objectives.

$$\max_{x \in \Omega^+} \mu_{\mathcal{FD}}(x) = \max_{x \in \Omega^+} \frac{1}{M}(\mu_{\mathcal{J}_1}(x) + \ldots + \mu_{\mathcal{J}_M}(x)) \tag{36}$$

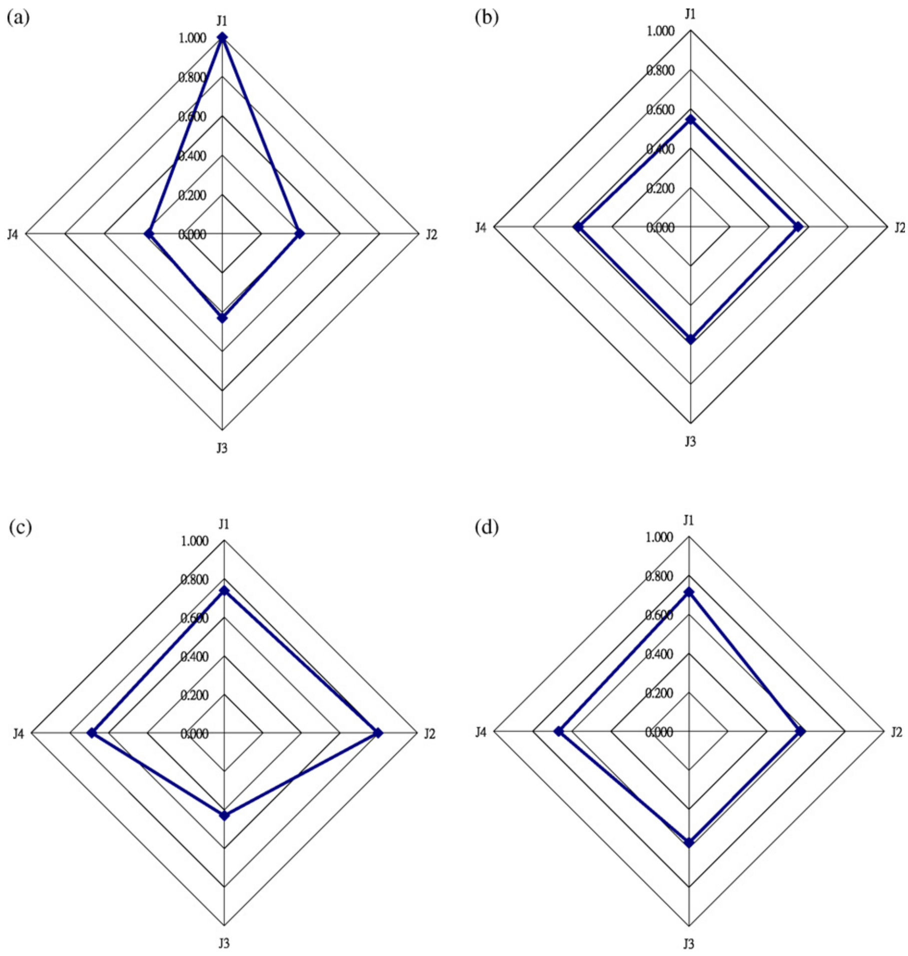

Fig. 3. Radar plots using single objective (a), or minimum (b) and average operator (c) (single-phase optimization) and proposed two-phase optimization method (d).

where

$$\Omega^{+} = \Omega \cap \{\mu_{\mathcal{J}_m} \geq \mu_{\min} | \forall m\} \quad (37)$$

It is noted that, in the proposed two-phase optimization approach, parameters in these objective functions are not usually independent and they cannot be completely separated. Though a global solution is not guaranteed, the proposed strategy can provide a definite procedure to reach a single compensatory solution among all participants of the supply chain.

5. Numerical example

Consider a typical supply chain consisting of 2 plants, 4 candidate warehouses, 7 candidate distribution centers, 8 customer zones, and 5 products. Two plants manufacture 5 different types of products and are located in two different locations. Each plant produces several products using a number of shared production resources. There are 4 candidate locations of warehouses and 7 candidate locations of distribution centers. Each candidate warehouse and distribution center has its own establishing cost, capacity, and local incentive. The whole planning horizon is 3 periods. The product demand scenarios are shown in Table 1 and the assigned probabilities are $\mathrm{PPD}_{s=1} = 0.4$, $\mathrm{PPD}_{s=2} = 0.3$ and $\mathrm{PPD}_{s=3} = 0.3$, for the case study. Also, in order to simplify the problem, the fluctuating rate for cost parameters is neglected. Other indices and sets are $[\mathcal{K}] = 4$ and $[\mathcal{N}] = 6$.

Values of all fixed transport cost parameters are listed in Tables 2 and 3, unit transportation cost and transportation time are shown in Table 4, resource coefficients are listed in Table 5, and other parameters in Table 6.

The problem includes 11,478 equations, 7,622 continuous variables, and 3,415 binary variables. To solve this mixed-integer linear programming problem for the supply chain model, the Generalized Algebraic Modeling System (GAMS, Brooke *et al.*, 2003), a well-known high-level modeling system for mathematical programming problems, is used as the solution environment. The MILP solver used is CPLEX 7.5.

One can first apply the single objective programming method to minimize the total cost, the most common method in the traditional supply chain planning. Then, the result is projected, caused by single objective programming, to the membership functions, such as shown in Fig. 3 and Table 8. Obviously, the satisfaction levels are extremely unbalanced, since the objective function is only taking the total cost into consideration. So, one should consider all objectives simultaneously, and use

Table 3
Fixed transport costs of an illustrative example

FTC^k_{dc}																											
k	*d*	*c*	$	*k*	*d*	*c*	$	*k*	*d*	*c*	$	*k*	*d*	*c*	$	*k*	*d*	*c*	$	*k*	*d*	*c*	$	*k*	*d*	*c*	$
1	1	1	100	1	2	1	700	1	3	1	700	1	4	1	300	1	5	1	600	1	6	1	300	1	7	1	200
2	1	1	200	2	2	1	1400	2	3	1	1400	2	4	1	600	2	5	1	1200	2	6	1	600	2	7	1	400
3	1	1	300	3	2	1	2100	3	3	1	2100	3	4	1	900	3	5	1	1800	3	6	1	900	3	7	1	600
4	1	1	400	4	2	1	2800	4	3	1	2800	4	4	1	1200	4	5	1	2400	4	6	1	1200	4	7	1	800
1	1	2	700	1	2	2	100	1	3	2	800	1	4	2	600	1	5	2	1300	1	6	2	1000	1	7	2	900
2	1	2	1400	2	2	2	200	2	3	2	1600	2	4	2	1200	2	5	2	2600	2	6	2	2000	2	7	2	1800
3	1	2	2100	3	2	2	300	3	3	2	2400	3	4	2	1800	3	5	2	3900	3	6	2	3000	3	7	2	2700
4	1	2	2800	4	2	2	400	4	3	2	3200	4	4	2	2400	4	5	2	5200	4	6	2	4000	4	7	2	3600
1	1	3	500	1	2	3	700	1	3	3	200	1	4	3	600	1	5	3	1000	1	6	3	900	1	7	3	700
2	1	3	1000	2	2	3	1400	2	3	3	400	2	4	3	1200	2	5	3	2000	2	6	3	1800	2	7	3	1400
3	1	3	1500	3	2	3	2100	3	3	3	600	3	4	3	1800	3	5	3	3000	3	6	3	2700	3	7	3	2100
4	1	3	2000	4	2	3	2800	4	3	3	800	4	4	3	2400	4	5	3	4000	4	6	3	3600	4	7	3	2800
1	1	4	100	1	2	4	700	1	3	4	500	1	4	4	200	1	5	4	700	1	6	4	400	1	7	4	300
2	1	4	200	2	2	4	1400	2	3	4	1000	2	4	4	400	2	5	4	1400	2	6	4	800	2	7	4	600
3	1	4	300	3	2	4	2100	3	3	4	1500	3	4	4	600	3	5	4	2100	3	6	4	1200	3	7	4	900
4	1	4	400	4	2	4	2800	4	3	4	2000	4	4	4	800	4	5	4	2800	4	6	4	1600	4	7	4	1200
1	1	5	700	1	2	5	1200	1	3	5	1000	1	4	5	800	1	5	5	100	1	6	5	100	1	7	5	600
2	1	5	1400	2	2	5	2400	2	3	5	2000	2	4	5	1600	2	5	5	200	2	6	5	200	2	7	5	1200
3	1	5	2100	3	2	5	3600	3	3	5	3000	3	4	5	2400	3	5	5	300	3	6	5	300	3	7	5	1800
4	1	5	2800	4	2	5	4800	4	3	5	4000	4	4	5	3200	4	5	5	400	4	6	5	400	4	7	5	2400
1	1	6	300	1	2	6	800	1	3	6	1000	1	4	6	600	1	5	6	700	1	6	6	100	1	7	6	500
2	1	6	600	2	2	6	1600	2	3	6	2000	2	4	6	1200	2	5	6	1400	2	6	6	200	2	7	6	1000
3	1	6	900	3	2	6	2400	3	3	6	3000	3	4	6	1800	3	5	6	2100	3	6	6	300	3	7	6	1500
4	1	6	1200	4	2	6	3200	4	3	6	4000	4	4	6	2400	4	5	6	2800	4	6	6	400	4	7	6	2000
1	1	7	200	1	2	7	800	1	3	7	600	1	4	7	300	1	5	7	500	1	6	7	500	1	7	7	100
2	1	7	400	2	2	7	1600	2	3	7	1200	2	4	7	600	2	5	7	1000	2	6	7	1000	2	7	7	200
3	1	7	600	3	2	7	2400	3	3	7	1800	3	4	7	900	3	5	7	1500	3	6	7	1500	3	7	7	300
4	1	7	800	4	2	7	3200	4	3	7	2400	4	4	7	1200	4	5	7	2000	4	6	7	2000	4	7	7	400
1	1	8	1100	1	2	8	1100	1	3	8	400	1	4	8	1000	1	5	8	1200	1	6	8	1600	1	7	8	1200
2	1	8	2200	2	2	8	2200	2	3	8	800	2	4	8	2000	2	5	8	2400	2	6	8	3200	2	7	8	2400
3	1	8	3300	3	2	8	3300	3	3	8	1200	3	4	8	3000	3	5	8	3600	3	6	8	4800	3	7	8	3600
4	1	8	4400	4	2	8	4400	4	3	8	1600	4	4	8	4000	4	5	8	4800	4	6	8	6400	4	7	8	4800

Table 4
Unit transportation costs and transportation times of an illustrative example

$\mathrm{UTC}^k_{pw}, \mathrm{UTC}^k_{wd}, \mathrm{UTC}^k_{dc}(\$)$ and $\mathrm{TT}_{pw}, \mathrm{TT}_{wd}, \mathrm{TT}_{dc}(\mathrm{h})$																	
p	*w*	*d*	$	h	*w*	*d*	*c*	$	h	*d*	*c*	$	h	*d*	*c*	$	h
1	1		5	40	3	1		45	30	2	1	32.5	50	5	1	30	40
1	2		35	70	3	2		47.5	20	2	2	42.5	60	5	2	65	80
1	3		35	30	3	3		5	60	2	3	30	70	5	3	50	70
1	4		15	40	3	4		30	30	2	4	35	80	5	4	35	60
2	1		40	10	3	5		60	10	2	5	60	40	5	5	42.5	10
2	2		5	60	3	6		62.5	30	2	6	40	50	5	6	35	30
2	3		45	20	3	7		40	30	2	7	40	50	5	7	25	40
2	4		30	30	4	1		12.5	40	2	8	55	10	5	8	60	20
	1	1	5	20	4	2		30	50	3	1	35	20	6	1	35	30
	1	2	35	10	4	3		25	50	3	2	40	40	6	2	50	30
	1	3	35	30	4	4		5	70	3	3	30	60	6	3	45	70
	1	4	10	20	4	5		40	20	3	4	25	40	6	4	20	30
	1	5	30	40	4	6		27.5	10	3	5	50	60	6	5	30	10
	1	6	15	50	4	7		15	30	3	6	50	60	6	6	30	60
	1	7	7.5	80		1	1	50	40	3	7	30	20	6	7	25	20
	2	1	35	40		1	2	35	30	3	8	52.5	60	6	8	52.5	20
	2	2	5	70		1	3	25	10	4	1	37.5	30	7	1	35	20
	2	3	37.5	40		1	4	37.5	30	4	2	30	20	7	2	45	50
	2	4	27.5	50		1	5	35	70	4	3	30	10	7	3	35	20
	2	5	65	30		1	6	30	50	4	4	37.5	50	7	4	25	30
	2	6	40	80		1	7	25	70	4	5	40	70	7	5	30	70
	2	7	40	20		1	8	50	20	4	6	30	40	7	6	25	10
										4	7	25	50	7	7	40	60
										4	8	50	60	7	8	60	40

multi-objective programming methods to elevate satisfaction level of individual objectives.

According to the problem description, mathematical formulation, and parameter design mentioned previously, one can solve the multi-objective mixed-integer linear program by using the fuzzy procedure discussed in Section 4.

Step 1. Select suitable ranges for defining membership functions. Relevant lower/upper limits, $\underline{J}^0_{\mathrm{m}}$ and $\overline{J}^1_{\mathrm{m}}$, and selected effective ranges, $[J^0_{\mathrm{m}}, J^1_{\mathrm{m}}]$, for membership functions are shown in Table 7. As mentioned previously, one can subjectively select values for J^0_{m} and J^1_{m} for each objective if meaningful lower/upper bounds can be expected. One can, thus, directly use $[\underline{J}^0_{\mathrm{m}}, \overline{J}^1_{\mathrm{m}}]$ as the effective range for defining fuzzy objectives such as local incentives. Using $\underline{J}^1_{\mathrm{m}}$ as the upper bound is suggested, and the second lower value as the lower bound such as the total cost and transport time. Apply the second largest value as the upper bound and the second lower value as the lower bound for robustness measurement.

Step 2. (Phase I) To maximize the degree of satisfaction for the worst objective by using the minimum operator. The result is $\mu_{\min} = 0.55$.

Table 5
Resource coefficients of an illustrative example

Resource coefficient ρ^i_{pnts}																			
i	*p*	*n*		*i*	*p*	*n*		*i*	*p*	*n*		*i*	*p*	*n*		*i*	*p*	*n*	
1	1	1	0.0	2	1	1	0.4	3	1	1	0.3	4	1	1	0.2	5	1	1	0.3
1	1	2	0.0	2	1	2	0.4	3	1	2	0.4	4	1	2	0.5	5	1	2	0.2
1	1	3	0.2	2	1	3	0.0	3	1	3	0.4	4	1	3	0.1	5	1	3	0.0
1	1	4	0.3	2	1	4	0.0	3	1	4	0.0	4	1	4	0.1	5	1	4	0.4
1	1	5	0.4	2	1	5	0.2	3	1	5	0.0	4	1	5	0.0	5	1	5	0.3
1	1	6	0.5	2	1	6	0.3	3	1	6	0.2	4	1	6	0.0	5	1	6	0.0
1	2	1	0.6	2	2	1	0.4	3	2	1	0.3	4	2	1	0.2	5	2	1	0.0
1	2	2	0.0	2	2	2	0.1	3	2	2	0.1	4	2	2	0.7	5	2	2	0.2
1	2	3	0.0	2	2	3	0.7	3	2	3	0.1	4	2	3	0.0	5	2	3	0.1
1	2	4	0.2	2	2	4	0.0	3	2	4	0.3	4	2	4	0.0	5	2	4	0.3
1	2	5	0.1	2	2	5	0.0	3	2	5	0.0	4	2	5	0.0	5	2	5	0.1
1	2	6	0.4	2	2	6	0.2	3	2	6	0.0	4	2	6	0.2	5	2	6	0.4

Table 6
Other parameters of an illustrative example

Unit handling cost, UHC^i_*								Max prod. PQ^{max}_{ips}			Unit estab. cost, UEC_*			Loc. Inc. LI_*		
I	*w*	*d*	$	*i*	*w*	*d*	$	*i*	*p*		*w*	*d*	$	*w*	*d*	
1	1		15	2		1	3	1	1	150	1		190000	1	1	30
1	2		15	2		2	3	2	1	600	2		80000	2		60
1	3		2	2		3	15	3	1	400	3		100000	3		70
1	4		2	2		4	15	4	1	1000	4		120000	4		40
2	1		15	2		5	8	5	1	100		1	80000		1	70
2	2		15	2		6	8	1	2	200		2	70000		2	30
2	3		2	2		7	8	2	2	700		3	80000		3	90
2	4		2	3		1	3	3	2	400		4	110000		4	50
3	1		15	3		2	3	4	2	700		5	110000		5	80
3	2		15	3		3	15	5	2	150		6	70000		6	40
3	3		2	3		4	15					7	110000		7	60
3	4		2	3		5	8	Max cap. SQ^{max}_*			Unit prod. cost, UPC^i_p			Resource R_{pnts}		
4	1		15	3		6	8	*w*	*d*							
4	2		15	3		7	8	1		2700	*i*	*p*	$	*p*	*n*	
4	3		2	4		1	3	2		1500	1	1	140	1	1	600
4	4		2	4		2	3	3		1800	2	1	140	11	2	800
5	1		15	4		3	15	4		2000	3	1	100	11	3	300
5	2		15	4		4	15		1	1200	4	1	60	11	4	150
5	3		5	4		5	8		2	1000	5	1	40	11	5	200
5	4		2	4		6	8		3	1000	1	2	130	11	6	340
1		1	3	4		7	8		4	1500	2	2	130	22	1	310
1		2	3	5		1	3		5	1400	3	2	100	22	2	300
1		3	15	5		2	3		6	1000	4	2	60	22	3	200
1		4	15	5		3	15		7	1400	5	2	40	22	4	150
1		5	8	5		4	15	*k*		TCL^k_*	Q^{max}_{*s}			22	5	350
1		6	8	5		5	8	1		500	2000			22	6	200
1		7	8	5		6	8	2		1000	Q^{min}_{*s}			α^i_w		
SQ^{min}_w				SQ^{min}_d				3		1500	1			1		
1				1				4		2000	Note : $* \in \{pw, wd, dc\}$			β^1_d		
														1		

Step 3. (Phase II) Re-optimize the problem with new constraints of guaranteed minimum satisfaction for all fuzzy objectives. The results will be shown and discussed in the following.

The radar plots for the total cost, robustness measure, local incentives, and transport time are shown in Fig. 3, where the numerical value of each objective indicates its satisfaction level, and the resulting objective and membership function values are listed in Table 8.

As shown in Fig. 3(a) and Table 8, when one make a decision by considering a single objective such as minimizing the total cost (J_1), the satisfaction levels for other conflict objectives would be quite low (0.39, 0.43, 0.39) though the satisfaction level concerning total cost can be as high as 1. From the results obtained by directly selecting ‘‘minimum’’ as the *t*-norm (see Fig. 3(b)), one can get a more balanced level of satisfaction among all objectives where the degrees of satisfaction are all around 0.55. It means that the overall satisfaction levels are not concerning, though one can maximize the minimum satisfaction level of the worst objective. By using ‘‘average operator’’ to guarantee a unique solution, however, the results are unbalanced with a lower degree of satisfaction for local incentives (0.43, as shown in Fig. 3(c). On the other hand, the high robustness measure is given very high emphasis. Obviously this is not desirable for obtaining a compromise solution. Overcoming the drawbacks of the single-phase method, the proposed two-phase method can incorporate advantages of these two *t*-norms. The minimum operator is used in phase I to find the maximal satisfaction for the worst situation (0.55), and the average operator is applied in phase II to maximize the overall satisfaction with guaranteed minimal

Table 7
Parameters for defining membership functions for objectives

m	J_m	J^0_m	J^0_m	J^1_m	$\overline{J^1_m}$
1	–TCO	−1,913, 513	−1,584, 529	−1,219,554	−1,219,554
2	RI	−189, 103	−163, 203	−124, 319	0
3	TLI	60	60	130	130
4	–OTT	−1270	−800	−290	−290

Table 8
Resulting objective and membership function values

Operator		TCO	RI	TLI	OTT
Single objective (J_1)	J_m	1, 219, 554	−151, 557	90	610
	$\mu_{\mathcal{J}m}$	1.00	0.39	0.43	0.37
Minimum	J_m	1, 330, 728	−144, 736	100	510
	$\mu_{\mathcal{J}m}$	0.55	0.55	0.57	0.57
Average	J_m	1, 315, 214	−133, 465	90	450
	$\mu_{\mathcal{J}m}$	0.74	0.80	0.43	0.69
Two-phase	J_m	1, 323, 772	−143,685	100	460
	$\mu_{\mathcal{J}m}$	0.71	0.57	0.57	0.67

fulfillment for all fuzzy objectives. The average satisfaction level is increased from 0.56 (by applying the minimum operator) to 0.63, as shown in Fig. 3(d).

The optimal network structures are shown in Figs. 4 and 5, where triangle means plant, square means warehouse, hexagon means distribution center, and circle means customer zone. The values in the network structures are the total transport quantities through the whole planning horizon. Fig. 4(a) is the result of considering total cost, where other objectives are not taken into account. The transport time is quite large in this case, as shown

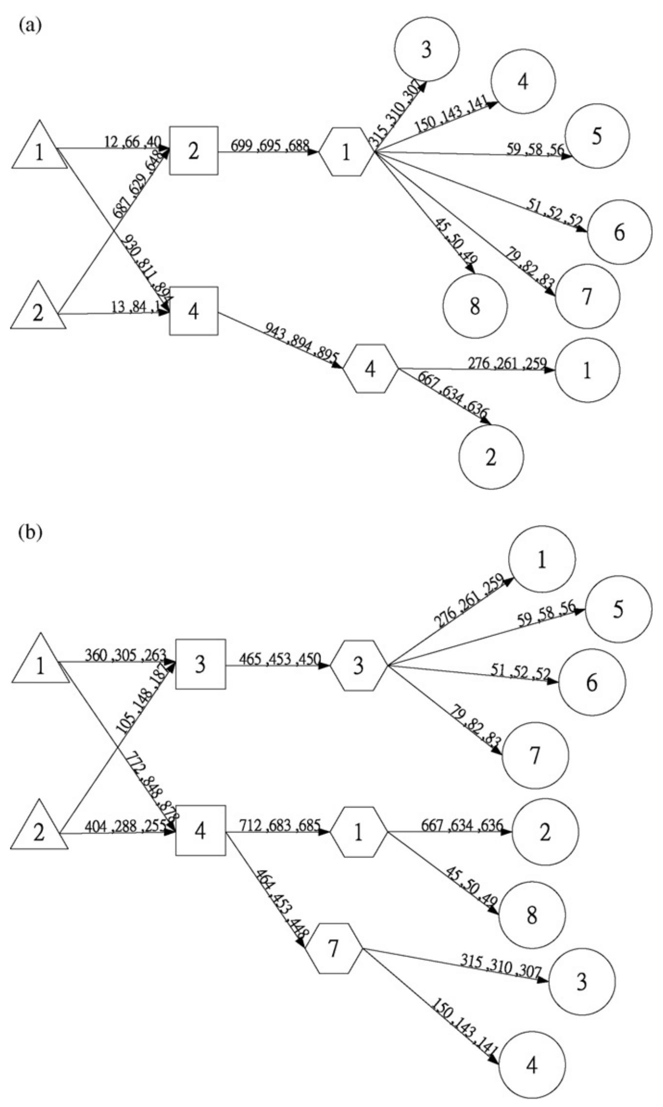

Fig. 4. Optimal network structure using single objective (a) and minimum operator (b).

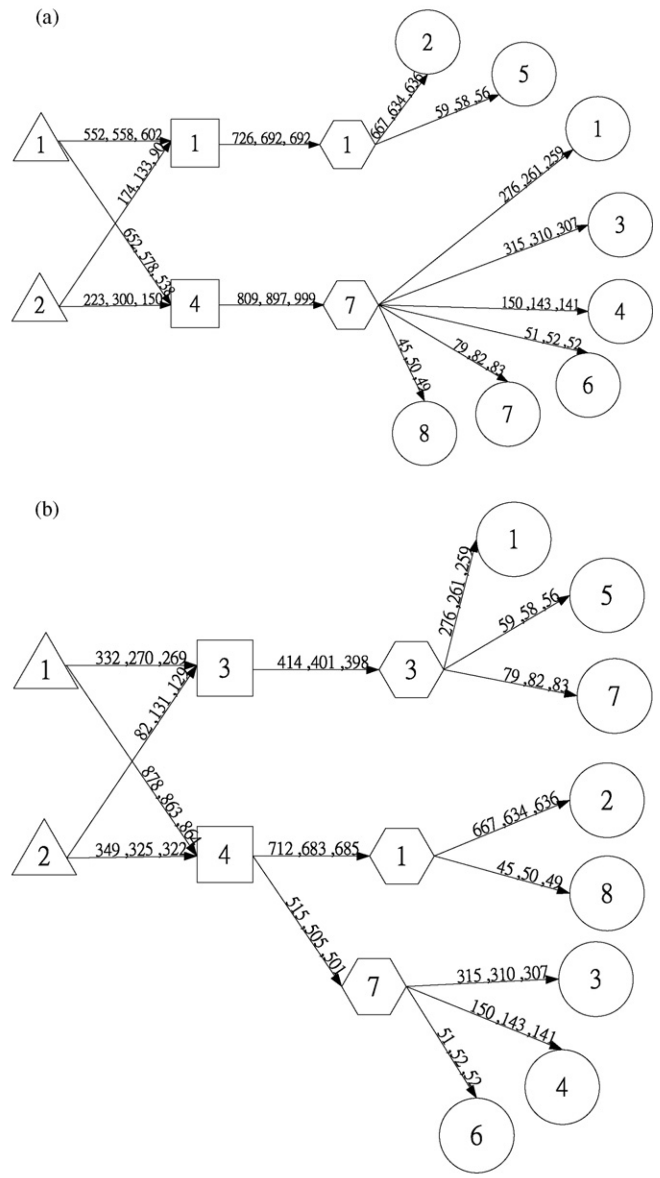

Fig. 5. Optimal network structure using average operator (a) and two-phase optimization method (b).

in Table 8. The result of ''average operator'', Fig. 5(a), also does not care about the worst objective, where the local incentive is quite low. The results of ''minimum operator'' and the two-phase method are quite similar, where customer zone 6 is serviced by distribution center 3 and 7, respectively. The supply chain network designed by the two-phase method can provide superior overall performance.

6. Conclusion

This paper investigates the simultaneous optimization of multiple conflict objectives problem in a typical supply chain network with market demand uncertainties. The demand uncertainty is modeled as discrete scenarios with given probabilities for different expected outcomes. In addition to the total cost, the project considers the influence of local incentives and transport time to location decision. The problem is formulated as a mixed-integer linear programming (MILP) model to achieve minimum total cost, maximum robustness to demand uncertainties, maximum local incentives, and minimum total transport time. To find the degree of satisfaction of the multiple objectives, the linear increasing membership function is used; the final decision is acquired by fuzzy aggregation of the fuzzy goals, and the best compromised solution can be derived by maximizing the overall degree of satisfaction for the decision. The implementation of the proposed fuzzy decision-making method, as one can see in the case study, demonstrates that the method can provide a compensatory solution for the multiple conflict objectives problem in a supply chain network with demand uncertainties.

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供應鏈網路中最佳倉儲與配銷中心選址多目標模糊決策

陳誠亮　袁子偉　李文誠
國立台灣大學化學工程學系

摘　要

本研究旨在探討供應鏈網路中的最佳倉儲與配銷中心選址策略問題。考慮一個多產品、多階層、多規劃週期的生產配送網路，其包含了固定地點的數個生產多產品之工廠與數個顧客區，和數個未決定建立地點之候選倉儲與候選配銷中心。需決定之決策變數有各工廠的生產計畫及所需原物料，倉儲和配銷中心的數量、處理量與建立地點，供應鏈網路架構之配送計畫。此外，在建構本模式時，使用現實工業界中常見的經濟批量運送方式。並且使用數個不同的需求量方案來處理顧客對產品需求的不確定性。在傳統供應鏈規劃中處理這種類型的問題時，常以系統總成本或收益作為目標函數來進行單目標規劃，而本研究同時考慮整體成本最小化、韌性指標最大化、地點選擇分數最大化與運輸時間最小化等四個績效指標。為了能同時滿足四個目標，本模式將形成一個多目標混合整數非線性規劃問題。再利用模糊多目標規劃法簡單易懂與求解方便的優點來對所建構模式求解，並使用兩階段求解方法，在階段一找出各目標可接受的最低滿意度，階段二中則基於這個各目標可接受的最低滿意度上，尋求各目標隸屬度函數平均的最大。藉由兩階段法，使得多目標規劃中的各目標函數能在彼此互斥的關係下，相互妥協。最後，我們提出一個模擬範例，應用多目標規劃法來求解，並發現使用兩階段法，可使多目標問題有相當滿意的解。

出席國際學術會議心得報告

供應鏈網路整合性多目標模糊決策規劃研究

計畫編號： NSC 95－2214－E－002－001－
計畫主持人：陳誠亮
執行單位： 國立臺灣大學化學工程學系

本計劃提供主持人出席國際學術會議，研究期間主要的出席會議包括美國化工年會、電腦輔助程序操作會議等，共計三次，開會地點包括美國邁阿密、舊金山、辛辛那堤。本人共計發表與供應鍊網路相關的論文三篇，其中，一篇有關供應鏈網路整合性多目標模糊決策規劃研究的論文更獲得電腦輔助程序操作會議的最佳論文(最佳論文共計三篇)，備感榮性。

電腦輔助程序操作會議每五年舉行一次，規模雖然不大，但是大會通常會安排二十位左右的知名學者或工業界人士依規劃的主題作專題演講，除了檢討近來主要研究成果，也相當強調未來研判方向，同時，每場演講之後也很注重出席人員間的討論，因此，整體呈現的內容相當紮實，與會者多能有深刻的體會和學習，本人首次參加後的感受是很震撼，更加深了作一流研究的期許了。

美國化工年會的規模相當龐大，每年出席人數都有五千人之多，內容包羅萬象，如果不謹慎篩選規劃，很容易在會場迷路，錯失有興趣的演講。本人通常會將想聽的場次依時間記錄起來，再依序跑攤，也就是說通常並不會出席固定的議題，而是滿場換教室，可以學習到新點子，也可以觀摩不同國家人士的演講技巧，雖辛苦但是也很有趣，記得一位博士班學生跟我開會幾天後，表示以後不敢當教授，因為太辛苦了！

出席國際學術會議，一方面可以發表自己最新研究成果，另一方面也是最好的學習機會，相信自己在國際間的表現，沒有辜負國科會的要求與期望。