TABLE DES MATIÈRES

Page

LISTE DES TABLEAUX

LISTE DES FIGURES

CHAPITRE 1

INTRODUCTION ET OBJECTIFS DE RECHERCHE

1.1 Introduction

Pour répondre à une demande variable en produits et en quantité, les entreprises manufacturières continuent d'adapter leur système de production et d'améliorer leur performance en assurant des coûts de production minimum. Actuellement, ces entreprises ne peuvent développer un avantage concurrentiel sans qu'elles soient intégrées dans des réseaux logistiques performants. Pour cette raison, la maîtrise de la logistique, plus généralement de la chaîne d'approvisionnement est incontournable dans tous les secteurs industriels. Plus spécifiquement, ce sont les contextes de la mondialisation, les nouvelles technologies de l'information, les coûts globaux et la vision du service au client qui ont été les précurseurs du développement des réseaux de chaînes d'approvisionnement et l'émergence de nouvelles problématiques pour les décideurs. L'objectif principal à atteindre pour une chaîne d'approvisionnement est d'optimiser les coûts et surtout d'améliorer le niveau de service à la clientèle. Pour répondre à ces problématiques, les travaux de recherche dans ce domaine s'intéressent de plus en plus à la conception, l'analyse ou le contrôle de la chaîne d'approvisionnement en considérant deux ou plusieurs maillons de la chaîne toute entière.

Par ailleurs, les systèmes manufacturiers, une composante des chaînes d'approvisionnement, ont connu le développement du concept des systèmes manufacturiers cellulaires (SMC), une application de la technologie de groupe (TG). Cette dernière est une des approches qui a connu une large utilisation dans les industries manufacturières. Il s'agit d'y identifier des groupes fixes de machines associées à des familles de produits. Ces systèmes ont prouvé être un moyen efficace pour améliorer la productivité dans les systèmes de production par lots. Les décisions majeures liées à la production par une configuration cellulaire sont : le choix des machines et de ressources de manutention, l'implantation des équipements et la planification de la production. Cependant, la formation des cellules de production constitue la principale étape pour la conception d'un système manufacturier cellulaire. Les principaux avantages de ces systèmes concernent les économies dans les coûts de transport et de manutention, la réduction des stocks en cours et une meilleure coordination de la gestion de production. Par ailleurs, la conception des systèmes cellulaires suppose que la demande est affectée à un seul site de production lequel sera configuré selon une base de cellules manufacturières. Maintenant, les SMC doivent opérer dans un contexte logistique où les frontières de l'entreprise sont poussées. Par conséquent, cette entreprise va évoluer dans un réseau où la performance doit être analysée globalement (intégrant les partenaires amont et/ou aval) plutôt qu'individuellement. Dans ce contexte, les systèmes de production, qu ils associent au minimum un acteur en amont ou en aval (fournisseurs de matières premières ou centres d'assemblage) deviennent acteurs d'un réseau de chaîne d'approvisionnement.

L'impact des configurations de type cellulaire sur les chaînes d'approvisionnement peut être vu sous deux angles :

- Quelles sont les différences entre un SMC sur un seul site et un SMC établi sur plusieurs sites, vus dans un contexte de chaîne d'approvisionnement?
- Quel est l'effet d'intégrer les systèmes manufacturiers cellulaires (SMC) multi-sites sur les mesures de performances de la chaîne d'approvisionnement?

Les principaux avantages réalisés grâce à un système de production cellulaire sont les économies de coûts de transport et de manutention, la réduction des en cours, la réduction des cycles de production et une meilleure coordination de la gestion de production. Ces avantages suggèrent la question de l'impact de la conception cellulaire des sites de production sur l'efficacité de la conception des chaînes d'approvisionnement auxquelles appartiennent ces sites de production.

Dans la littérature sur la conception des réseaux de chaînes d'approvisionnement (Arntzen et al., 1995; Cakravista et al., 2002; Simchi-Levi et al., 2000; Srinivasan, 1999), les modèles mathématiques incorporent des données agrégées pour représenter les centres de production à savoir :

- les produits sont considérés individuellement ou en familles,
- des coûts fixe et variable sont chargés à chaque alternative de centre de production,
- les capacités des centres de production sont globales et liées au flux annuel maximal des produits.

Les sites de production alternatifs sont différenciés par des coûts de production et de livraison des produits. Le compromis est établi entre les coûts de production, les coûts d'approvisionnement et les coûts de livraison au client. Dans un contexte de SMC à établir sur plusieurs sites, les compromis de coûts sont étendus aux coûts du système cellulaire multi site. Par conséquent, une nouvelle problématique émerge : examiner l'optimisation de la structure à l'intérieur d'un échelon de la chaîne d'approvisionnement simultanément avec la conception de toute la chaîne d'approvisionnement. Particulièrement, deux questions sous jacentes sont engendrées:

1) La dimension de la configuration des centres de production sur la base d'un système cellulaire et son impact sur la conception de chaînes d'approvisionnement par rapport au processus d'approvisionnement en matières première et par rapport à l'affectation des demandes clients aux sites de production
2) Lors de l'établissement d'un contexte de chaîne d'approvisionnement en décloisonnant plusieurs centres de production qui collaborent pour réaliser l'ensemble des produits, y aurait-il un avantage lié à un compromis entre l'investissement en équipement et les coûts des flux entre les centres de production?

Dans cette thèse, nous nous proposons d'amener une contribution répondant à cette problématique. Nous nous proposons d'intégrer les décisions stratégiques de conception d'une chaîne d'approvisionnement et les décisions impliquant la conception de SMC multi-site. Pour les décideurs, l'intégration des ces décisions procure un avantage concurrentiel en améliorant la flexibilité de production et de livraison, surtout dans un contexte de grande compétition. Différents modèles mathématiques sont développés, appuyés par des approches de résolution établissant des contextes de chaînes d'approvisionnement différents et démontrant des gains potentiels en intégrant la conception de type SMC aux décisions de conception de la chaîne d'approvisionnement.

1.2 Généralités

Dans cette section, nou nous proposons de rappeler quelques définitions et notions relatives aux systèmes manufacturiers cellulaires et aux chaînes d'approvisionnement.

1.2.1 Systèmes manufacturiers cellulaires

La configuration des systèmes manufacturiers implique la détermination de la meilleure combinaison de facteurs pour optimiser un ou plusieurs critères de performance de telle manière que les temps de séjour des ordres, les stocks d'en cours, le taux de demande non satisfaite et le coût de production soient minimisés. Dans cette sous section, nous présentons les différents types de système de production et particulièrement les avantages d'un SMC.

1.2.1.1 Définitions

Il existe deux principaux types de systèmes de production:

- Systèmes de production en ligne « Flow shop » : systèmes de production organisés en ligne où les produits sont peu variés et suivent la même séquence (figures 1.1). Ils sont conçus pour assurer une grande productivité.
- Systèmes de production par lot « Job shop » : systèmes de productions organisés en sections homogènes où chaque section concerne une seule technologie et où les cheminements des ordres de production sont multiples (figure 1.2). Ils sont caractérisés par la flexibilité, en termes de variété et volume de produits.

Les SMC (figure 1.3) sont des systèmes hybrides qui associent les avantages d'une production de type « job shop » (flexibilité de produire une grande variété de produits) et d'une production de type « flow shop » (efficacité du flux de production). Ce type de système de production est le résultat de l'application du principe de la technologie de groupe qui consiste à regrouper les pièces en familles tout en exploitant leurs similtudes; ces familles sont destinées à être fabriquées dans les mêmes cellules de machines.

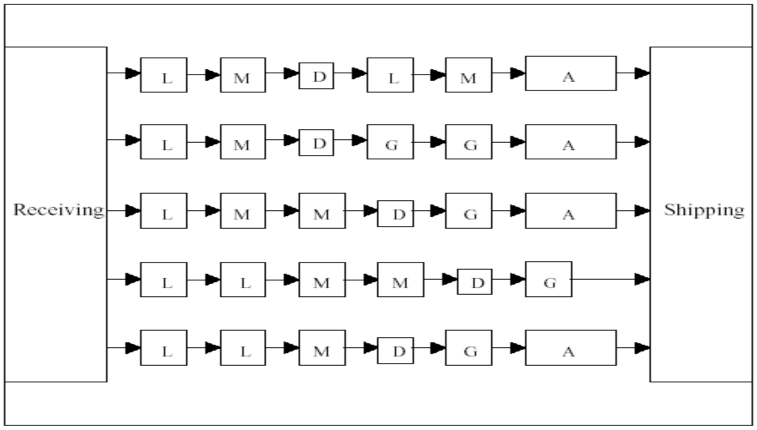


Figure 1-1 Système manufacturier en ligne « flow line »
Tirée de Black (1991)

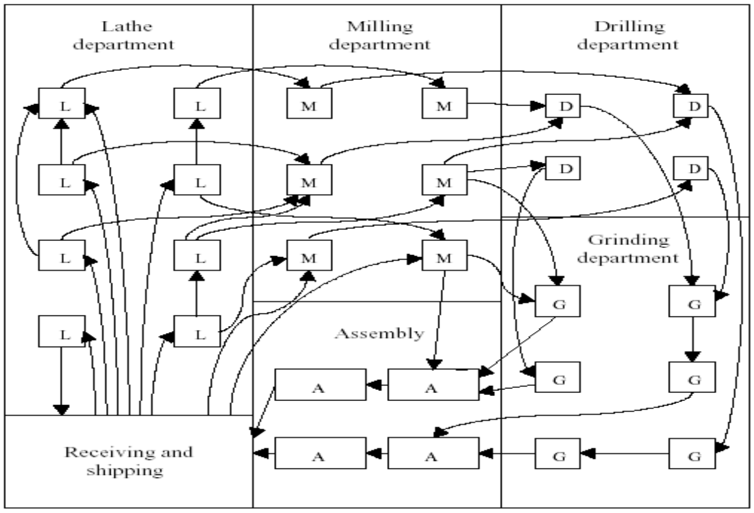


Figure 1-2 Système manufacturier d'ateliers à cheminements multiples « Job shop »
Tirée de Black (1991)

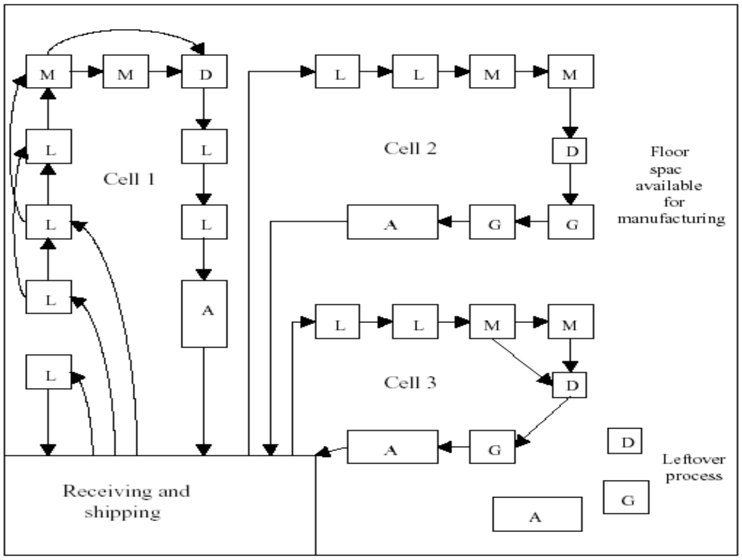


Figure 1-3 Système manufacturier cellulaire
Tirée de Black (1991)

1.2.1.2 Avantages des systèmes manufacturiers cellulaires

Les systèmes manufacturiers cellulaires (SMC) sont des systèmes de production où les produits sont regroupés en familles et les machines en îlots, les produits d'une même famille sont idéalement réalisés dans une seule cellule. Ce sont des systèmes qui allient la flexibilité des systèmes « job shop » à la grande productivité des systèmes « flow shop ». Comparés aux systèmes de production traditionnels, les avantages engendrés par un système manufacturier cellulaire sont nombreux. Ces derniers ont été établis grâce à des études de simulation, des études analytiques ou des implémentations réelles en industrie. Les avantages les plus cités sont résumés ci-dessous (Singh, 1996; Wemmerlov, 1997):

1. Réduction des temps de réglage,
2. Réduction des tailles de lot de production,
3. Réduction des en cours et des stocks de produits finis,
4. Réduction du temps et des coûts de manutention,
5. Réduction des temps de transfert,
6. Amélioration de la qualité du produit, et

7. Meilleur contrôle des opérations.

1.2.2 Chaînes d'approvisionnement

Dans cette section, nous présentons les principales notions de base relatives à la chaîne d'approvisionnement directement liées à notre problématique de recherche.

1.2.2.1 Définitions

La littérature offre des définitions différentes sur les chaînes d'approvisionnement. La définition la plus utilisée (Arntzen et al., 1995; Simchi-Levi et al.,2000; Cakravista et al., 2002) est : C'est un système comprenant des fournisseurs, des producteurs, des distributeurs, des détaillants et des clients avec des flux matières des fournisseurs vers les clients et des flux d'informations en amont et en aval à travers les échelons. Une chaîne d'approvisionnement représente un système intégré qui synchronise un ensemble de processus opérationnels inter reliés pour assurer l'acquisition de matières premières et de pièces, transformer ces dernières en produits finis, leur ajouter de la valeur, distribuer ces produits aux détaillants ou aux consommateurs, faciliter l'échange d'information entre les entités des différents processus (fournisseurs, producteurs, distributeurs et détaillants).

Comme l'illustre la figure 1.4, une chaîne d'approvisionnement est aussi un réseau de sites de production et d'options de distributions qui fonctionne pour s'approvisionner en matières premières, transformer ces matières premières en produits intermédiaires ou en produits finis et distribuer ces produits aux clients. La complexité d'une chaîne d'approvisionnement peut varier d'une industrie à une autre. À cet égard, des liens entre les sites de production et entre les centres de distribution peuvent aussi exister, comme le précise la revue de travaux de Melo et al., 2009.

Par ailleurs, les définitions sur les chaînes d'approvisionnement convergent vers le principe d'intégration des mesures de performance à travers les différentes entités de la chaîne et de tous les processus opérationnels, et non plus en considérant la perspective d'une seule entité.

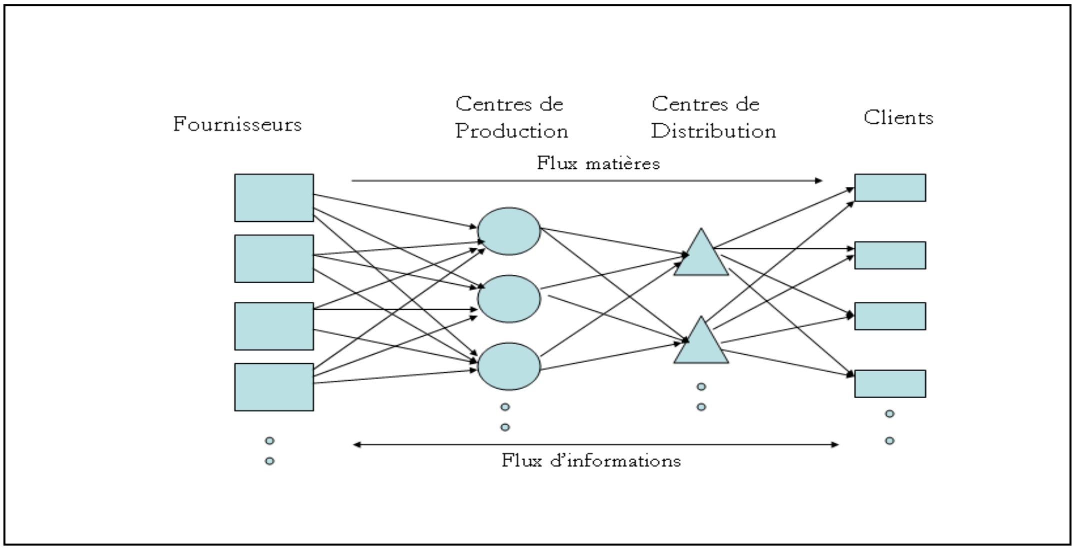


Figure 1-4 Structure de la chaîne d'approvisionnement

1.2.2.2 Niveaux d'analyse de la chaîne d'approvisionnement

Croom et al. (2000) propose une classification à plusieurs dimensions. Concernant le type de problème examiné dans les travaux de recherche sur les chaînes d'approvisionnement, il utilise le facteur *niveau d'analyse*. Trois niveaux sont identifiés :

1. Niveau dyadique : qui considère seulement la relation entre deux échelons de la chaîne telle que la relation entre un fournisseur et un producteur ou un producteur et un distributeur/détaillant;
2. Niveau chaîne : qui englobe un ensemble de relations dyadiques comprenant un fournisseur, le fournisseur du fournisseur, un client et le client du client, ce qui traduit le sens originel du mot « chaîne »;
3. Niveau réseau : qui concerne le réseau d'opérations (en amont et en aval).

1.2.2.3 Les variables de décision d'une chaîne d'approvisionnement

Les variables de décision sont un moyen pour contrôler la performance de la chaîne d'approvisionnement. Selon Beamon (1998); Min et Zhou (2002) et Martel (2001), les objectifs ou les mesures de performances d'une chaîne d'approvisionnement sont généralement exprimés comme des fonctions d'une ou plusieurs variables de décision. Parmi ces variables, nous citons :

- Localisation : ce type de variable permet de déterminer où doivent être localisés les usines de production, les centres de distribution, les points de consolidation et les fournisseurs.
- Affectation : ce type de variable détermine quels usines de production, centres de distribution et points de consolidation vont servir quels clients.
- Structure du réseau : ce type de variable détermine quelle combinaison d'usines de production, de centres de distribution, de points de consolidation et de fournisseurs va être utilisée, pour identifier la centralisation ou la décentralisation du réseau de distribution.
- Nombre des différents types d'entités : cette variable détermine combien d'usines de production, de centres de distribution et de points de consolidation sont nécessaires pour satisfaire les besoins des clients.
- Nombre d'échelons : c'est une variable qui détermine combien d'échelons sont inclus dans la chaîne d'approvisionnement.
- Volume : cette variable inclut le volume d'achat, de production, de livraison à chaque nœud (fournisseur, producteur, distributeur) de la chaîne d'approvisionnement.
- Niveau de stock : cette variable détermine le niveau optimal de chaque matière première, pièce, produit intermédiaire et produit fini à garder en stock à chaque échelon de la chaîne d'approvisionnement.

1.2.2.4 Mesures des performances des chaînes d'approvisionnement

Beamon (2001) distingue deux types de mesures de performance : les mesures de performance qualitatives et les mesures de performance quantitatives. Les premières ne représentent pas une valeur numérique, bien que certains de ses aspects puissent être quantifiés. Par exemple, la satisfaction du client est identifiée dans ses différentes phases avant, pendant et après la réalisation d'une transaction du client.

De plus, la flexibilité de la chaîne d'approvisionnement est un facteur important qui mesure la réponse aux fluctuations de la demande. La considération des éléments de risque auxquels la chaîne d'approvisionnement est soumise contribue à mieux les gérer. Par ailleurs, la performance des fournisseurs évalue la qualité et l'efficacité des fournisseurs en termes de délai et de qualité. Pour analyser une chaîne d'approvisionnement, Beamon (2001) a utilisé trois types de mesures de performance : ressource, output et flexibilité.

1. La mesure des ressources permet de quantifier le niveau de ressources du système qui sont utilisées pour atteindre les objectifs du système tels que le niveau moyen périodique des stocks et le coût moyen de transport des matières.
2. Les mesure d'outputs correspondent à des objectifs stratégiques pour la satisfaction des clients comme le pourcentage d'unités de matières de commandes non satisfaites pendant une période ou aussi l'efficience des débits matières.
3. Les mesures de flexibilité.

Par ailleurs, la minimisation de coûts totaux est un des objectifs traditionnellemnet utilisé pour la configuration d'une chaîne d'approvisionnement, pour répondre aux demandes clients. Ces coûts totaux incluent les coûts de transport, les coûts de production et de distribution, les coûts des installations, les coûts des niveaux d'inventaires, les coûts des matières premières et etc.

Le tableau 1.1 présente quelques mesures de performance de chaîne d'approvisionnement utilisées dans la littérature. Ces différentes mesures ont été choisies pour modéliser la fonction économique à optimiser pour des modèles mathématiques pour la conception de chaînes d'approvisionnement.

Tableau 1-1 Quelques mesures de performance de la chaîne d'approvisionnement

Mesures de performance	Références
Profit	Cohen et Lee (1989) Viswanadham et al. (2003)
Coûts	Arntzen et al. (1995) Ghodsypour et O'brien (2001) Goetschalkx et al. (2002) Yan et al. (2002) Dasci et Verter (2001) Sabri et Beamon (2000) Talluri et Baker (2002)
Flexibilité	Voudouris (1996) Sabri et Beamon (2000)
Niveau de service	Sabri et Beamon (2000)
Niveau d'insatisfaction des clients	Li et O'brien (2001)

1.3 Problématique

Dans la littérature, les modèles pour la conception de réseaux de chaînes d'approvisionnement ont été étendus pour intégrer plus de variables et plus d'hypothèses qui permettent de mieux représenter la réalité industrielle en termes d'alternatives de production, d'approvisionnement ou de livraison au client. La prise en compte de ces variables qui vont affecter la structure de la chaîne d'approvisionnement est un défi majeur aussi bien pour les décideurs que pour les chercheurs. Cependant, le choix explicite de la configuration des systèmes manufacturiers a été limité à des buts de validation (Talluri et Baker, 2002), ou a été développé sur une combinaison de paramètres à choisir (Martel, 2001). Des décisions de choix de technologie ou de configuration pour la conception de réseaux manufacturiers ont été introduites dans les travaux de Paquet et al. (2004) et Paquet et al. (2008). En effet, l'optimisation de la chaîne est une étape dissociée et non simultanée à l'étape d'optimisation à l'intérieur des nœuds du réseau. Par ailleurs, les modèles de conception de systèmes manufacturiers cellulaires supposent que la conception est effectuée sur un seul site de production, ignorant les enjeux logistiques amont et aval. La flexibilité en termes de processus opératoires est certes considérée dans quelques travaux de recherche mais reste confinée à l'environnement d'un seul système de production, sans la vision globale d'un environnement d'un ensemble d'autres systèmes de production potentiels, pouvant interagir pour satisfaire la demande client. De plus, si nous associons les fournisseurs à ces sites de production, ce contexte ci établira ce que nous identifions par la chaîne d'approvisionnement. La distinction entre les deux environnements sus indiqués est illustré par les figures 1.5 et 1.6.

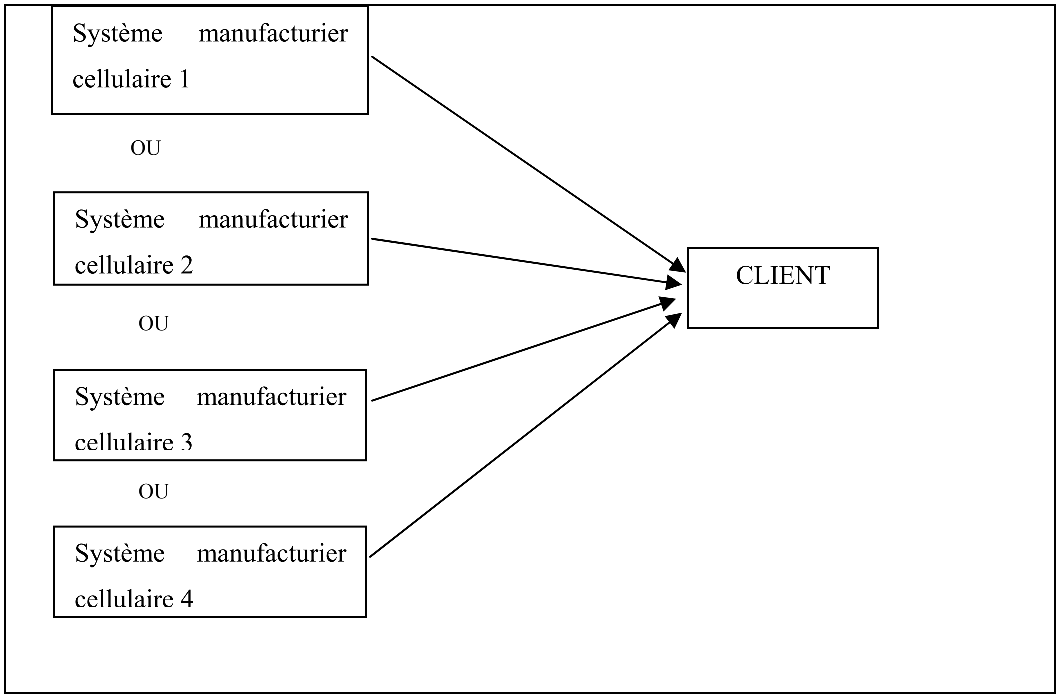


Figure 1-5 Schéma classique du lien entre un client et plusieurs systèmes manufacturiers cellulaires mutuellement exclusifs

Notre objectif alors est de proposer une méthodologie qui intègre la conception de chaînes d'approvisionnement dans le contexte de la conception de systèmes manufacturiers cellulaires. Les systèmes cellulaires génèrent plusieurs avantages liés à l'application de la technologie de groupe. Cependant, ignorer les enjeux logistiques avec lesquels interagit le système de production ne garantit pas la performance de la chaîne d'approvisionnement. Par ailleurs, la littérature sur la conception de chaîne d'approvisionnement traite peu de la configuration interne du nœud sites potentiels de production. Ceci justifie le besoin de développer une méthodologie pour la conception de systèmes cellulaires de production multi-site dans un contexte de chaînes d'approvisionnement.

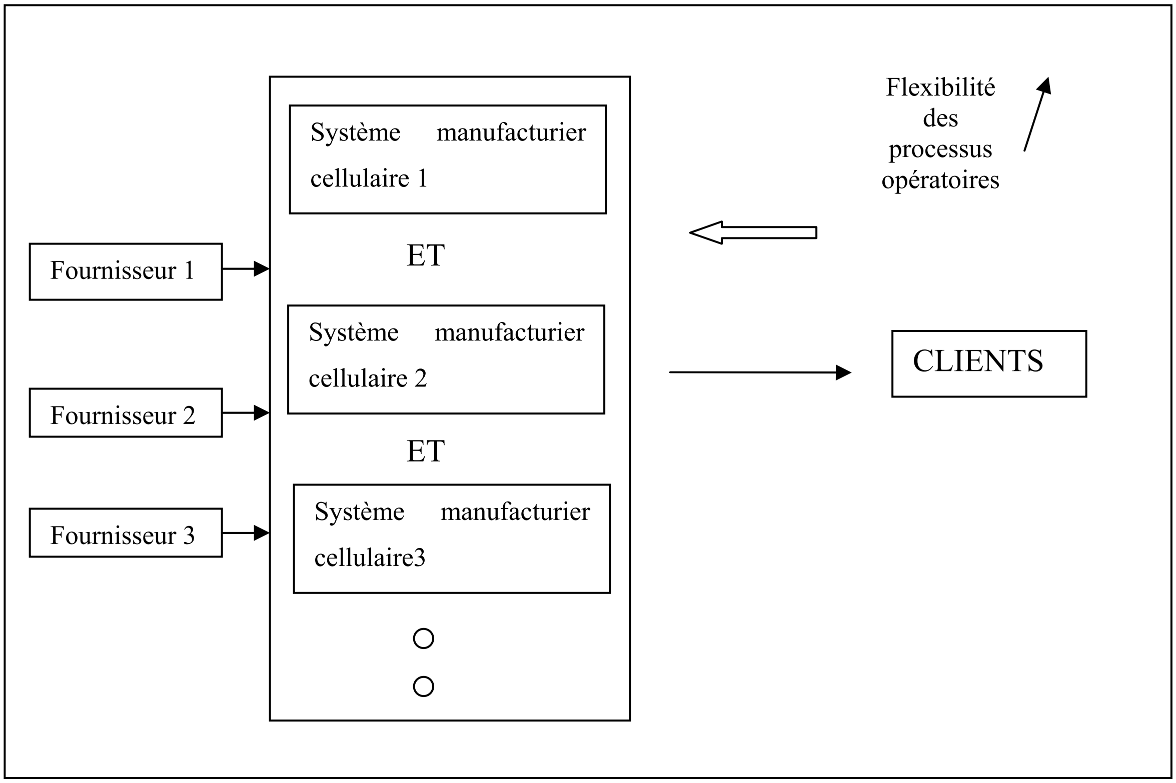


Figure 1-6 Nouveau schéma du lien entre un client et l'union de plusieurs systèmes manufacturiers cellulaires

D'une manière explicite, dans la conception de chaînes d'approvisionnement à trois échelons fournisseur-producteur- client, l'hypothèse concernant le maillon producteur est définie par l'existence de sites de production alternatifs variant selon le coût d'exploitation du site, des coûts de transport des flux convergeant au site de production (provenant de fournisseurs) et des coûts de transport divergeant du site de production (vers le nœud client). Cette hypothèse n'assurera pas que la chaîne d'approvisionnement choisie réalise un compromis entre les coûts de production et les coûts logistiques amont et aval.

Si nous considérons plusieurs sites de production, la question de concevoir un système manufacturier cellulaire tout en tenant compte de l'existence de fournisseurs potentiels en amont et de zones clients à desservir survient. Approcher ce problème s'identifie aussi par la génération de chaînes d'approvisionnement associant des coûts issus de la configuration cellulaire, des coûts engendrés par les nœuds fournisseurs et les coûts de livraison aux clients.

En généralisant la question précédente, nous aurons à approcher la problématique de la conception de chaînes d'approvisionnement de plusieurs produits, où des sites de production alternatifs sont considérés. Précisément, le contexte considéré est un ensemble de systèmes manufacturiers caractérisés pouvant réaliser un ensemble de produits. Notre proposition est de décloisonner ces systèmes initialement indépendants et de les configurer en réseau manufacturier cellulaire multi-site. Nous ne sommes plus dans une situation où la conception d'une chaîne d'approvisionnement repose sur le choix de sites de production mais plutôt sur la formation puis l'affectation de cellules de production pouvant exister sur un seul ou sur plusieurs sites. Ce schéma de conception devra être compétitif, contribuant efficacement au coût total de conception de la chaîne d'approvisionnement. Conceptuellement, la formation de cellules de production localisées sur plus d'un site de production pourra tolérer ou interdire des flux inter sites. Ainsi, la conception de chaînes d'approvisionnement va se réaliser simultanément avec la conception d'un réseau manufacturier cellulaire qui tient compte des coûts logistiques amont (approvisionnement des fournisseurs) et des coûts logistiques aval vers les clients. Nous ne considérons plus chaque site de production séparément mais un ensemble de sites de production (existants ou potentiels) où sera manufacturée l'union des produits objet des demandes client.

Cette nouvelle vision de conception multi-site permet de capitaliser les avantages de l'îlotage des moyens de production de plusieurs environnements de production, appuyée principalement par la flexibilité en termes de processus vu la considération de plusieurs sites de production. Elle pourra aussi offrir des alternatives multiples pour répondre aux demandes de produits, en pemettant des flux entre les sites de production. En effet, la conception de systèmes manufacturiers cellulaires ne restant plus confinée aux données d'un seul système de production inclut les impératifs d'opérer dans une chaîne d'approvisionnement. Elle va s'orienter pour réaliser un compromis entre les coûts logistiques et les coûts de conception de systèmes de production cellulaires. L'industrie aéronautique s'apparente le mieux aux hypothèses de la problématique où le réseau de chaînes d'approvisionnement consiste en plusieurs manufacturiers travaillant initialement séparément mais pouvant travailler conjointement, ces manufacturiers sont associés à des fournisseurs pour répondre à la demande de clients.

1.4 Revue de littérature

L'objectif est de présenter une revue des travaux sur (1) les modèles de conception de chaîne d'approvisionnement et (2) les modèles de conception de systèmes cellulaires. Pour les systèmes manufacturiers cellulaires, nous montrons l'évolution des modèles de conception. Enfin, en particulier, nous mettons en relief quelques recherches que nous classons comme travaux associant le concept technologie de groupe et un contexte de chaîne d'approvisionnement. Notons que chaque chapitre comporte une revue de littérature liée à un aspect spécifique de la problématique**.**

1.4.1 Modèles de conception de chaînes d'approvisionnement

Croom et al. (2000) ont élaboré une topologie générale du domaine des chaînes d'approvisionnement qui peut servir comme outil de classification de la recherche dans ce domaine et comme moyen procurant une architecture pour permettre l'identification des contenus clés du sujet. Deux critères de classification sont utilisés :

1. Contenu : Ce critère considère individuellement ou simultanément le niveau d'analyse de la chaîne (dimension de la chaîne) et l'élément d'échange (flux matières, flux d'informations, flux financiers, flux de connaissances entre échelons);
2. Méthodologie : Ce critère a pour but de distinguer les travaux sous deux points de vue théorique ou empirique et prescriptif ou descriptif.

Beamon (1998) a développé une taxonomie qui distingue trois types de modèles mathématiques : déterministe, stochastique, de simulation. Min et Zhou (2002) ont suppléé cette classification par une nouvelle catégorie à savoir les modèles conduits par les outils de technologie de l'information (modèles TI). Cette classification est illustrée par la figure 1.7.

Selçuk Erenguç et al. (1999) ont réalisé une revue de travaux sur les modèles de conception des systèmes intégrés de production et de distribution, ils proposent une taxonomie d'analyse de la chaîne d'approvisionnement d'un point de vue opérationnel en identifiant les décisions à prendre à chaque stade (production, distribution).

Par ailleurs, la taxonomie la plus développée est celle qui catégorise les modèles mathématiques de chaînes d'approvisionnement :

- Modèle déterministe et modèle stochastique,
- Modèle avec un seul objectif ou modèle avec des objectifs multiples.

Comme les modèles de chaîne d'approvisionnement exigent de réaliser un compromis entre plus d'un processus opérationnel, alors *tout modèle qui tente d'intégrer différents échelons est considéré comme modèle de chaîne d'approvisionnement*. Dans la littérature, les modèles de conception des chaînes d'approvisionnement sont classés en trois catégories à savoir :

- les modèles d'une chaîne d'approvisionnement à deux échelons;

- les modèles d'une chaîne d'approvisionnement multi échelons nommés aussi système intégré de production et de distribution;
- les modèles d'une chaîne d'approvisionnement globale.

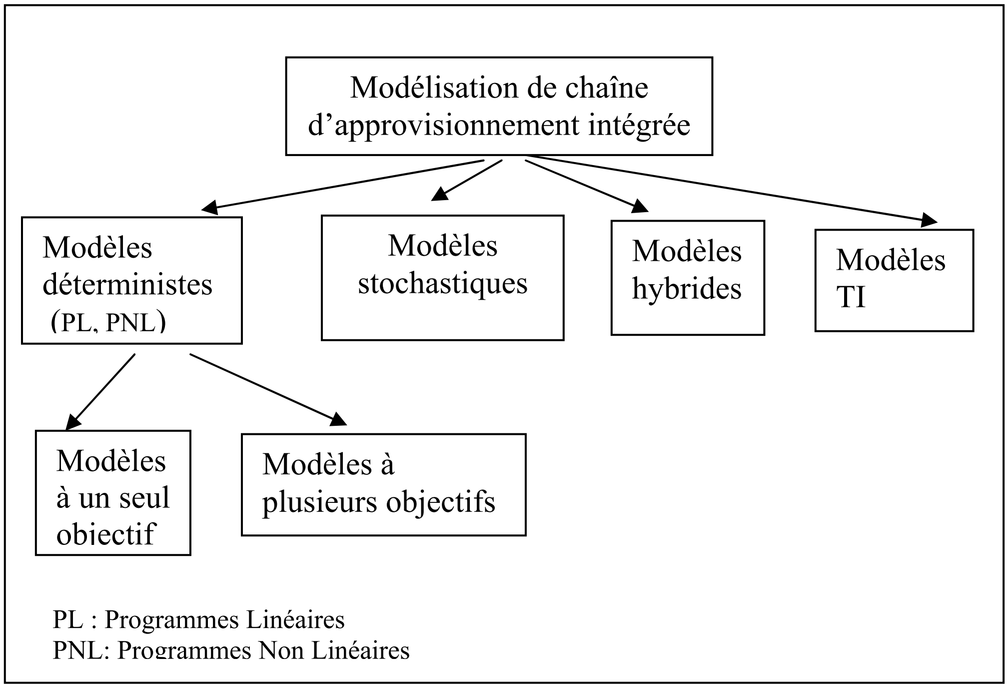


Figure 1-7 Types de modélisation de chaîne d'approvisionnement intégrée

1.4.1.1 Modèles déterministes

Selon Min et Zhou (2002), le premier modèle de chaîne d'approvisionnement remonte à 1979 suite aux recherches menées sur un système qui intègre trois parties : fournisseurs, entreposage et planification de la demande client.

Par ailleurs, Arntzen et al. (1995) ont développé un modèle de chaîne d'approvisionnement global pour une entreprise oeuvrant dans l'industrie electronique (Digital Equipment Corporation). Le modèle a pour but d'évaluer plusieurs configurations de chaîne d'approvisionnement en minimisant une fonction pondérée incluant : (1) les jours d'activité et (2) les coûts associés à la production, aux stocks, à la manutention et au transport.

Cohen et Lee (1989) ont développé un programme mathématique non linéaire en nombres entiers déterministe, basé sur les techniques de la quantité économique pour développer une politique globale de déploiement des ressources. La fonction objectif du modèle consiste à maximiser les profits après impôt. Le modèle est soumis aux contraintes de ressources et de production et aux limites de la demande. Les résultats du modèle sont : (1) l'affectation des produits et sous ensembles aux sites de production, les fournisseurs aux centres de distribution et les centres de distributions aux clients; (2) Les quantités des composants, des sous ensembles et des produits finis à livrer entre les différents composant de la chaîne. Ce modèle a été étendu par Cohen et Moon (1991) pour étudier les effets de plusieurs paramètres sur le coût de la chaîne d'approvisionnement. Ils y considèrent en particulier le problème de détermination des usines ou des centres de distribution à ouvrir, les effets des économies d'échelle. La fonction objectif est liée au coût fixe et variable de la production et au coût du transport. Les contraintes identifient les limites de capacité, la satisfaction de la demande et les besoins en matières premières. Les auteurs ont principalement conclu que les coûts de transport représentent une partie significative du coût total de la chaîne.

Camm et al. (1997) ont aussi développé un modèle où il s'agit de minimiser le coût total lié aux choix des centres de distributions à ouvrir, l'affectation des clients aux centres de distribution, en respectant un nombre limite de centres de distribution à ouvrir et les contraintes d'affectation.

Martel (2001) présente un modèle mathématique de conception de chaînes d'approvisionnement, s'inspirant en partie du modèle de Verter et Dincer (1992). Le modèle concerne le choix de devis technologiques pour les centres de production ou les entrepôts. Deux niveaux de décision sont à prendre : décider si l'on doit exploiter un centre de production et décider quel devis technologique utiliser. En particulier pour les centres de productions, chaque devis est modélisé par trois éléments (1) un ensemble de technologies, (2) une valeur actuelle nette du centre de production, (3) une capacité annuelle par famille de produits, et (4) un coût variable par produit. Ces éléments sont intégrés soit dans la fonction objectif à minimiser soit dans les contraintes du modèle.

Yan et al. (2002**)** ont proposé un modèle déterministe à plusieurs produits, à plusieurs échelons et à une seule période. Sa particularité est qu'il intègre les nomenclatures des produits dans le processus de conception d'un système de production-distribution. Des contraintes logiques ont servi pour représenter ces nomenclatures ainsi que les liens entre les différentes entités de la chaîne d'approvisionnement (fournisseurs, producteurs, et centres de distribution). Ces relations sont formulées par un modèle de programmation en nombres entiers illustrant le rôle des structures de produits dans la sélection des fournisseurs et dans la conception stratégique de la chaîne d'approvisionnement. Le modèle développé a pour but de choisir des fournisseurs parmi un ensemble de fournisseurs candidats de matières premières (ou composants), de localiser un nombre donné de producteurs et de centres de distribution en respectant des restrictions de capacité des producteurs et des centres de distribution.

Viswanadham et Gaonkar (2003) ont développé un programme linéaire en nombres mixtes où ils intègrent la sélection des partenaires et la planification dans un environnement de réseaux manufacturiers dynamiques. La fonction-objectif concerne la maximisation du profit. Les contraintes vont être du type logistique ou de production. La dynamique de la configuration de la chaîne est étudiée par rapport à différentes localisations d'acheteurs, différents profils de demande et l'utilisation éventuelle de points de consolidation.

La majorité des modèles introduits par les travaux cités dans cette section reposent sur une formulation par les programmes en nombres entiers, cependant, Dasci et Verter (2001) ont proposé une modélisation alternative, à savoir un modèle continu pour la conception d'un système intégré de production et de distribution. Leur modèle utilise des fonctions continues pour représenter les distributions spatiales des coûts et des demandes client. Il permet de connaître les effets des paramètres de la chaîne sur les décisions de conception.

Une approche à objectifs multiples a été proposée par Min et Melachrinoudis (1997) pour configurer les réseaux de chaînes d'approvisionnement à plusieurs échelons. Leur modèle

AHP considère aussi la planification par contingence associée aux configurations de la chaîne d'approvisionnement. Melachrinoudis et Min (2000) ont étendu le modèle précédent en développant un modèle à objectifs multiples sur plusieurs périodes : (1) maximisation du profit sur un horizon temporel, (2) minimisation du temps total d'accès à partir de l'installation de production ou d'entreposage vers les fournisseurs ou vers les clients, (3) maximisation d'une mesure qualitative agrégée de chaque localisation, qui détermine les nouvelles localisations possibles d'un système de production et de distribution.

Ghodsypour et O'brien (2001) ont développé un système de prise de décision pour réduire le nombre de fournisseurs et gérer le partenariat avec les fournisseurs. Ils ont utilisé l'approche AHP associée à un programme linéaire en nombres mixtes, où ils considèrent les contraintes de capacité des fournisseurs et les contraintes de l'acheteur en termes de budget et de qualité. Les mêmes auteurs ont développé un modèle pour la sélection des fournisseurs sous l'hypothèse d'approvisionnement d'un article de plusieurs fournisseurs (*multi sourcing*), qui tient compte de plusieurs critères et de la politique de remises de prix. Ils considèrent les effets des contraintes de budget, de qualité et de capacité des fournisseurs. L'approche AHP est utilisée pour permettre aux décideurs de considérer les facteurs qualitatifs et quantitatifs dans l'activité d'achat.

1.4.1.2 Modèles stochastiques

Comme dans l'environnement des systèmes manufacturiers, les chaînes d'approvisionnement sont aussi soumises à plusieurs sources d'aléas et d'incertitudes tels la demande des clients, les délais (de production et de transport) et les fluctuations de production. C'est pourquoi, la conception des modèles stochastiques de chaînes d'approvisionnement est importante pour tenter d'apporter une représentation réaliste.

Pyke et Cohen (1993) ont développé un modèle de programmation mathématique pour une chaîne d'approvisionnement de trois échelons à plusieurs produits en utilisant des sous modèles stochastiques qui calculent les valeurs de variables aléatoires incluses dans un programme mathématique.

Towill et al. (1992) ont proposé des modèles ou ils étudient la réponse de plusieurs configurations de chaînes selon des demandes aléatoires des produits. Les auteurs utilisent les outils de la théorie des filtres et de la simulation pour spécifier les besoins minimaux en stock de sécurité permettant d'atteindre un niveau de service donné

Tzafestas et Kapsiotis (1994) emploient en premier une approche de programmation mathématique déterministe pour optimiser une chaîne d'approvisionnement, puis utilisent les techniques de simulation pour analyser un exemple numérique de leur modèle. L'optimisation est réalisée en considérant trois scénarios différents (Optimisation au niveau des installations de production, optimisation de la chaîne globale, optimisation décentralisée pour chaque composant de la chaîne), le constat des auteurs est que les différences entre les résultas des scénarios ne sont pas significatives

D'autres auteurs ont tenté d'évaluer l'impact du déséquilibre entre la demande et l'offre dans la chaîne logistique, c'est le cas de Fisher et al. (1997) qui ont développé un programme stochastique minimisant les coûts de surproduction et de sous production pour affronter le problème de déséquilibre entre l'offre et une demande incertaine dans la chaîne.

Srinivasa et Viswanathan (1999) ont utilisé les réseaux de Petri stochastiques pour analyser les réseaux de chaînes d'approvisionnement. Leur modèle permet de calculer le délai moyen pour une chaîne de type fabriquer sur commande.

Azaron et al. (2008) ont développé des modèles stochastiques à plusieurs objectifs où l'incertitude de plusieurs paramètres de la chaîne d'approvisionnement est considérée (demande, approvisionnement, capacitéd'expansion de la production). Les objectifs à minimiser incluent le coût total des investissements, de transport, de pénurie et d'expansion de la capacité, la variance du coût total et le risque financier.

1.4.1.3 Modèles hybrides

Un modèle hybride est un modèle qui associe l'outil de simulation aux modèles analytiques de chaînes d'approvisionnement. Karabakal et al. (2000) ont combiné la simulation aux modèles de programmation mathématique en nombres entiers pour déterminer le nombre et la localisation des centres de distribution et les zones de marché qu'ils couvrent, en évaluant la capacité de la chaîne à livrer un produit choisi par un client sur une fenêtre de temps donnée.

Petrovic et al. (1998) ont développé un modèle de chaînes d'approvisionnement où deux sources d'incertitudes sont considérées : la demande des clients et la livraison de matières première par les fournisseurs. Celles-ci ont été représentées et interprétées par les concepts des ensembles flous. En plus des modèles de chaînes flous, un simulateur de la chaîne d'approvisionnement est développé qui fournit une vue dynamique de la chaîne et estime l'impact des recommandations des modèle flous sur la performance de la chaîne. Petrovic (2001) a étendu cette combinaison de modèles en ajoutant un troisième facteur d'incertitude à savoir les délais de livraison.

Lee et Kim (2002) ont considéré un réseau de chaîne d'approvisionnement à plusieurs échelons, à plusieurs produits et à plusieurs périodes. Pour résoudre le problème de planification, ils proposent une procédure analytique associée à un modèle de simulation. Le modèle analytique considère que les capacités des machines et de distribution sont stochastique et sont réajustées selon les résultats du modèle de simulation incluant les caractéristiques générales de la chaîne de distribution. Comparée aux modèles analytiques seuls, la combinaison de modèles a permis de donner des réponses réalistes.

Cakravista et al. (2002) ont développé un modèle analytique du processus de sélection des fournisseurs pour la conception d'un réseau de chaînes d'approvisionnement, en considérant la contrainte de capacité de chaque fournisseur. L'objectif de la chaîne d'approvisionnement est de minimiser le niveau d'insatisfaction du client sous les critères de prix et de délai de livraison. Le modèle opère à deux niveaux : le niveau opérationnel et le niveau chaîne.

1.4.2 Conception de systèmes manufacturiers cellulaires

La conception de systèmes manufacturiers cellulaires est un processus complexe engageant plusieurs critères et nécessitant plusieurs étapes. La conception de SMC est désignée dans la littérature par la formation de cellules, formation de familles de pièces/cellules de machines, et conception de cellules de production (Singh, 1996).

Connaissant l'ensemble de types de pièces, les processus opératoires, les demandes par type de produit et les ressources machines requises, le processus de conception des SMC comporte les étapes suivantes :

1. Les familles de pièces sont formées selon leurs processus opératoires;
2. Les machines sont regroupées en cellules de production;
3. Les familles de pièces sont affectées aux cellules.

Ces trois étapes ne sont pas nécessairement réalisées dans cet ordre. Les familles de pièces et les cellules de production peuvent être obtenues simultanément. Selon Singh (1996), une grande partie des méthodologies de conception des systèmes manufacturiers cellulaires est classée selon qu'elles soient basées sur la programmation mathématique et la théorie des graphes ou sur les méthodes de regroupement par les coefficients de similitude.

Les revues de littérature de Mansouri et al. (2000) et de Papaioannou et Wilson (2010) apportent une classification des travaux sur la conception des SMC établie par rapport aux paramètres de conception intégrés, aux objectifs à optimiser et aussi selon la variété d'approches utilisées. Ces approches de conception de SMC se déclinent par rapport aux détails du système de production intégrés tels que la demande des produits, la capacité des machines et les processus opératoires alternatifs pour les produits. Certaines approches relèvent des SMC de nature statique telles que les travaux de Ramabhatta et Nagi (1989), Beaulieu et al. (1997) et Malakooti et Yang (2002). Cependant, les applications montrent que leurs inconvénients sont dus à ce caractère statique des produits et des séquences d'opérations, d'où en résultent la réduction de la flexibilité des ateliers et du taux d'utilisation des capacités machine. Pour pallier cela, d'autres hypothèses ont été incluses pour représenter une évolution naturelle des SMC classiques, à savoir les SMC virtuels et les SMC dynamiques. Nous tentons ci-dessous de les définir à travers l'environnement auquel ils s'appliquent.

1.4.2.1 Systèmes manufacturiers cellulaires virtuels

Un système manufacturier cellulaire virtuel est un ensemble de cellules virtuelles. Chaque cellule virtuelle n'est pas identifiée par un regroupement physique de machines, mais par un ensemble de fichiers de données et de processus intégrés dans un système de contrôle (Drolet, 1989; Mak and Wang, 2002). Autrement dit, une cellule virtuelle est un regroupement logique de machines à l'intérieur d'un système de contrôle. Quand un ordre client nécessite un ensemble de machines, un contrôleur de la cellule virtuelle prend en charge le contrôle de ces machines et établit une communication entre elles sachant qu'une machine peut être membre d'un pool de machines disponibles ou membre de cellules virtuelles.

Drolet (1989) a développé les bases pour le contrôle et l'exploitation des organisations cellulaires virtuelles pour atteindre des niveaux de performance en termes de productivité, de temps de séjour des ordres, de stocks d'encours et de flexibilité dans un environnement changeant. Un SMC virtuel va naturellement s'agrandir si la demande croit. Comparé aux implantations d'ateliers par produit ou par processus, l'efficacité d'un SMC virtuel peut même augmenter avec la croissance de la taille du système de production. Une conséquence immédiate à cela est la multiplication des alternatives de processus opératoires comme résultat de l'évolution de la densité de chaque cellule virtuelle. Grâce à cette discontinuité physique et à cet aspect dynamique de la configuration, les effets d'une demande difficile à prédire ou des changements des produits ne vont pas être significatifs sur l'efficacité ou sur l'opération des SMC virtuels.

1.4.2.2 Systèmes manufacturiers cellulaires dynamiques

L'approche des SMC dynamiques intègre la dimension de la variabilité de la demande ainsi que la variété des produits demandés par les clients. Cette approche apparaît être efficace dans un environnement très turbulent comme c'est le cas des sous traitants. Ces derniers sont spécialisés dans quelques processus et vendent leur capacité et leur savoir faire pour produire une variété de produits à un nombre de clients; ils se doivent d'être flexibles et compétitifs. La configuration d'un SMC dynamique est soumise au changement dans le temps. Le but de la configuration est de minimiser le coût total de relocalisation des machines et de transfert de produits entre les cellules, pour répondre à des besoins de production sur un horizon de planification donné.

Rheault et al. (1996) ont développé un modèle de programmation en nombres entiers qui a pour objectif de minimiser le coût de reconfiguration des cellules, représenté par le coût marginal total de manutention (de pièces et de machines) sur un horizon temporel donné. D'autres travaux ont tenté d'intégrer aussi les coûts machines ou les coûts de flux intercellulaires dans la fonction objectif à minimiser, incluant Wicks and Reasor (1999), Mungwattana (2000), Balakrishnan and Cheng (2005), Tavakkoli-Moghaddam et al. (2005) et Pillai and Subbarao (2008).

Concernant les travaux qui ont introduit les décisions de planification de production et la conception de systèmes cellulaires, nous citons Chen (2001) et Chen et Cao (2004). Ces travaux ont proposé des modèles intégrant les options de production et de stockage dans un contexte où la demande et la variété des produits sont dynamiques. Chen (2001) a utilisé une méthode de décomposition pour déterminer la structure des cellules, des familles de pièces et le plan de production. Chen et Cao (2004) ont proposé une procédure basée sur la recherche tabou (*Tabu search*) pour déterminer le plan de production défini par les périodes de production et les niveaux de stock à maintenir pour les produits finis. Plus récemment, les travaux de Defersha et Chen (2006), Safaei et Saidi-Mehrabad (2008) et Defersha et Chen (2009) ont développé des modèles mathématiques qui intègrent en plus les coûts fixe et variable des machines, les coûts de reconfiguration et le coût des flux intercellulaires. Safaei et Saidi-Mehrabad (2008) utilisent une approche hybride basée le recuit simulé. Defersha et Chen (2009) développent une approche basée aussi sur le recuit simulé, mais caractérisée par des chaines de Markov multiples permettant la recherche simultanée de solution dans plusieurs voisinages.

1.4.3 Application de la technologie de groupe dans un contexte de chaîne d'approvisionnement

Potok et Ivezic (1999) ont approché le problème qui concerne une nouvelle application de la TG soutenue par l'objectif d'une gestion flexible de la chaîne d'approvisionnement : au lieu de regrouper les pièces selon un ensemble connu de possibilités de fabrication, les groupes sont développés selon un ensemble général de pièces de manufacturiers. Ce sont toutes les opérations de la chaîne d'approvisionnement entière qui vont être considérées. Le contexte industriel considéré par les auteurs est une chaîne d'approvisionnement comprenant plusieurs sous-traitants candidats à être fournisseur de pièces de rechange à une unité de maintenance d'avions militaires. Les auteurs ont développé un système multi-agent qui permet de regrouper l'ensemble des produits de plusieurs manufacturiers pour améliorer les performances logistiques.

Samatova et al. (2001) ont analysé le même problème en s'appuyant sur les travaux de Potok et Ivezic (1999). Ils ont développé une approche de regroupement généralisée des pièces. Pour résoudre le problème généralisé de regroupement des produits, les auteurs ont développé une approche nommée modèle de perturbation d'un vecteur espace. Ils relatent en premier les distinctions majeures dans les problèmes de regroupement entre un système traditionnel de production et un système de type chaîne d'approvisionnement : *L'approche traditionnelle* de la TG a pour but d'améliorer l'efficacité de la production dans un environnement de production unique. Ceci est réalisé en identifiant des groupes de pièces et en construisant des cellules de production de telle façon que chaque groupe de pièces soit fabriqué dans une cellule. Par contre, *dans le problème généralisé de regroupement de produits*, l'objectif est de construire des familles de pièces pour optimiser l'efficacité de toute la chaîne d'approvisionnement plutôt que de considérer un seul site de production. Le processus consiste à regrouper les pièces selon les gammes opératoires, choisir un fournisseur pour construire chaque famille à partir d'un ensemble de fournisseurs et de réarranger l'environnement de production choisi pour construire efficacement ces familles de pièces.

Une méthodologie proposée par Poornachandra et Chankong (2005) a tenté d'approcher la problématique de conception de systèmes manufacturiers cellulaires en intégrant l'aspect assemblage succédant aux opérations de fabrication. Traditionnellement, le design de cellules de production a pour objectif de minimiser les flux intercellulaires en exploitant la similitude des processus de fabrication des pièces. Toutefois, en réalité, les flux de pièces de fabrication convergent vers les centres d'assemblage. En exploitant conjointement les similitudes en processus de fabrication et d'assemblage, des modèles de conception de systèmes manufacturiers cellulaires ont été élaborés tout en considérant la similitude de routage de ces pièces vers l'assemblage. Le modèle mathématique développé détermine l'affectation des pièces, des machines et des sous-ensembles à des cellules manufacturières.

Par ailleurs, dans le même esprit de notre problématique, Poornachandra et Mohanty (2003) explorent les relations qui existent entre la conception de systèmes manufacturiers cellulaires et la conception de chaînes d'approvisionnement. À travers un exemple illustratif, ils montrent comment la conception de systèmes cellulaires peut être intégrée pour répondre aux objectifs d'une chaîne d'approvisionnement à coût minimal. Les auteurs considèrent une chaîne d'approvisionnement à deux échelons (fournisseur – sites de production). Les cellules de production à concevoir ne vont pas appartenir obligatoirement au même site de production mais vont plutôt être localisées dans plusieurs sites de production, afin de permettre d'identifier des configurations des chaînes d'approvisionnement fournisseur - sites de production à moindre coût.

1.5 Conclusion

Cette revue de littérature a permis en premier de relater les efforts accomplis par les travaux dans l'intégration des détails du système de production pour la modélisation de chaînes d'approvisionnement. Elle a permis aussi de souligner l'évolution des modèles de conception de SMC par la variété de contextes étudiés et par les différents paramètres de production intégrés qui projettent de s'aligner au mieux aux objectifs des industriels. Cependant, l'intégration explicite du problème de configuration cellulaire d'un système de production multi-site dans la conception de chaînes d'approvisionnement, de surcroît permettant des flux matières entre les sites de production, n'a aucunement été approchée. En effet, les enjeux logistiques (approvisionnement en matières premières, livraison aux clients) et de localisation doivent être analysés dans un contexte de SMC à établir sur plusieurs sites, pour assurer des chaînes d'approvisionnement plus profitables.

Le défi relevé par ce travail doctoral est donc de développer une approche qui permet d'intégrer les décisions relatives à la conception de systèmes manufacturiers cellulaires, aux décisions de conception de la chaîne d'approvisionnement.

1.6 Objectifs de recherche et approche de recherche

Cette thèse a pour objectif de proposer une approche de conception de systèmes cellulaires multi-site et de démontrer le potentiel induit par son intégration dans un contexte de chaîne d'approvisionnement.

La réalisation de cet objectif dérive de la réalisation des objectifs secondaires suivants :

1. Développer des modèles mathématiques intégrés qui établissent l'aspect chaîne d'approvisionnement dans la conception de systèmes manufacturiers cellulaires à deux

niveaux : (i) le lien avec des fournisseurs ou avec des zones clients, (ii) le lien entre les sites de production.

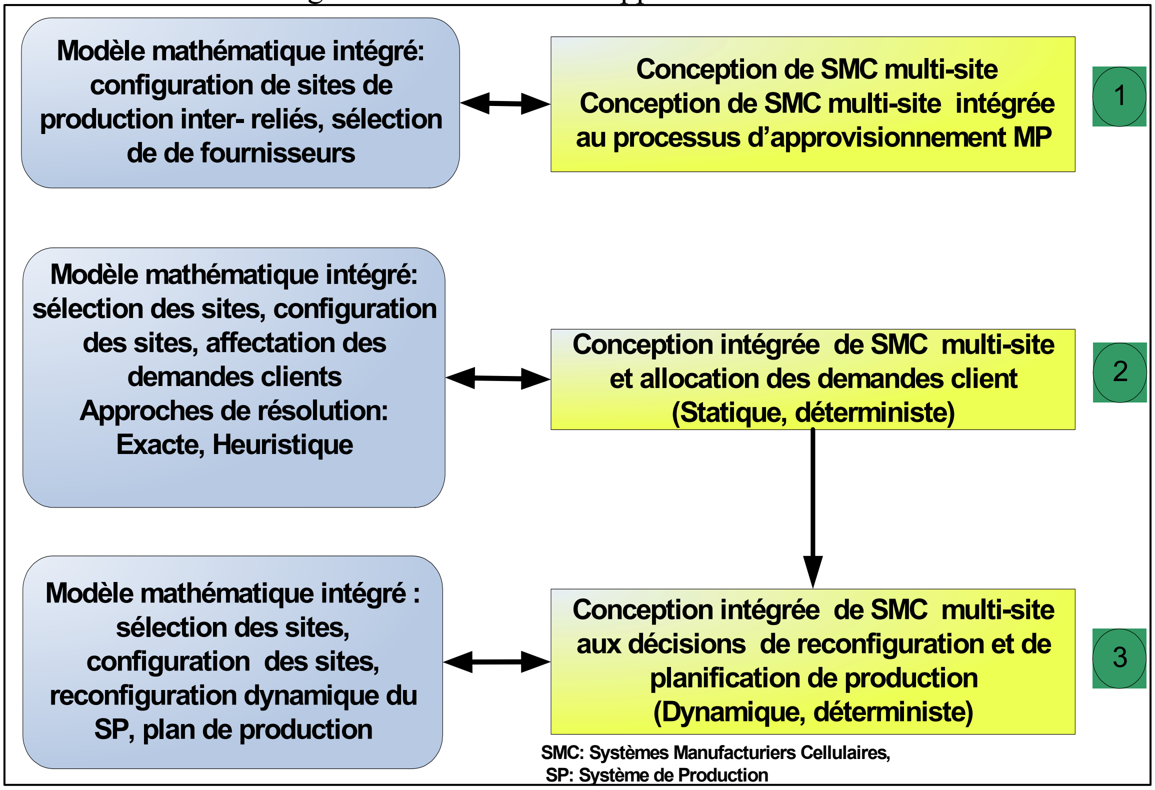
2. Proposer des approches de résolution des modèles qui démontrent la supériorité des modèles intégrés de conception de systèmes cellulaires multi-site sur les modèles dissociant la configuration cellulaire sur plusieurs sites de production des enjeux de choix de fournisseurs ou d'affectation des demandes client.

Les trois étapes de l'approche de recherche sont résumées dans la figure 1.8. Dans ce qui suit, nous donnons quelques détails sur le points cités aux trois étapes.

1. Développement de modèles mathématiques qui réunissent les paramètres de conception de système cellulaire associant le processus d'approvisionnement (modèles du chapitre 2), le processus de livraison de demande (statique et dynamique) aux clients (modèles des chapitres 3 et 4).
2. Proposition d'approches de résolution basées sur des formes linéaires pour les modèles mathématiques permettant de résoudre exactement des problèmes de petites tailles en utilisant Cplex Solver, d'en analyser les résultats relativement à l'intégration du contexte logistique (chapitres 2 et 3).
3. Développement d'une approche multi-phase basée sur le recuit simulé pour résoudre le modèle du chapitre 3.
4. Validation des solutions obtenues par l'approche proposée comparées à celles obtenues avec les solutions exactes obtenues par la résolution du modèle linéarisé (chapitre 3), moyennant Cplex Solver, pour un ensemble de données problèmes issus de la littérature.
5. Évaluation de l'approche proposée au chapitre 3 (utilisant un processus de perturbation de solution modifié) par rapport à un processus de perturbation par recuit simulé conventionnel.
6. Évaluation des gains engendrés en comparant l'approche intégrée à l'approche séquentielle (chapitre 3).
7. Analyse du modèle dynamique (chapitre 4) par rapport à l'intégration séquentielle et simultanée de plusieurs hypothèses.

8. Analyse de sensibilité du modèle dynamique (chapitre 4) à la variation de certains paramètres de conception.

Figure 1-8 Structure de l'approche de recherche



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1.7 Structure de la thèse

Les contributions de cette thèse sont introduites dans les chapitres 2, 3 et 4 et présentées sous la forme d'articles.

Le chapitre 2 présente la première originalité de cette recherche doctorale. Nous nous adressons au problème de la conception d'un système manufacturier multi sites, soumis au choix de fournisseurs de matières premières. En premier, nous proposons un modèle mathématique qui permet la conception d'un système manufacturier cellulaire établi sur plusieurs sites. La demande client n'est pas affectée à un seul site, comme c'est le cas dans les modèles de SMC classiques. L'hypothèse principale ajoutée est que les pièces à manufacturer peuvent aussi utiliser les ressources machines d'un autre site manufacturier, pour compléter la réalisation de leurs opérations. Ensuite, nous étendons le problème en considérant simultanément le choix de fournisseurs et la conception de systèmes cellulaires établi sur plusieurs sites manufacturiers. Nous démontrons, à travers l'expérimentation, les gains induits par l'intégration de flux inter sites dans la conception cellulaire multi-site. Ce chapitre fait l'objet du premier article soumis et accepté au Journal of Operations and Logistics (JOL).

Le chapitre 3 présente un deuxième aspect original de cette thèse. Nous considérons le problème qui intègre deux types de décisions : la sélection des sites manufacturiers et la conception cellulaire multi-sites pour satisfaire la demande répartie sur plusieurs zones clients. Nous proposons un modèle mathématique qui établit un lien entre les sites manufacturiers par les flux matières entre les sites, qui permet d'affecter les demandes clients aux sites choisis et aussi de les configurer selon une structure cellulaire. La demande est supposée connue. Nous identifions clairement que le coût des ressources machines est un paramètre majeur qui affecte le potentiel d'intégration simultanée des décisions de conception de SMC multi-site, de choix des sites de poduction et d'allocation des demandes client. Le problème est NP difficile, d'où le recours à des méthodes méta-heuristiques est incontournable. Pour cela, une approche méta-heuristique multi-phase, basée sur le recuit simulé, a été développée intégrant graduellement les décisions de sélection de sites et de conception cellulaire des sites manufacturiers. L'approche par recuit simulé est caractérisée par un processus de perturbation de solution se distinguant du processus de perturbation conventionnel. Ce chapitre est le deuxième article de cette thèse. Il est intitulé «Multi-plant cellular manufacturing systems design integrated with customer allocation» et est soumis à International Journal of Production Research.

Le chapitre 4 représente le troisième article réalisé dans le cadre de cette thèse. Nous y considérons une extension du problème étudié dans le chapitre 3 où la demande client est connue sur un horizon de planification. En effet, nous considérons la problématique de conception d’un système manufacturier cellulaire multi-site dans un contexte dynamique à laquelle, nous intégrons aussi les décisions de planification de la production et de reconfiguration des sites de production à chaque période de l’horizon de planification. Dans ce contexte, nous développons un modèle mathématique qui réunit dans la fonction-objectif les coûts de conception des sites, le coût de sélection des sites, le coût de livraison des demandes client et les coûts du plan de production. Particulièrement, le modèle introduit la possibilité de flux matières entre sites soit pour un partage de ressources machine soit pour satisfaire une demande client à partir d’autres sites manufacturiers. Nous montrons clairement, à travers l’expérimentation, l’intérêt d’intégrer les decisions de planification de la production, le recours à la reconfiguration du système manufactier et la possibilité de transférer une production vers un autre site, comme moyen pour réduire le coût total de conception et pour offrir plus flexibilté de production et de routage des demandes client. Ce chapitre est le troisième article réalisé dans le cadre de cette thèse, intitulé «Dynamic multi-plant cellular manufacturing systems design with production planning décisions and system reconfiguration» et est soumis à International Journal of Production Economics.

Pour terminer, nous présentons une conclusion ainsi que des recommandations pour des recherches futures.

CHAPITRE 2

ARTICLE 1: MULTI-PLANT CELLULAR MANUFACTURING SYSTEM DESIGN WITHIN A SUPPLY CHAIN

Abstract

In this paper, we consider the problem of integrating a multi-plant cellular manufacturing design simultaneously with a supply chain design. The supply chain consists of a number of plant facilities for manufacturing a variety of parts with deterministic demands. Raw materials can be procured from alternative suppliers. Traditionally, cellular manufacturing systems have been designed at a single manufacturing facility. Also, the design of supply chains is analysed without considering the manufacturing plant design. A one-period nonlinear model is proposed to design a supply chain in which the multi-plant manufacturing system is configured as a cellular manufacturing system subject to supply process selection. Aimed to demonstrate the potential benefits of such a design, illustrative examples are shown using a proposed linearized form of the problem. Cplex solver is used to solve two sets of small-sized problems demonstrating the potential benefits gained through increasing routing flexibility over plants on investment costs and the effect of integrating the supply process in a multi-plant cellular manufacturing configuration.

2.1 Introduction

Supply chain (SC) analysis involves the integration of different functions (e.g. purchasing, production, distribution) through which products flow in order to effectively satisfy customers. The main objective of a supply chain design is to determine the structure of the supply chain, namely, the decision regarding the location of the manufacturing plants, the assignment of products to plants, the distribution channel options, and the supply process decisions. Effective design and management of the supply chain aid in the production and delivery of a variety of products at low cost, high quality, and short lead times (Talluri and Baker (2002)). While it has been seen that performing separate analyses of the different processes does not completely provide answers to managerial issues, the fact though, is that to achieve an efficient supply chain management, an effective design and integration of the supply chain functions is critical. Today, product parts or components may be produced in different networked manufacturing plants, and to improve delivery time and the resource utilisation rate, a part may be completed in more than one manufacturing plant.

For manufacturing plants, their performance is closely linked to configuration decisions. In batch manufacturing, cellular design has been widely implemented in industry. Cellular Manufacturing System (CMS) design involves the application of group technology recognised for its ability to offer performance marked by shorter delivery times, a wider range of manufactured parts, shorter set-up times, reduced throughput times, reduced work-in-process inventory and material handling, and of course, lower production costs (Wemmerlov and Johnson, 1997). CMS design is initially realized with the identification of part families and independent machine cells. Each part family should be manufactured entirely within a machine cell. However, in the real manufacturing world, parts may be processed in more than one cell. In fact**,** if the cells are to be located within a single manufacturing plant, the steps of the design process for the corresponding supply chain (identification of part families and machines cells, raw material supply process decisions and distribution channel choices) may be conducted independently. The cells will behave like small manufacturing plants. Obviously, this integrated SC design will contribute to speed up delivery time and reduce inventory, with regard to the outbound part flows and reduce the global design cost in its corresponding supply chain. However, constraints on the supply process may affect the operation and the performance of the CMS, and in turn, the entire supply chain.

However, if the cells can be located in at least two different manufacturing plants, then, to preserve CMS advantages, especially those associated with levelling inventories and delivery time, the cellular manufacturing design should not be addressed independently from the supply process and distribution decisions; supply costs and constraints on the supply process may affect the operation and the performance of the CMS, and consequently, the entire supply chain. The CMS design will be redefined as identifying machine cells and part families combined with cell location and assignment of part families over the plants, supplier selection and customer distribution channel. The whole design process must create a balance between the cellular design cost in the different plants, the supply cost and the distribution cost.

Additionally, this balance may be created in terms of management of inventory levels for product items (reduction of inventory levels and stockout) through all the plants considered, as an integrated cellular manufacturing system. Such design questions arise both in situations involving investment in a new supply chain of known potential manufacturing plants or the upgrading of an existing supply chain with a manufacturing plant cellular design.

In this paper, our objective is to demonstrate the utility of integrating a manufacturing configuration into the supply chain design process. A cost-based mathematical model is developed to design a supply chain in which the multi-plant manufacturing system is configured as a cellular manufacturing system subject to the supply process selection. The manufacturing design parameters include processing operation time, routing flexibility, reject rate at each operation, capacity resource limits, and machine availability.

This paper is organised as follows: Section 2 presents a review of the literature on cellular manufacturing design, supply chain design and the integration of the manufacturing system design into the supply chain design. Section 3 presents the model developed for a multi-plant CMS design integrating the raw material supply process. In section 4, two sets of problems of illustrative examples are shown through experimentation based on a proposed linearized form of the model. Finally, the conclusion is given in section 5.

2.2 Literature review

2.2.1 Cellular manufacturing design

In the literature, various approaches are proposed and attempted in order to consider practical design parameters for designing cellular manufacturing systems. Berardi et al. (1999). evaluated alternative cluster formulations based on the mathematical model of Shafer et al. (1992). Three strategies were used to eliminate exceptional elements, namely, the duplicating machine, intercellular moves and subcontracting. Taboun et al. (1998). proposed methods for developing part family and machine cell configuration to handle manufacturing system configuration or new system design. Their procedures take into account machine and intercell handling cost as well as subcontracting costs in order to obtain better utilised cells. Initially, a developed heuristic is used to form the machines cells and part families, and then the result of the heuristic is integrated into a mathematical model to optimize the various design costs. Beaulieu et al., (1997) considered machine capacity, alternative routing and constraints on cell size. The authors proposed a two-phase approach: formation of independent cells, followed by the introduction of intercell flow to optimize machine investment cost. To solve the same problem, Jayaswal and Adil (2004) proposed a methodology comprised of simulated annealing and local search heuristics.

Over the last ten years, another practical parameter design in cellular manufacturing design has gained attention, as shown in the design dynamics. Dynamic CMS was addressed in a number of research papers. Tavakkoli et al. (2002) proposed different metaheuristics to solve cell formation problems, considering routing flexibility, machine flexibility and machine relocation cost. Balakrishnan and Cheng (2005) addressed the problem of CMS across a multi-period horizon, with dynamic programming used to select the best cell configuration minimizing the sum of the shifting and material handling cost within the planned horizon. Jeon et Herman (2006) developed a new methodology based on a new similarity coefficient, which integrates routing flexibility during machine failure, and demand changes for multiple periods. The methodology is implemented in two sequential phases: identification of part families and machine assignment to part families using sequential and simultaneous cost-based mixed-integer programming models, and considering the scheduling and operational aspects in cell design under demand changes. Poornachandra Rao and Mohanty(2003) simultaneously incorporate processing and assembly considerations in cell design. The authors propose mathematical models introducing new similarity coefficients between parts, machines and subassembly, and use the Lagrangian relaxation approach to solve large data problems. Recently, production planning and dynamic CMS was addressed by Defersha and Chen, (2009) and by Safaei et al., (2009). Ahkoon et al., (2009) investigates the problem of cellular manufacturing systems design with multi-period production planning, dynamic system reconfiguration, operation sequence, duplicate machines, machine capacity and machine procurement, with a new aspect of alternate contingency process routings in addition to alternate main process routings for all part types.

All the research on cellular manufacturing design has been conducted at a single-plant facility. However, in a supply chain environment, multiple plants may interwork to manufacture parts, and different cells in different plant locations may in turn contribute to satisfy a part demand.

2.2.2 Supply chain design

The manufacturing system is a major component with regard to suppliers and distributors, and the integrated components form a supply chain. From a strategic perspective, supply chain design aims to provide an optimal platform for efficient and effective management of these integrated components. The key issues considered in a supply chain design (SCD) are: the manufacturing strategy, the supply process design and the distribution strategy. An effective design and management of supply chains aims to deliver products at a low cost and over a short lead time. The challenge is to determine the number, location, production capacity and distribution facilities. Over the last ten years, different research studies have been conducted in supply chain design (Goetschalcks et al., 2002), Graves and Whilem (2005), Talluri and Baker (2002). Originally, Arntzen et al. (1995) addressed the problem of worldwide supply chain management at the Digital Equipment Corporation. The authors proposed a model which integrates production costs, inventory charges and distribution expenses, and determines alternative supply chain structures to meet estimated demand for multiple parts.

Goetschalckx et al. (2002) considered the production distribution design problem and proposed a mixed integer linear program methodology which integrates strategic and tactical decisions rather than working in a hierarchical fashion. For the production stage particularly, alternative manufacturing lines are considered, which differ by their technology and capacity, and with the resource requirement and the marginal cost for manufacturing a particular product on a particular production line known. Paquet et al. (2004) introduced technology selection in the design of a manufacturing network, with the proposed methodology aimed at defining the optimal structure with a selected technology and capacity for each facility, using Bender's decomposition. Talluri and Baker (2002) developed a multi-phase mathematical programming approach for effective supply chain design based on a combination of multi-criteria efficiency models and linear and integer programming methods. Park (2005) has proposed an integrated approach for production and distribution planning regarding production details, such as processing and set-up time of manufactured items. Chauhan and Proth (2004) addressed the problem of supply chain design when production/distribution of a new market opportunity is considered. The authors proposed a large-scale mixed-integer linear programming model to address the strategic capacity planning in a three staged supply chain for a new market opportunity. To meet the deterministic customer demand at a minimal cost, production capacity and transportation limits are considered through the three stages.

Graves and Whilem (2005) addressed how to configure the supply chain for a new product with multiple raw material supplier options, various manufacturing choices and different modes of transportation to the customer. A cost-based dynamic model was proposed to select a supply chain configuration at a minimal total cost.

Some research has emphasized the relationship between cellular manufacturing and the supply chain. Samatova et al. (2001) proposed a generalized approach to group parts based on the similarity of their operation sequence from a broad set of part manufacturers rather than grouping parts based on a single manufacturing floor, to optimize the efficiency of the entire supply chain. Poornachandra Rao and Mohanty (2003) investigated the impact of CMS design on SCD decisions and described the interrelationship between the two approaches through an illustrative example. However, no framework model was proposed to integrate cellular manufacturing design and the supply chain. More recently, Schaller (2008) proposed a mathematical model and a tabu search approach to integrate cellular manufacturing design in more than one plant to customer demand distribution.

The literature on supply chains also addresses supply chain scheduling or coordinated logistics scheduling. The inter factory linkage flexibility was investigated by Ferdows and Carabetta (2006), who examined the nature of the relationship between inter-factory linkage flexibility and inventory and backlog levels in integrated process industries. A simulation approach was used to demonstrate that increased flexibility reduces inventory levels for parts by increasing the inter-factory linkage flexibility than investing in extra capacity. Lee et al. (2002) discussed the scheduling model in a supply chain with outsourcing options. Chung et al. (2005) studied a job shop scheduling problem with an assumption that an operation of a job can be performed either on an in-house machine or on an outsourcing machine. Qi (2006) proposed a logistics scheduling model for two processing centers that are located in different cities; Qi (2008) subsequently considered a two-stage supply chain scheduling problem and designed an integrated scheduling that considers both in-house production and outsourcing. Hall and Potts (2003) considered the coordination of scheduling, batching, and delivery decisions, both at a single stage and between different stages of a supply chain, with the objective minimizing the overall scheduling and delivery cost. This is achieved by forming batches of orders, each of which is delivered from a supplier to a manufacturer or from a manufacturer to a customer, in a single shipment.

All the supply chain design models currently available consider that the alternative plants have known configurations. Additionally, the classical design process of a CMS is conducted in a single facility. In practice, a dominant partner in a supply chain may own a number of plants and wish to optimize their configurations simultaneously in order to respond to a market demand. Considering basically alternative routing plans for parts into just one plant, the value added by inter-plant flexibility will contribute to minimize the number of underutilised machines. Thus, the integration of multiple production systems for a simultaneous multi-plant CMS design, allowing interplant flow will promote savings in global design cost and provide planning flexibility.

In summary, the literature on cellular manufacturing design focuses essentially on a single production plant, and to the best of our knowledge none of the existing methodologies considers the implication of cellular design of manufacturing systems over multiple plant locations, and moreover if integrated with the raw material supply process, and such features exist in real world manufacturing. There is therefore a need for a simultaneous analysis of a supply chain defined as multiple manufacturing plants to be connected to suppliers.

Furthermore, since cell design is part of the design of a manufacturing system, and the system is expected to last for a long time, even a small improvement in overall investment design cost can be valuable over the life of the manufacturing system. Thus, the potential benefits of multi-facility cellular manufacturing design for the supply chain structure need to be demonstrated. Based on the above analysis, our objective in this paper is to develop a cost-based mathematical model to design a supply chain in which the multi-plant manufacturing system is configured as a cellular manufacturing system subject to supply process selection, and which also allows interplant flows. Compared with the Schaller model (Schaller (2008)), our supply chain design addresses the linkage between different manufacturing plants to be designed as CMS, with the selection process of raw material suppliers, and moreover, allows material flow between plants. Further, the design parameters in our proposed model cope with real-life production and supply parameters such as processing operation time, routing flexibility, quality issues at the manufacturing phase, capacity resource limits, machine duplication, intercellular flows, supply process costs and supplier capacity. Such a problem with these features, to the best of our knowledge, has not been encountered in literature.

2.3 Problem description

The challenge is to develop a framework which allows the simultaneous optimization of production facilities and of the supplier selection process. It is clear that such a model and solution methodology can yield significant savings for a corporation seen as the dominant partner in a supply chain, and likely to be linked to alternative suppliers in order to satisfy market demand in several customer zones. Figure 2.1 illustrates the structure of this supply chain with a manufacturing system split across multiple plants, and linked to its inbound flows.

The production system consists of a number of plants which will produce multiple parts, and with each part requiring one raw material. Annual part demand is assumed to be deterministic, and demand for a part in a year in all customer zones is summed up. The machine capacity is thus also limited on a yearly basis. Routing flexibility is considered, that is, each part operation can be completed on alternative machines with different processing times and different reject rates. For each operation on a part, a variable cost is incurred. There is no storage capacity at the plants, and the splitting of demand between machines is not allowed.

The mathematical model (model P) aims to define a cellular manufacturing structure in a multi-plant manufacturing system and the flows between plants, simultaneously with supplier selection and optimization of the flows between suppliers and production plants. The models will identify:

- Part family assignment and machine cell location in the multi-plant manufacturing system.
- Flows between plants.

- Selection of suppliers from a set of raw material suppliers.
- Flows between suppliers and production plants.

2.3.1 Notations

Before formulating the models, we define the problem parameters and decision variables as follows:

i	Index of parts
j	Index of operations
m	Index of machine types
l	Index of manufacturing plants
c	Index of production cells
f	Index of suppliers
NP	Number of parts
NO_i	Number of operations of part i
NL	Number of manufacturing plants
NC	Number of manufacturing cells
NF	Number of suppliers
NM	Number of machine types
D_i	Annual demand for part i
R_{ij}	Reject rate of operation j on part i
DO_{ij}	$= D_i \Big/ \left(\prod_{k=1}^{NO_i} (1-R_{ik}) \right)$ Adjusted annual demand for operation j on part i
a_{ijm}	=1 If a machine of type m can be used to process operation j on part i, = 0 otherwise.
t_{ijm}	Process time to complete operation j on part i on a candidate machine

	m
B	Batch size for interplant and inter-cellular flows
MFC_m	Annual fixed cost of machine type m
MVC_m	Variable cost of machine type m for each time unit
cap_m	Annual machine capacity of machine type m (time unit)
L	Lower number of machine in a cell
U	Upper number of machine in a cell
fc_f	Operation fixed cost of supplier f
vc_{ilf}	Variable cost integrating purchasing and transportation of raw material for part i from a candidate supplier f to a plant l
ISC	Transportation cost of a batch between two production plants
ICC	Material handling cost for a batch transferred between two cells
CF_{if}	Supplier f capacity for raw material needed for part i

2.3.2 Decision variables

MNB_{mcl}	Number of machine type m to purchase for cell c in production plant l
OP_{ij}^{mcl}	0-1 variable indicating whether or not operation j on product i is performed on machine m of cell c of the production plant l
YF_f	0-1 variable indicating whether or not supplier f is selected
Y_{if}	0-1 variable indicating whether or not material of product i is supplied from supplier f
WF_{ilf}	Total units of material for product i supplied from supplier f to production plant l
WW_{i1f}	=1 if raw material for part i is shipped from supplier f and 0 otherwise

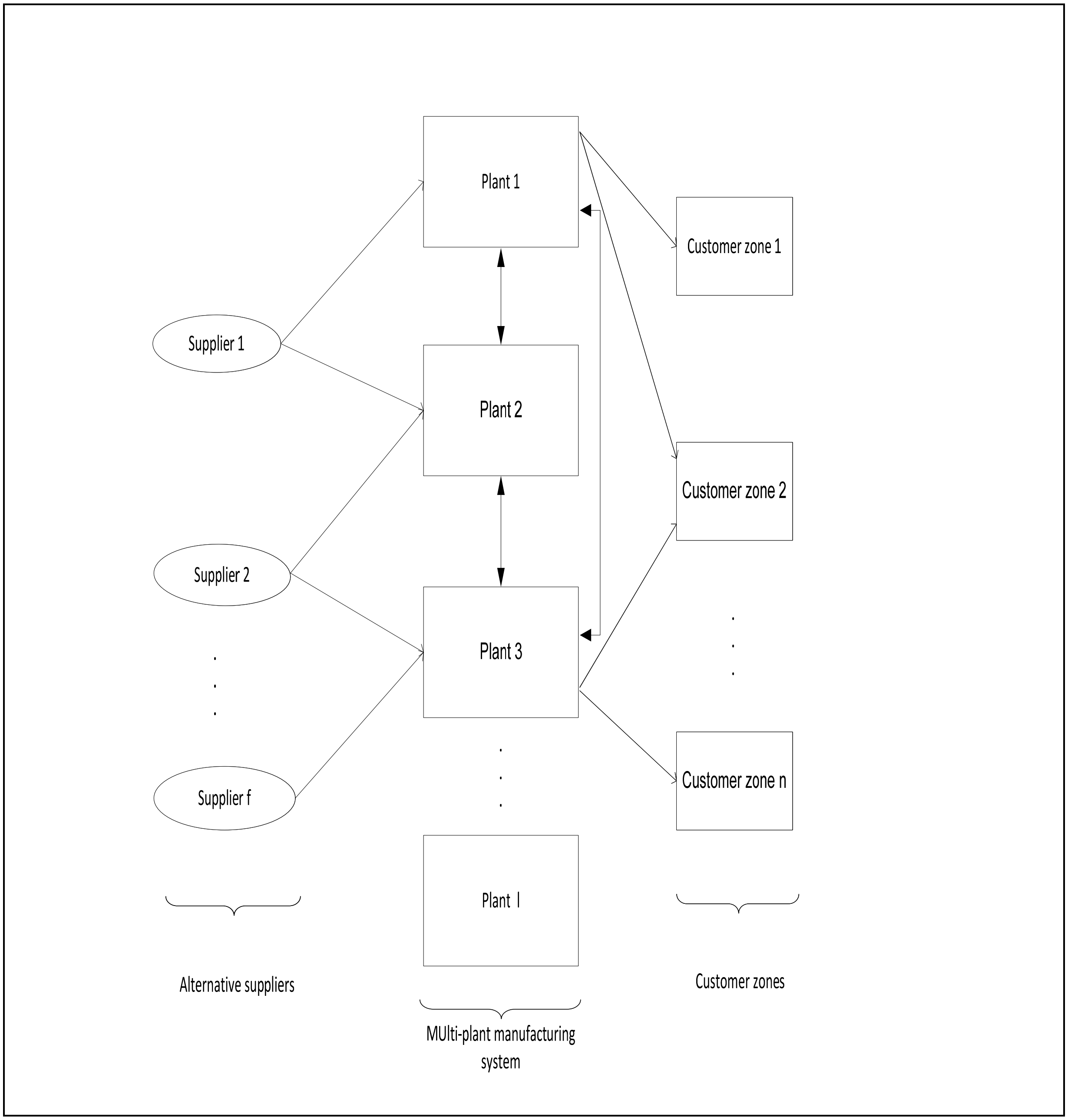

Figure 2-1 Supply chain structure

2.3.3 Mathematical model

The model P illustrates the multi-plant cellular manufacturing system integrated with the supply process design allowing flows between plants to satisfy customer demand. While the plants are assumed to be chosen, the designer may however introduce plant selection in the mathematical model, simultaneously integrating plant location selection from potential plants and cellular design of the selected plants. The supply process is integrated with the multi-plant cellular manufacturing design. Selecting a raw material supplier is linked to the part operation assignment. Each supplier is defined by the shipment capacity for each raw material part, a fixed production setup or ordering cost and a variable cost integrating purchasing and transportation of raw materials for a part i from a candidate supplier f to a plant l. Thus, the model P allows the simultaneous selection of a raw material supplier for each part, design machine cells and part families at each plant, satisfying demand requirements.

For a supply chain with a single facility and alternative suppliers, the problem as designed in model P can be decomposed in two independent problems. The first aims to design the cellular manufacturing system for the facility plant, and the second will select raw material suppliers with a minimum purchasing and transportation cost. However, for a supply chain with multiple plants allowing sharing production capacity, the parts families, machine cells and supplier selection determination problem must be considered simultaneously. In the particular case where there are no cross-flows between plants, to the best of our knowledge, the problem is still not analysed in the literature. Thus, our model will analyse the best location of cells with regard to the integration of the supplier echelon in the supply chain design.

Model P

Min

$$\begin{aligned}
&\Biggl(\sum_{\mathrm{l}=1}^{\mathrm{NL}}\Biggl(\sum_{\mathrm{c}_1=1}^{NC}\Biggl(\sum_{m=1}^{NM}\Biggl(MNB_{mcl} \ast MFC_m + \sum_{i=1}^{NP}\sum_{j=1}^{NO} DO_{ij} \bullet t_{ijm} \bullet OP_{ij}^{mcl} \ast MVC \\
&+\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO} ISC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{i,j+1}^{mcl}\right| \\
&+\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\sum_{c=1}^{NC}\left|\sum_{m=1}^{NM} OP_{ij}^{mcl} - \sum_{m=1}^{NM} OP_{i,j+1}^{mcl}\right| \\
&-\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{i,j+1}^{mcl}\right| \\
&+\sum_{f=1}^{NF}\left(fc_f \bullet YF_f + \sum_{i=1}^{NP}\sum_{l=1}^{NL} WF_{ifl} \bullet WW_{i1l} \bullet vc_{ifl} \right)
\end{aligned} \tag{2.1}$$

Subject to

$$\sum_{l=1}^{NL}\sum_{c=1}^{NC}\sum_{m=1}^{NM} a_{ijm} \ast OP_{ij}^{mcl} = 1 \qquad \forall i, j \tag{2.2}$$

$$\sum_{m=1}^{NL} MNB_{mcl} \geq L \qquad \forall c, l \tag{2.3}$$

$$\sum_{m=1}^{NL} MNB_{mcl} \leq U \qquad \forall c, l \tag{2.4}$$

$$\sum_{i=1}^{NP}\sum_{j=1}^{NO} DO_{ij} \bullet t_{ijm} \bullet OP_{ij}^{mcl} \leq cap_m \bullet MNB_{mcl} \qquad \forall m, c, l \tag{2.5}$$

$$\sum_{f=1}^{NF} Y_{if} = 1 \qquad \forall\ i \tag{2.6}$$

$$\left(NP \bullet YF_f - \sum_{i=1}^{NP} Y_{if} \right) \geq 0 \qquad \forall\ f \tag{2.7}$$

$$\sum_{l=1}^{NL} WF_{ifl} \leq CF_{if} * Y_{if} \qquad \forall i, f \qquad (2.8)$$

$$\left.\begin{array}{lll} OP_{ij}^{mcl} & \in \{0,1\} & \forall i, j, m, c, l \\ Y_{if}, Y_f & \in \{0,1\} & \forall i, f \\ MNB_{mcl} & \geq 0 \text{ and integer} & \forall m, c, l \\ WF_{ifl} & \geq 0 \text{ and integer} & \forall i, f, l \end{array}\right. \qquad (2.9)$$

The objective function (2.1) in the model P is a nonlinear integer equation. It expresses the total cost of the multi-plant cellular manufacturing system and the total supply costs. These two types of costs are interrelated and could be conflicting. First, the total production cost in all production plants is split on fixed machine costs, variable machine costs, intra-plant intercellular flow cost and total cost of flow between plants when machine resources are shared. Allowing interplant flow states that successive manufacturing operations on a part may be performed in different plants where machine capacity is available. A fixed transportation cost per batch is assumed. This interplant linkage will increase operation routing flexibility, and attempts to minimise underutilised machine rate and therefore optimise the total supply chain design cost. A linear cost is assumed for both interplant and intra-plant flows, and therefore optimises the total supply chain design cost. Second, the supply process cost includes fixed ordering cost and flow cost between selected suppliers and manufacturing plants.

Constraint set (2.2) ensures that each operation on a part is completed on only one machine type, in one cell and in one plant. Constraint sets (2.3) and (2.4) limit the lower and the upper number of machines in a cell. Constraint set (2.5) allows cell design with realistic availability machine percentages. Constraint sets (2.6), (2.7) and (2.8) are related to supplier selection and limited flows between suppliers and plants. Binary and integer restrictions on decision variables are enforced through constraint sets (2.9). WW_{i1f} is an artificial binary variable linked to the first part-operation assignment defined as: $WW_{i1f}=\sum_{l=1}^{NL}\sum_{c=1}^{NC}\sum_{m=1}^{NM}OP_{i1}^{mcl}$

Specific constraints may be added to the model, such as available floor space at each plant, budget at each plant, overall budget, the balance of the number of parts in each plant, or a constraint avoiding or limiting backtracking flows between plants.

2.4 Solution approach and illustrative problems

The proposed model involves nonlinear mixed-integer programs. The objective function presents a nonlinear form because of absolute terms and a polynomial term. Using classical linearization techniques, additional variables and constraints are introduced in order to obtain a mixed-integer linear problem. The original problem of cellular manufacturing design is recognised to be NP-hard, and obviously, the proposed linearized model is NP-hard as well. Experimentation is thus demonstrated on small-sized problems solved with Cplex solver.

2.4.1 Linearized model

The objective function in P contains two absolute terms. In the literature, the classical scheme used to handle this type of nonlinearity in the objective function involves introducing new binary variables and new constraints, as used in Mungwattana (2000) or Tavakkoli-Moghaddam et al. (2005). Hence, the first absolute term in (2.1) is transformed into a linear form as follows: two types of binary variable QOP_{ijl} *and* ROP_{ijl} are introduced and the related objective term is rewritten as follows:

$$\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1}ISC\bullet\left\lceil\frac{DO_{ij}}{B}\right\rceil\bullet\sum_{l=1}^{NL}\left(QOP_{ijl}+ROP_{ijl}\right) \tag{2.10}$$

Accordingly, a new set of constraints must be added to the original model showing the relation between the original variables and the newly introduced variables.

$$WW_{i,j+1,l} - WW_{ijl} = QOP_{ijl} - ROP_{ijl} \qquad \forall\ i,j,l \tag{2.11}$$

$$WW_{ijl} = \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP_{ij}^{mcl} \qquad \forall\ i,j,l \tag{2.12}$$

Likewise, to transform the second absolute term lying in (2.1) into a linear form, the binary variables MOP_{ijcl} *and* NOP_{ijcl} are introduced and the related objective term becomes:

$$\begin{aligned} &\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC\bullet\left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet\sum_{l=1}^{NL}\sum_{c=1}^{NC}\left(MOP_{ijcl} + NOP_{ijcl}\right) \\ &-\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC\bullet\left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet\sum_{l=1}^{NL}\left(QOP_{ijl} + ROP_{ijl}\right) \end{aligned} \tag{2.13}$$

Similarly, a new set of constraints must be added to the original model showing the relation between the original variables and the newly introduced binary variables:

$$ZZ_{i,j+1,cl} - ZZ_{ijcl} = MOP_{ijcl} - NOP_{ijcl} \qquad \forall\ i,j,c,l \tag{2.14}$$

$$ZZ_{ijcl} = \sum_{m=1}^{NM} OP_{ij}^{mcl} \qquad \forall\ i,j,c,l \tag{2.15}$$

In addition to the two absolute terms, the model includes a polynomial term in (2.1). A new non-negative variable Z_{ifl} is introduced, where $Z_{ifl} = WF_{ifl}\bullet WW_{i1l}$

The related objective will be rewritten as follows:

$$\sum_{f=1}^{NF}\left(fc_f\bullet YF_f + \sum_{i=1}^{NP}\sum_{l=1}^{NL} Z_{ifl}\bullet vc_{ifl} \right) \tag{2.16}$$

And thus a new set of constraints must be added:

$$
\begin{aligned}
&\mathrm{Z}_{\mathrm{ifl}} \leq DO_{i1} \bullet WW_{i1l} && \forall i, f, l \\
&\mathrm{Z}_{\mathrm{ifl}} \leq WF_{ifl} && \forall i, f, l \\
&\mathrm{Z}_{ifl} \geq WF_{ifl} - DO_{i1} \bullet (1\text{-}\mathrm{WW}_{i1l}\ ) && \forall i, f, l \\
&\sum_{l=1}^{NL} WF_{inl} \leq \ CF_{in} * Y_{in} && \forall i, f \\
&DO_{i1} \bullet \ \mathrm{WW}_{i1l} \leq \sum_{f=1}^{NF} \mathrm{Z}_{ifl} && \forall i, l
\end{aligned}
\tag{2.17}
$$

The linearized model named LP has the following structure:

Model LP

Min

$$
\begin{aligned}
&\left(\sum_{\mathrm{l=1}}^{\mathrm{NL}} \left(\sum_{\mathrm{c_1=1}}^{NC} \left(\sum_{m=1}^{NM} \left(MNB_{mcl} * MFC_m + \sum_{i=1}^{NP} \sum_{j=1}^{NO} DO_{ij} \bullet t_{ijm} \bullet OP_{ij}^{mcl} * MVC_m \right) \right) \right) \right) \\
&+ \frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL} \sum_{c=1}^{NC} \left(MOP_{ijcl} + NOP_{ijcl} \right) \\
&- \frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL} \left(QOP_{ijl} + ROP_{ijl} \right) \\
&+ \frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ISC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL} \left(QOP_{ijl} + ROP_{ijl} \right) \\
&+ \sum_{f=1}^{NF} \left(fc_f \bullet YF_f + \sum_{i=1}^{NP} \sum_{l=1}^{NL} Z_{ifl} \bullet vc_{ifl} \right)
\end{aligned}
\tag{2.18}
$$

Subject to

(2.2) to (2.9), (2.11), (2.12), (2.14), (2.15) and (2.17)

$$
\begin{aligned}
&MOP_{ijcl}, NOP_{ijcl} \in \{0,1\} && \forall i, j, c, l \\
&QOP_{ijl}, ROP_{ijl} \in \{0,1\} && \forall i, j, l \\
&\mathrm{Z}_{ifl} \geq 0 && \forall i, f, l
\end{aligned}
\tag{2.19}
$$

2.4.2 Illustrative examples

To verify the performance of the proposed models, experiments are conducted on small-sized examples and summarized on two sets of problems. The first set is performed on the LP model with a relaxation of the supply process cost and corresponding constraints (2.6) to (2.8) and (2.17), while the second set considers the entire model (LP). We employed CPLEX (Cplex 9.0) available in the commercial optimization suite OPL Studio 3.7 on an AMD Athlon 2 Core computer (2.20 GHz, 2.00 Go Ram).

In these examples, we assume the same number of operations for all parts to be manufactured and a null reject rate when processing operations. There is a maximum of four operation routings on a part, while we have at most two alternative routings for an operation. The model is also specified by a lower bound of two parts to be assigned to each cell in each plant. We evaluate the potential benefits gained through linked CMS plants integrating the raw material supply process, achieved with routing flexibility inside and outside the first plant visited. Numerical data are based on extensions of data examples gathered from cell design literature (Beaulieu et al. (1997), Mungwattana (2000)).

In the first set of problems, the proposed model LP is solved for a two-plant manufacturing system. The multi-plant manufacturing system should be designed to manufacture 8 parts using 10 machine types. A limit of two cells at each plant is considered. The lower and upper bounds of the number of machines at each cell are 2 and 10, respectively. Material handling cost is fixed at 20 for intercellular flows and at 60 for interplant flows. Tables 2.1 and 2.2 present data for problem 1. Through the first problem, Table 2.3 shows a summary comparison between independent multi-plant facility cell design and linked multi-plant cell design, using different performance measures. In the first design, no interplant flow is allowed, as shown in Table 2.6; in other words, sharing capacities between plants is not allowed. The optimal solution was obtained in around 60.05 seconds. In the second one, manufacturing operations on parts can be completed using more than one plant, with an additional cost called the interplant transportation cost, which is shown in Table 2.7. The optimal solution was obtained in 5560.3 seconds. The second multi-plant CMS design results in savings of 2 machines and an improvement in the overall average machine utilisation rate (AMU) (49.1%) compared with separated CMS plant design (41.66%). Moreover, the two configurations have totally different configurations: the part families and the respective machine cells are dissimilar except for cell 2 in plant 2, which is preserved, as shown in Tables 2.4 and 2.5.

We further illustrate the model using nine other examples. The data of these examples are generated by extending the data in problem 2. The common data are: two manufacturing plants and two cells for each plant. The variable data do not follow any particular pattern, and involve the following:

- Intercellular cost and interplant cost.
- Number of parts.
- Number of machine types.
- Number of operations per part.
- Part demand.

A summary of the impact of sharing machine capacity between plants on the objective cost and the total number of machines obtained for these problems is given in Table 2.8. The last column of this table shows the improvements of the objective function varying from 0% to 8.5%, demonstrating the potential benefit of allowing operation flexibility between plants. This benefit, if realized, is also confirmed by decreasing the total number of machines required to satisfy the annual demand. It can be challenging to improve customer delivery time with such a manufacturing system design when there is demand variability. To attain the optimum, the maximum runtimes were 0.25 hour for independent manufacturing plants and 2 hours for linked manufacturing plants. In problem 7, only a feasible solution is kept after 5 hours running.

Tableau 2-1 Parts demand and operation requirements

Part, i	**Part demand**	**Operation, j**	**Number of alternatives**	**Machine type m, t_{ijm} (h)**
P1	3900	OP11	1	M10 (0.47)
		OP12	2	M5 (0.7), M8 (0.65)
		OP13	1	M2 (1)
		OP14	1	M7 (0.92)
P2	2980	OP11	1	M10 (0.33)
		OP12	1	M4 (0.75)
		OP13	1	M1 (0.5)
		OP14	1	M2 (0.78)
P3	2700	OP11	1	M3 (0.13)
		OP12	2	M2(1), M4(0.55)
		OP13	1	M1(0.5)
		OP14	1	M6(0.93)
P4	2990	OP11	1	M3(1.05)
		OP12	1	M3(0.62)
		OP13	1	M3(0.52
		OP14	1	M1(0.54)
P5	1000	OP11	2	M5(0.35), M8(0.2)
		OP12	1	M4(0.63)
		OP13	1	M5(0.89)
		OP14	1	M3(0.92)
P6	2400	OP11	1	M3(0.13)
		OP12	2	M2(1), M4(0.25)
		OP13	1	M1(0.5)
		OP14	1	M6(0.73)
P7	2500	OP11	1	M3(0.23)
		OP12	2	M2(1), M4(0.65)
		OP13	1	M1(0.7)
		OP14	1	M6(0.73)
P8	2450	OP11	1	M3(0.33)
		OP12	2	M2(1), M4(0.65)
		OP13	1	M1(0.7)
		OP14	1	M6(0.73)

Tableau 2-2 Ressource data

Machine type	Annual fixed cost	Variable cost	Annual Capacity (hour)
M1	52640	24	7000
M2	62800	74	7000
M3	42600	36	7000
M4	72600	40	7000
M5	52550	47	7000
M6	52640	40	7000
M7	62800	28	7000
M8	42600	42	7000
M9	72600	27	7000
M10	52550	49	7000

Tableau 2-3 Some performance measures of multi-plant cellular design (Independent plants, linked plants)

Performance measures	Independent plants	Linked plants	Improvement (%)
Overall cost	2904749.2000	2825829.2000	2.71
CPU time (seconds)	(60.05)	(5349.32.3)	
Fixed machine cost	842060.0000	756860.0000	10.1
Variable and fixed machine cost	2900989.2000	2815789.2000	2.9
Number of machines	16	14	12.5
Intercellular cost	3760	5900	
Number of intercellular flows	4	5	
Interplant cost	0	4140	
Number of interplant flows	0	2	
Overall AMU (%)	41.66	49.1	6.6

Tableau 2-4 Average machine utilisation per cell in multi-plant cell design with independent plants

	Plant 1		**Plant 2**	
Cells	Cell 1	Cell 2	Cell 1	Cell 2
Parts	5,6	4,7	3,8	1,2
Machines	3,8	1,3,4,5,6	1,3,4,6	2,7,8,10
AMU (%)	3.65	56.9	54.7	51.4

AMU %: Average Machine Utilisation percentage

Tableau 2-5 Average machine utilisation per cell in multi-plant cell design with linked plants

	Plant 1		**Plant 2**	
Cells	Cell 1	Cell 2	Cell 1	Cell 2
Parts	3,7	4,6	1,2	5,8
Machines	1,3,4,5,6	3,6	1,4,10	2,3,7,8
AMU (%)	64.4	37.4	46.9	47.7

Tableau 2-6 Multi-plant cell design with independent plants (intercellular flows allowed)

Plant	**Cell**	**Machine type /#**	**Parts**							
			5	**6**	**4**	**7**	**3**	**8**	**1**	**2**
1	1	3	1							
		8		1						
	2	1		1	1	1				
		3(2)	1		1	1				
		4	1	1		1				
		5	1							
		6		1		1				
2	1	1					1	1		1
		3					1	1		
		4					1	1		1
		6					1	1		
	2	2							1	1
		7							1	
		8							1	
		10							1	1

Tableau 2-7 Multi-plant cell design with linked plants

Plant	Cell	Machine type/ #	Parts							
			3	7	4	6	1	2	5	8
1	1	1	1	1	1	1				
		3	1	1	1				1	
		4	1	1		1			1	
		5							1	
		6	1	1						
	2	3			1	1				
		6				1				1
2	1	1						1		1
		4						1		1
		10					1	1		
	2	2					1	1		
		3					1			1
		7					1			
		8							1	

Tableau 2-8 Impact of interplant flows on the objective function value and the machine requirements

Pb	Number of parts	Number of machine types	Independent plants		Linked plants		Improve--ment (%)
			Total design cost	Machine needed	Total design cost	Machine needed	
2	6	10	578521.55	10	529481.55	9	8.5
3	6	10	578521.55	10	531881.55	9	8.06
4	8	10	676966.65	12	637106.65	11	5.8
5	8	10	676966.65	12	638306.65	11	5.7
6	8	10	956380.35	17	956380.35	17	0
7*	12	10	1570587.64	27	1538735.98	26	2.03
8	12	5	513702.40	14	508559.95	12	1.0
9	13	5	608998.08	14	606411.06	12	0.4
10	13	5	608998.08	14	601426.08	12	1.24

*Feasible solution

In the second set problems, the entire model LP detailed in section 2.3 is used. For all the solved examples, the optimum is reached over a maximum running time of 7 minutes for a supply chain with independent manufacturing plants, and over a maximum time of one hour for a supply chain with linked manufacturing plants. In this second set of problems, the supply chain under study consists of two alternative raw material suppliers for a two-plant manufacturing system which should satisfy a known demand. Compared with the relaxed model used in the first set of experiments, although the size of the problem (i.e., the number of variables and constraints) increases, experiments show a decrease in the resolution time compared with the same data problem resolved in the first set problems, which is explained by the addition of supply constraints to the model.

Table 2.9 shows summarized results for eight problems. The fourth column shows the objective function value and the supply cost. The last column presents the improvements realized in the objective function value and the supply cost, respectively. As can be seen from the table, the simultaneous integration of the raw material supply process and the design of a cellular configuration over multiple manufacturing plants have resulted in significant overall improvement, ranging from 2% to 13.1%. Cost savings are generated by the variation of the supply cost coupled with a decreased machine investment cost, explained by a balance cost of the capacity sharing between plants and suitable selection of suppliers.

An experiment was specifically performed for a manufacturing system composed of three plants that would manufacture 12 parts requiring 5 machine types. Each part had a three-operation routing. To complete an operation, at most two alternatives were allowed. The manufacturing system was integrated with the raw material supply processes from 3 alternative suppliers, with each supplier defined by a fixed ordering cost, a variable cost and a capacity limit. As presented in Tables 2.10 and 2.11, the comparison of independent CMS plants and networked plants gives a pattern where the CMS structures of the different plants are partially different. For the networked plants, savings in investment costs are realized when completing operation in another cell of another plant.

Tableau 2-9 Impact of integration of supply process with multi-plant CMS design

			SC with independent plants		**SC with linked plants**		
Problem no	**Number of parts**	**Number of machine types**	**Total cost (supply cost)**	**Machine requirements**	**Total cost (supply cost)**	**Machine requirements**	**Improve--ment (%)**
1	8	10	799086.65 (122120)	12	748006.65 (105800)	11	6.4 (1.3)
2	8	10	1387190.35 (330690)	17	1359409.94 (289050)	17	2.00 (12.6)
3	9	10	2375287.75 (520990)	32	2325633.17 (434050)	32	2.09 (17)
4	10	5	306359.72 (189050)	13	299938.05 (189050)	11	2.09 (0)
5	10	5	976802.70 (212720)	11	848749.72 (189050)	9	13.1 (11.12)
6	12	5	356856.28 (226050)	15	345599.42 (226050)	11	3.15 (0)
7	12	5	475661.73 (251850)	12	450979.42 (226050)	11	5.3 (10.2)
8	12	5	356856.28 (226050)	15	350395.67 (226050)	12	1.8 (0)

Other experiments illustrate two other result patterns. The first demonstrates that machine cells are partially or totally preserved, while part families and supplier selection change totally especially when a flow is allowed between plants. The second shows that the machine cells and part families are preserved however plants where cells (and their corresponding part families) are located, changed.

2.5 Conclusion

This paper considers the problem of integrating CMS design in SC design. Therefore, multi-plant cellular manufacturing design is examined, taking into account cross-linkage between plants and supplier selection. Operation routing is enabled through alternatives paths in a single plant or in the remaining plants. Thus, allowing interplant flows as a novel design feature of a SC will contribute in minimizing equipment investment and give a background to cope with dynamic demand. A nonlinear model is constructed to consider these factors. To demonstrate the potential benefits, a linearized model is proposed. Two sets of small-sized problems are solved using Cplex 9.0, and an analysis of the results shows the usefulness of networked multi-CMS plants and the effect of integrating the supply process in the cell location within a multi-plant manufacturing system. The savings generated with this integration are demonstrated through a comparison of linked multi-plant CMS with independent multi-plant CMS. Moreover, the potential benefits are identified through the decreased total supply chain cost and the improved machine utilisation rate. Such a supply design approach is challenging in helping design capacity in the face of demand variability; a question which is currently under investigation. Further, since the proposed model is NP hard, heuristic approaches are presently under construction, allowing the solution of industrial problem instances and demonstrating realistic supply chain issues.

Tableau 2-10 Multi-plant cell design with three independant plants

	Plant 1		**Plant 2**		**Plant 3**	
Cells	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2
Parts Machines	1,4 1(2)	3,7 1,4	2,8 4,5	5,9 2,3	10,12 2,3	6,11 1,4

Tableau 2-11 Multi-plant cell design with three linked plants

	Plant 1		**Plant 2**		**Plant 3**	
Cells	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2
Parts	1,3	5,9	10,12	7,11	2,8	4,6
Machines	1,5	2,3	2,3	1,4	4,5	1(2)

CHAPITRE 3

ARTICLE 2: MULTI-PLANT CELLULAR MANUFACTURING SYSTEM DESIGN INTEGRATING CUSTOMER ALLOCATION DECISIONS.

Abstract

In this paper, we focus on the design of a multi-plant manufacturing system linked to a number of customer zones with the aim of combining cellular manufacturing advantages and supply chain integration efficiency. In today's supply chain environment, the manufacturing system may be set across multiple plants, and managers face the problem of customer demand allocation decisions in the multi-plant cellular manufacturing system. Thus, a cellular manufacturing system may outperform on each plant when only manufacturing system design is considered, but lack integration of a customer delivery process. To overcome this, we have developed an integrated nonlinear model which determines the selection of plants, the cellular manufacturing structure at each plant, and customer demand allocation. The model introduces originally the multistage part completion and covers many practical parameters of cellular manufacturing. Since it is not practical to solve even the linearized form of the model for real size problems, a multi phase decision making approach is proposed. At first the approach starts by generating an initial solution which is refined through an improved simulated annealing algorithm embedding a solution refinement procedure at the perturbation process, followed by an improvement solution phase. Computational experiments, using the solution approach, on literature data problems confirm the potential of integrated decisions with the developed model over a sequential decision process, and show a significant combined effect of multistage part completion on multi-plant CMS design. Moreover, experimentation shows that the SA-based approach with an improved random perturbation outperforms the same approach with the conventional random perturbation, in terms of solution quality and speed.

3.1 Introduction

Today, the manufacturing environment is characterized by the development of supply chain (SC) networks involving multiple suppliers, multi-plant manufacturing systems and scattered customers. To be competitive, such a system faces the challenge of integrating all decisions, going from the raw material process to delivery to customers. Research on the integrated supply chain design is seen as crucial for practitioners, and is a subject of much focus among researchers.

SC network design identifies the strategic supply chain management process (Simchi-Levi, 1999), and involves the determination of how to structure a supply chain. This design process affects decisions at the manufacturing stage as well as the supply process and the delivery to customers. These integrated decisions bring benefits to the entire SC. Specifically, manufacturing decisions cover the location, the configuration and the capacity of the manufacturing plants, and will simultaneously determine the delivery to customers.

For manufacturers, cellular manufacturing (CM) is a well-known paradigm that provides a competitive advantage, and is defined as a system configuration which brings about several levels of benefits, such as simplified planning and control procedures, reduced throughput times, reduced work-in-process inventory, reduced set-up and reduced material handling (Wemmerlov and Hyer,1989; Marsh et al., 1999). Cellular manufacturing system design includes cell formation, cell layout, operation allocation issues, and short term scheduling and performance evaluation. Cell design or cell formation is the basic step to which other objectives may be added sequentially to realize the true advantages of cellular manufacturing. In a traditional decision making process, strategic facility location decisions and cellular manufacturing design decisions are performed sequentially, resulting in suboptimal supply chain design. This paper therefore addresses the multi-plant design problem with combining CM advantages and integration efficiency to supply chain issues, compared to a CM system which may outperform on each plant when only manufacturing system design is considered, but lack integration of a customer delivery process. Various solution approaches have been used to address the design of a cellular manufacturing system in a bid to propose near-optimal solutions which cannot be achieved using mathematical models. Mansouri et al. (2000) reviewed the modern approaches to multi-criteria cell design, and provide a classification based on input data, criteria, solutions approaches and output across selected literature. A recent review of Papaioannou and Wilson (2010) focuses on solutions approaches and attempts to make a cross-comparison. The authors point out that cell formation must focus on multiple objectives models as well as on applicability in an industrial context, They find that in recent decades, metaheuristics have constituted the approach most commonly used in research, including by Zolfaghari and Liang (1998), Sofianopoulou (1999), Adenso-Díaz et al. (2001), Baykasoglu et al. (2001) and Asokan et al. (2001).Other proposed approaches are hybrid, which combines metaheuristics with a branch-and-bound method (Caux et al., 2000), with large-scale optimization techniques (Nsakanda et al., 2006), or with local search (Jayasawal and Adil, 2004). Throughout the mathematical models developed and the solution approaches used for the cell formation problem, the tendency has been to cover most manufacturing attributes. Among these models and corresponding approaches, production volume, multi-period time horizon, alternative part routing, operation sequence, machine duplication, variable and fixed machine costs, machine capacity, and allowance of intercellular flows have received the most attention with respect to the cell formation problem. Poornachandra and Changkong (2005) attempt to introduce assembly considerations within cell formation. To bring more flexibility to CMS design, the models of Defersha and Chen (2006), Safaei et al. (2008) and Defersha and Chen (2009) are among the models which show a high level of integration of the manufacturing attributes mentioned above; in particular, Ahkoon et al. (2009) further introduced contingency alternate process routings to control machine breakdowns.

Most of the research literature on the cell formation problem assumes that the configuration of a cellular manufacturing system is completed at a single hypothetic manufacturing plant; part demand by scattered customers may be aggregated and assigned to a single manufacturing plant. The issue of responsiveness to multiple customers' demand when cellular manufacturing is performed at more than one plant – and moreover, on networked plants – has however, to the best of our knowledge, not been discussed. In a traditional process, the manufacturing plant locations are selected, and then the manufacturing configuration is performed separately at each plant. However, in today's supply chain environment, when the manufacturing system is set at multiple plants, managers will face the problem of customer demand allocation decisions in the multi-plant cellular manufacturing system. Effective supply chain design decisions are dependent on manufacturing design choices. The choice of a manufacturing configuration: flowshop, jobshop or cellular shop affect the production cost, the manufacturing system performance and the responsiveness to customer demand; consequently, the total supply chain design cost and performance would be affected as well. In a supply chain context, integrated manufacturing system configuration decisions and customer demand allocation will help provide a more accurate evaluation of different designs. Therefore, manufacturing decisions related to a cellular system set at different plants cannot be made independently of customer delivery decisions and of choice of manufacturing plant locations. Hence, in a multi-plant context, the customer delivery performance is dependent on the initial assignment of parts to the manufacturing plants, and consequently, on the assignment of the part families to plants. Accordingly, the location of machine cells in more than one plant becomes another problem to solve in conjunction with the cell formation problem.

The facility location problem was extensively discussed in Daskin (1995), with an emphasis on uncapacitated discrete location models (Uncapacitated Facility Location Problem, UFLP), where various algorithms and corresponding applications are highlighted. The strategic location refers to the location of facilities and allocation of customer demand to those facilities. However, when the maximum capacities of the facilities are introduced as constraints, customers could not be served by the nearest facility, as addressed in Erlenkotter (1978) and Sridharan (1995). Since the location of the manufacturing plant can affect the cost to ship to customers, the location of a machine cell in a multi-plant capacitated manufacturing system can as well affect the delivery performance between the manufacturing stage and the customer zone. Melo et al. (2009) reviewed the facility location models in the context of supply chain management and identified the basic features that such models must capture in order to support the decision-making involved in strategic supply chain planning. Specifically, the authors mention that features such as multiple facility layers, capacities or intra-layer flows are either disregarded or considered in specific aspects. With respect to configuration choices, Vila et al. (2006) introduce a variable decision to select a facility layout in their supply chain design model. However, most of the literature on supply chains as well as the review cited above do not assess the tradeoffs between manufacturing system configuration on a CM basis and the location decisions in a strategic design of a supply chain.

Poornachandra and Mohanty (2003) used an example to explain the interrelation between cellular manufacturing design issues and supply chain design. However, the authors do not provide a mathematical framework for the problem. Multi-plant cellular manufacturing design with supply chain considerations was analyzed and developed in Benhalla et al. (2007), who proposed an integrated mathematical model for a multi-plant cellular manufacturing design on existing plants, taking into consideration the raw material supply process, and linked supplier selection and raw material delivery costs to a multi-plant multistage cellular manufacturing design cost. Schaller (2008) considered the problem of configuring plants on a CM basis to satisfy different market demands. The author proposed a mathematical model and developed a taboo search approach, whose objective was to minimize the sum of the cellular manufacturing cost, the cost of opening plants and the cost of shipping part demand to markets. However, the author's model ignores operation sequence and intercellular flows.

Based on these considerations, the main contribution of this paper is to simultaneously address cellular manufacturing design at multiple manufacturing plants (Multi-plant CMS-SC: a multi-plant cellular manufacturing system in a supply chain context), using well reported manufacturing attributes and the selection of manufacturing facilities from which customer zones demand is delivered. The model bridges several problems: cell formation, machine selection, facility location linked to allocation of customer demand. The model is designed to carry out tradeoffs between three types of costs, namely, opened plant cost, multi-plant cellular manufacturing system cost and delivery cost, subject to manufacturing and delivery constraints. The features distinguishing this from Schaller's model (Schaller, 2008)) are (1) part routings are defined using operation sequence, which allows the control of the intercellular flows, and (2) multistage part manufacturing. Both features aim to increase CM flexibility. Indeed, a disadvantage reported to CM systems involving low utilization machine rates can be improved by intercellular flows in a supply chain context. Specifically, the multistage part completion hypothesis is incorporated to enhance flexibility for both manufacturing and shipping processes. Sharing a machine capacity existing on other manufacturing plants will induce alternative competitive routing of customer demand, concurrently with the total delivery cost to customers. Moreover, in this paper, a more accurate evaluation of the potential of integrating cellular manufacturing decisions with customer demand allocation is presented. To forgo the combinatorial complexity of the mathematical model, a multiphase solution approach combining constructive phases and a simulated annealing phase is proposed. Unlike cell formation approaches using simulated annealing, our approach stands apart with regard to the initial solution generation (random and heuristic) and to the solution perturbation process.

The paper is organized as follows. Section 2 introduces the notations and describes the nonlinear mixed-integer mathematical model, followed by an illustrative example demonstrating the benefits of the integrated model solved with a proposed linear form of the model. Section 3 proposes a solution approach for the model. Experimentation is shown in section 4 to highlight the efficiency of the approach. Finally, a conclusion and future research directions are given in section 5.

3.2 Problem description and mathematical model

The integrated model presented in this paper bridges the multi-plant CMS design with the strategic decision regarding manufacturing plant selection and the customer demand delivery process. The supply chain is defined (Figure 1), with NK scattered customer zones requiring NP parts with different demands. A part may be required by k customer zones ($k = 1,\ldots,NK$).

Parts manufacturing will be performed on a manufacturing system of l potential manufacturing plants located in different areas $(l = 1,...,NL)$, operating as networked processes. Each manufacturing plant is defined by a fixed opening cost and the corresponding cost to ship each part from a plant l to a customer zone k. These plants will manufacture different parts processed on dissimilar machine types, with alternative operation routings, and with given sequences. Each machine type is identified by an annual fixed cost, an annual variable cost and an annual time capacity. In manufacturing design based on CM, machines can be duplicated to meet capacity requirements and to control intercellular flows. In our model, an upper machine cell size is specified. Intercellular flows are allowed in the same plant or between plants. The annual demand for parts is the resultant of different customer zones demand, and is assumed to be deterministic. The flow of finished parts from a manufacturing plant to a customer zone takes place through direct shipping, meaning that the routing problem is not addressed. The model aims to make tradeoffs between four cost components, namely, the total cost of opening manufacturing plants, the total multi-plant machine investment cost, the total cost to deliver demand to customers and the total cost of intercellular flows over the networked plants. Specifically, the model integrates the operation sequence, the interplant link, which should increase operation flexibility (completion of parts in a plant different from the initial plant), and brings alternative routings of customer demand.

The notations and the decision variables used for the model are presented, followed by the model formulation. Next, an illustrative example of the decisions with the integrated model is shown, as compared to decisions made with a sequential approach.

3.2.1 Notation and definition of decision variables

i Index of parts ($i = 1,...,NP$)

j Index of operations ($j = 1,...,NO_i$)

m Index of machine types ($m = 1,...,NM$)

c Index of production cells ($c = 1,...,NC$)

l Index of manufacturing plants ($l = 1,...,NL$)

k Index of customer zones ($k = 1,...,NK$)

NP Number of parts

NO_i Number of operations of part i

NM Number of machine types

NC Number of manufacturing cells

NL Number of manufacturing plants

NK Number of customer zones

Parameters

$D_i = \sum_{k=1}^{NK} d_{ik}$ Annual demand for part i

d_{ik} Annual demand of customer zone k for part i

R_{ij} Reject rate of operation j on part i

DO_{ij} Annual demand for operation j on part i computed with: $DO_{ij} = D_i \Big/ \left(\prod_{k=j}^{NO_i} (1 - R_{ik}) \right)$

a_{ijm} Incidence matrix; =1 if a machine of type m can be used to process operation j on part i; 0 otherwise

t_{ijm} Process time to complete operation j on part i on a candidate machine m

B Batch size for interplant and intercellular flow

A_m Annual time capacity of machine type m

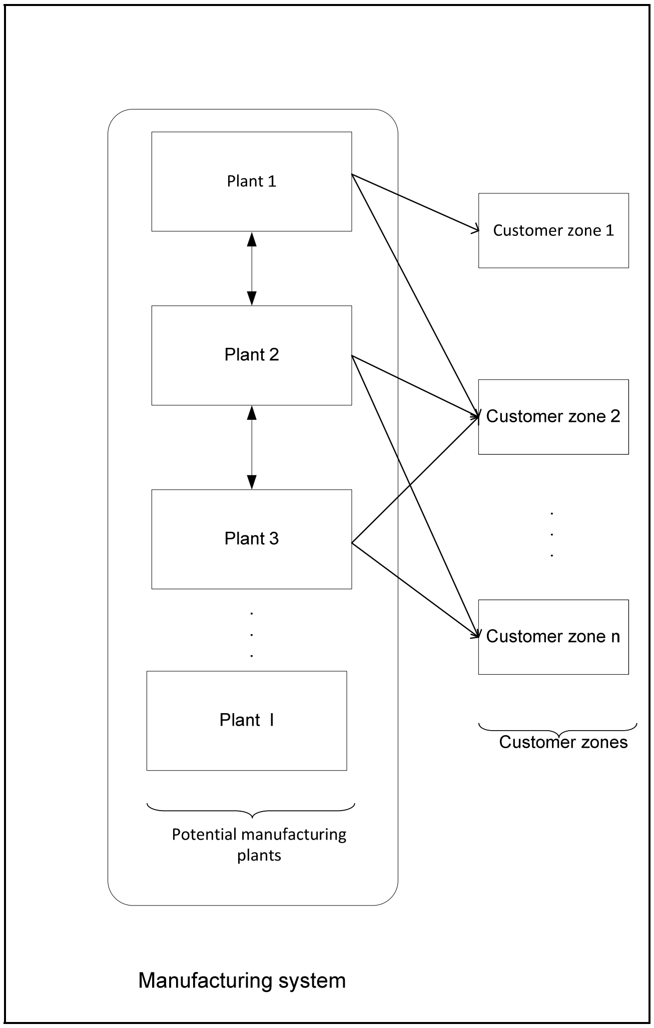

Figure 3-1 Multi-plant manufacturing system

MUT_m Maximum allowable utilization ratio of machine of type m

UT_m Uptime ratio of machine of type m

uu Upper bound cell size

Costs

fc_m Annual fixed cost of machine type m (depreciation)

vc_m Annual variable cost of one fully loaded machine of type m

pc_i Annual fixed cost to open manufacturing plant l

ICC Material handling cost for a batch transferred between two cells

ISC Transportation cost of a batch between two manufacturing plants $ICC < ISC$

sc_{ilk} Unit shipping cost of part i from manufacturing plant l to customer zone k

Model decision variables

N_{mcl}	= Number of machine type m to purchase for cell c in manufacturing plant l
FN_{mcl}	An artificial variable, = Fraction of machine type m for cell c in manufacturing plant l
OP_{ij}^{mcl}	= 1 if operation j on part i is performed on machine m of cell c of the manufacturing l; 0 otherwise.
$XS_{il} = \sum_{c=1}^{NC}\sum_{m=1}^{NM} OP_{i,NO_i}^{mcl}$	An artificial variable, = 1 if part i is shipped from plant l; 0 otherwise.
YS_l	=1 if manufacturing plant l is open; 0 otherwise
Z_r	Cost component of the objectif function $r = 1,..,6$

3.2.2 Model formulation

The MIP formulation of our model is as follows.

(Multi-CMS-SC)

Min

$$\sum_{r=1}^{6} Z_r \tag{3.1}$$

Subject to

$$Z_1 = \sum_{l=1}^{NL}\left(\sum_{c=1}^{NC}\left(\sum_{m=1}^{NM}\left(fc_m \bullet N_{mcl} + vc_m \bullet FN_{mcl}\right)\right)\right) \tag{3.2}$$

$$Z_2 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\sum_{c=1}^{NC}\left| \sum_{m=1}^{NM} OP_{ij}^{mcl} - \sum_{m=1}^{NM} OP_{i,j+1}^{mcl} \right| \tag{3.3}$$

$$Z_3 = -\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left| \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{i,j+1}^{mcl} \right| \tag{3.4}$$

$$Z_4 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left| \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{i,j+1}^{mcl} \right| \tag{3.5}$$

$$Z_5 = \sum_{l=1}^{NL} pc_l \bullet YS_l \tag{3.6}$$

$$Z_6 = \sum_{i=1}^{NP}\sum_{l=1}^{NL}\sum_{k=1}^{NK} sc_{ilk} \bullet d_{ik} \bullet XS_{il} \tag{3.7}$$

$$\sum_{l=1}^{NL}\sum_{c=1}^{NC}\sum_{m=1}^{NM} a_{ijm} \bullet OP_{ij}^{mcl} = 1 \qquad \forall (i, j) \tag{3.8}$$

$$FN_{mcl} = \left(\sum_{i=1}^{NP}\sum_{j=1}^{NO} DO_{ij} \bullet t_{ijm} \bullet OP_{ij}^{mcl} \right) / A_m \bullet UT_m \qquad \forall (m,c,l) \tag{3.9}$$

$$\sum_{i=1}^{NP}\sum_{j=1}^{NO} DO_{ij} \bullet t_{ijm} \bullet OP_{ij}^{mcl} \leq MUT_m \bullet A_m \bullet N_{mcl} \qquad \forall (m,c,l) \tag{3.10}$$

$$\sum_{m=1}^{NL} N_{mcl} \leq uu \bullet YS_l \qquad \forall\ (c,l) \tag{3.11}$$

$$\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} \leq YS_l \qquad \forall (i,j,l) \tag{3.12}$$

$$OP_{ij}^{mcl} \in \{0,1\} \qquad \forall (i,j,m,c,l) \tag{3.13}$$

$$YS_l \in \{0,1\} \qquad \forall\ l \tag{3.14}$$

$$N_{mcl} \text{ integer} \qquad \forall (m,c,l) \tag{3.15}$$

In the above formulation, the objective is to design the multi-plant CMS in a supply chain context (3.1), at a minimum cost, as stated by the sum of equations (3.2) through (3.7). The costs to minimize include production cost ((3.2) through (3.5)), fixed manufacturing facility operating costs (3.5) and shipping costs (3.7). The total shipping cost depends on the assignment of the last operation part which defines the chosen plant to route a customer demand. The production cost is composed of the multi-plant cellular manufacturing system cost, where equation (3.2) represents the sum of the fixed and variable machine costs of all cells set at the opened plants and the multi-plant intercellular cost (3.3) through (3.5). The total cost of intercellular flows is split between two flows types: intra-plant flows and interplant flows.

Two successive operations $j \; and \; j+1$ on a part i can be assigned to the same cell, to different cells located in the same plant, or to two different cells located in different plants. Thus, the term :

$$\sum_{l=1}^{NL}\sum_{c=1}^{NC}\left|\sum_{m=1}^{NM} OP_{ij}^{mcl} - \sum_{m=1}^{NM} OP_{i,j+1}^{mcl}\right|$$

compiles all intercellular flows, irrespective of whether the operations are done in cells located in the same plant or in different plants. However, the following term :

$$\sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP_{i,j+1}^{mcl}\right|$$

counts only intercellular flows between different plants. Naturally, the two-batch intercellular costs satisfy the inequality $ISC > ICC$.

Constraints (3.8) must hold for each operation of each part, meaning that each operation part must be completed on a machine existing in a machine cell and located at an opened manufacturing plant. Equations (3.9) compute the fraction of machines required to satisfy cumulative part demand. Constraints (3.10) impose the condition that in each cell of each opened plant, the generated load on each machine type may not exceed the available annual machine capacity. Constraints (3.11) control the upper cell size in an opened manufacturing plant. Constraints (3.12) ensures that each operation part can be assigned to a manufacturing plant unless it is not open. Binary and non-negativity constraints on the decision variables are enforced through constraint sets (3.13), (3.14) and (3.15).

Other constraints may be added to the model, such as constraining the maximum number of parts to be manufactured in a machine cell or imposing a minimum number of parts assigned to a plant to operate a potential manufacturing plant. A limit l_1 for the number of manufacturing plants visited to complete all the operations of a part may be restricted in the model. The following constraints may be added:

$$\sum_{j=1}^{NO_i}\left(\sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC}OP_{ij}^{mcl}-\sum_{m=1}^{NM}\sum_{c=1}^{NC}OP_{i,j+1}^{mcl}\right|\right)\leq l_1 \qquad \forall\ i \tag{3.16}$$

Additionally, the designer may identify a subset of parts P_1 of the whole set of parts P that should be completed in a single manufacturing plant, this restriction can be enforced through $ISC_i \gg ICC \quad (\forall\ i \in P_1)$.

The proposed model is a nonlinear mixed integer programming model because three absolute terms lie in equations (3.3), (3.4) and (3.5). The complexity of the problem depends on the parameters of the manufacturing and customer delivery stages: the number of potential manufacturing plants, the number of parts, operations and machines, the number of cells to open, the upper cell size and the number of scattered customer zones. However, the size of the model is a function of the manufacturing parameters. The total number of integer variables of the model is:

$$nb_{iv}=\left(\sum_{i=1}^{NP}NO_i\right)\bullet NM\bullet NC\bullet NL+NM\bullet NC\bullet NL+NL \tag{3.17}$$

And the number of constraints is:

$$nb_c=\left(\sum_{i=1}^{NP}NO_i\right)+NM\bullet NC\bullet NL+NC\bullet NL+\left(\sum_{i=1}^{NP}NO_i\right)\bullet NL \tag{3.18}$$

A linearized form for the model is proposed and given in Appendix 1. When a linearization of the model is performed, new integer variables and new constraints sets are added. The number of integer variables increases by $2\left(\sum_{i=1}^{NP} NO_i\right)\bullet NC\bullet NL + 2\left(\sum_{i=1}^{NP} NO_i\right)\bullet NL$ and the number of constraints becomes $nb_c + \left(\sum_{i=1}^{NP} NO_i\right)\bullet NC\bullet NL + \left(\sum_{i=1}^{NP} NO_i\right)\bullet NL.$

Even with the linearized model, the exact solution approach is not practical computationally. For an example of twenty parts, five operations ($NO_i = 5 \ \ \forall i = 1,...,20$) , eight machines, two cells, two potential manufacturing plants and three customer zones, the linearized mixed integer model will have 6450 integer variables and 1196 constraints. Therefore, developing good heuristic approaches is more appropriate in terms of solution efficiency.

3.2.3 Illustrative example

In a traditional decision making process, strategic location decisions and cellular manufacturing design decisions are made sequentially, resulting in suboptimal supply chain design. In this section, we illustrate the benefits obtained by integrating decisions regarding strategic location with cellular manufacturing design decisions, versus an approach in which the decisions are performed sequentially.

The integrated approach uses the linearized model given in Appendix 1, which aims to simultaneously minimize the cellular manufacturing design, the selection and location cost of the manufacturing plants and the shipment cost. The resolution of the model determines the manufacturing plants to open, the cellular structure at each opened plant, and the allocation of customer demand to the selected plants. The constraints of the maximum cell size and the maximum number of cells to form at each manufacturing plant introduce the capacitated facility location problem, which is a component of the problem under consideration.

The sequential approach uses two models denoted *Multi-CMS-SC-a* and *L-Multi-CMS-SC-b*. Both models are particular forms of the model Multi-CMS-SC. The first one ignores production costs and corresponding constraints, while the second disregards shipping costs and only considers one of the selected manufacturing facilities at a time, and attempts to find a cellular configuration subject to manufacturing constraints. The objective of the first model is to minimize the total fixed plant location and shipment cost from the manufacturing plants to the customer zones. This model represents the uncapacitated facility location problem (UFLP), which is clearly reported to be an NP complete problem (Daskin, 1995). The solution of the model gives in a partition of the set of parts required on n different sets, where n will represent the number of opened plants. The partition of parts over the opened plants will be the input for forming machine cells and part families on a plant-by-plant basis, using the second model. At each opened plant, the second model is used to minimize the cellular manufacturing design, which is classified NP complete as well, satisfying the same constraints handled in the proposed model. This step determines the production cost component of the total sequential cost. We then tie together the results obtained for the two models to get the total cost of the sequential approach.

To solve the problem with the two approaches, we develop the corresponding mathematical models using the ILOG OPL Studio 3.5 modeling language, and solve them to optimality with ILOG CPLEX 9.0. We specify here that cell formation at each opened plant is controlled by an upper number of cells and an upper cell size.

The example considers a supply chain context where 8 parts should be manufactured at 2 potential plants, to satisfy 3 customer zone demands. Manufacturing data (operation routing, fixed and variable machine costs) are extracted from Beaulieu et al. (1997). The other required data is presented in Table 3.1, showing the range of the design parameters of the supply chain.

Tableau 3-1 Design parameters used in the comparison of the two approaches

Supply chain parameter	Value
Fixed plant cost	25000
Unit shipping cost	[4,24]
Customer zone demand	[3500,5500]
Fixed machine cost	[2386,8510]
Variable machine cost	[3289,17760]
Operation time	[6,25]
Upper cell size	[4,6]
Upper number of machine cells in a plant	4

Tableau 3-2 Customer demand allocation and multi-plant cellular structure, for the two approaches

Approach	Total cost	Opened Manufacturing Plants	Customer Part Demand Partition	Part Families	Machine Cells
Sequential	343981,8	1	{2,8}	{2,8}	{M1,M2,M3,M4}
		2	{1,3,4,5,6,7}	{3,6,7}	{M2,M3,M6,M7}
				{1,4,5}	{M2,M3,M5,M6}
Integrated	340960 (0.89)	2	{1,2,3,4,5,6,7,8}	{2,6,8}	{M1,M2,M3,M6}
				{1,4,5}	{M2,M3,M5,M6}
				{3,7}	{M3,M4,M7}

For the supply chain configurations displayed in Table 3.2, the results show the total costs for each approach. The value in parentheses below the total integrated cost represents the percentage of cost savings due to integration. It can be seen in Table 3.2 that the partitions of the sets of parts at the potential manufacturing plants were different, with the two approaches used. With the integrated approach, the results show that all customer part demand is satisfied with only one manufacturing plant opened, where a cellular manufacturing design is performed. The part families obtained share manufacturing and delivery similarities. With the sequential approach, the partition of parts gives two part sets, where two manufacturing plants are to be opened to satisfy part demand. At each plant, the part families obtained share only manufacturing similarities.

Figure 3.2 illustrates that the percentage of cost savings due to integration increases as machine costs increase. The percentage rises to 7.31% when the number of potential plants is 2 and the demand originates from 4 customer zones. The results also show that the percentage of cost savings increases when the upper cell size increases. This is expected since increasing cell size contributes to more parts being clustered in a cell, and hence decreases the multi-plant cell machine cost. It can be concluded that the machine cost parameter, the spread of customer demand and the number of manufacturing plants are drivers of cost savings incurred with integration. This illustrative example demonstrates that companies which manufacture parts using large capital equipment will derive significant savings from integrating customer demand allocation and multi-plant cellular manufacturing design.

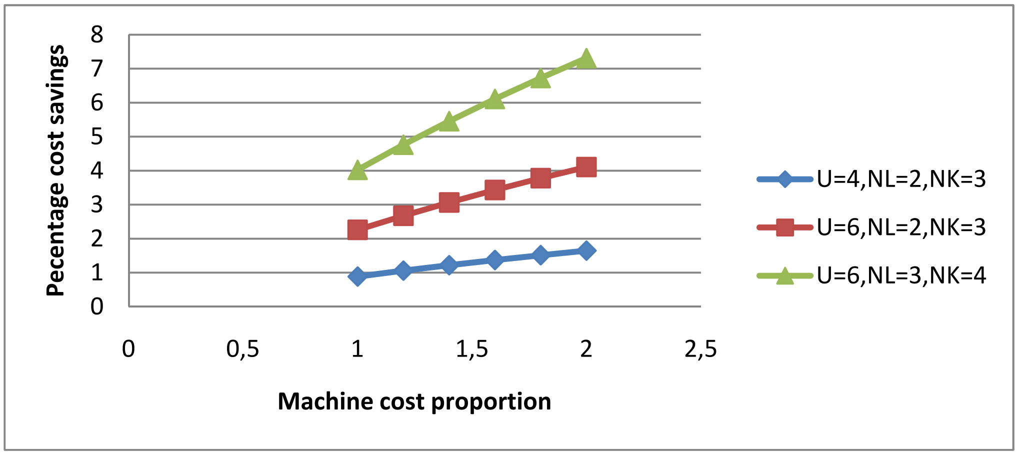

Figure 3-2 Sensitivity of cost savings due to integration, to machine cost variation

3.3 Solution approach

We developed a multiphase heuristic approach based on constructive phases and a simulated annealing phase, to obtain near-optimal solutions (Figure 3.3). The nonlinear structure of the model makes it difficult to obtain a global optimal solution for increased problem sizes, by complicated and time consuming optimization models. For such problems having combinatorial structures (NP-complete), the use of metaheuristic methods is very common (Aarts and Lenstra, 2003). Simulated annealing (SA) is one of these methods, which was reported as a prominent metaheuristic technique in combinatorial problems due to its simple and intelligent structure for searching for the solution space. Furthermore, in cellular manufacturing design literature, simulated annealing is well documented as being an efficient generic probabilistic meta-algorithm compared with taboo search or genetic algorithm approaches (Zolfaghari and Liang, 2002).

The first phase of the approach examines the initial solution generation to be used as an input for the SA phase. The initial solution identifies a supply chain configuration without intercellular flows, and consists of the cell location, the part families' structure and their corresponding machine cells structures, the selected manufacturing plants and the allocation of customer demand. Two approaches are used to generate an initial solution: (1a) a random approach used to generate a feasible solution without considering the number of cells to form, and (1b) a heuristic approach. The latter approach is carried out in two steps: Step (i) generates a cellular manufacturing system based on the whole set of parts, ignoring delivery issues, and based on a cell formation heuristic, while step (ii) generates the customer allocation pattern based on the result of the first step. The second phase uses the initial solution generated to be processed through the SA-based approach as an input. The third and fourth phases of the approach respectively concern the refinement phase of the independent cell configuration and the SA- based phase for the configuration with intercellular flows.

For the cell location/cell formation optimization problem, the SA approach aims to locate a near-optimal solution with regard to the total cost defined in equation (1), in a large search space. Therefore, in this paper, an improved simulated annealing algorithm is presented for the solution of the problem. In the following section, we present the approach details for the four phases shown in Figure 3.3.

3.3.1 Generation of an initial feasible solution

Two initial feasible solution generation approaches (phase 1) are used: random approach (RA) and heuristic approach (HA). The result of one of the approaches will be the input to implement the SA process (phase 2).

The random approach aims to generate a multi-plant cellular manufacturing system which implies random allocation of customer demand. The process is performed with a random assignment of each operation part to a machine, a cell number and to a plant between the potential manufacturing plants. A configuration is generated satisfying at least the maximum machine loading rate. A random feasible configuration will simultaneously identify the set of opened manufacturing plants, the machine cells locations, the machine cells structures and the customer demand allocation.

The heuristic approach is based on a two-step decision making where a constructive heuristic exploits the problem structure to build a solution. The first step consists in defining a manufacturing cellular configuration to the whole set of parts required by customers: identification of part families and the corresponding machine cells. The second step uses this result to generate a minimum allocation solution cost for all customer demand and for the set of manufacturing plants to open. Generating a good initial solution for an SA approach results in fast convergence, as argued by Gu and Huang (1994), Burke et al. (2004) and Safaei et al. (2008).

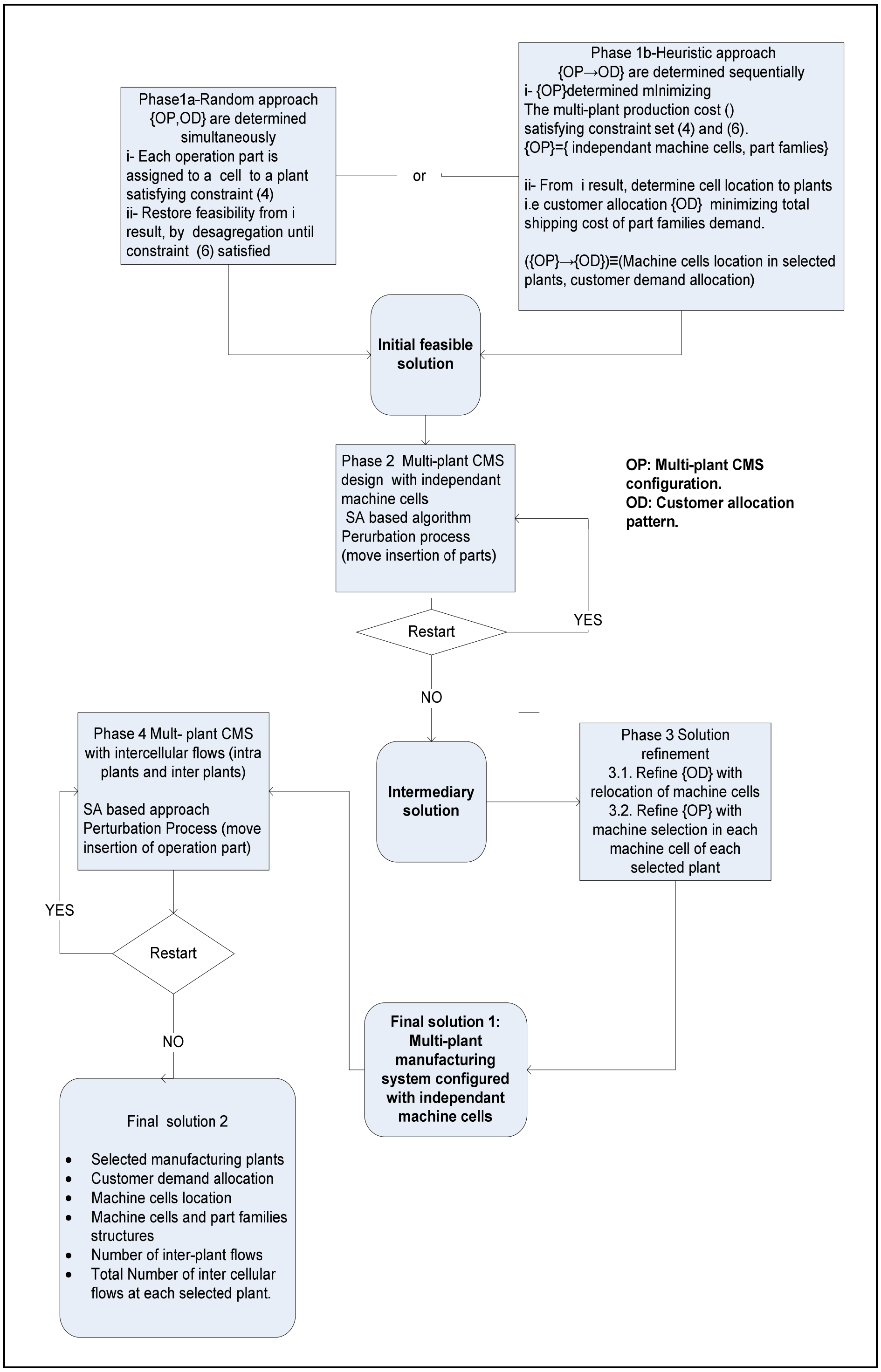

Figure 3-3 The multiphase approach flowchart

Explicitly, for the cell formation process (first step), the aim is to minimise the cell design cost: total of fixed machine cost and variable machine cost, identified through Eq. (3.2), ignoring the manufacturing plant selection and simultaneously satisfying the constraints given in Eqs (3.8), (3.9), (3.10) and (3.11). These constraints will control the size of the machine cells and the machines loading rate. First, the set of parts required by customers is identified, denoted by P, assuming the cumulative part demand. The cell formation algorithm is initiated with a successive aggregation of part families. Initially, each part is assigned to a machine cell containing the required machines. Since part operations may use alternative machines, each aggregation process is followed by a machine selection process, which contributes to decreasing each total machine cell cost. In fact, the machines cells, with a dynamic selection of machines, are gradually merged such that the total machine cost specified above is decreased until a specified number of machines cells is reached. The result of this step is then a set of part families, with their corresponding machine cells. Based on the first step result, the second step is intended to minimize the total shipping cost, given in objective Eq. (3.7), which in turn will define a strategic decision regarding the total cost of open plants, given in Eq. (3.6).

This process consists of computing the marginal cost for shipping customer demand for each part family from each potential manufacturing plant, and then assigning each family to the manufacturing plant corresponding to the least marginal cost, thereby satisfying the constraint of the maximum number of cells at each selected plant; this parameter can be set by the designer. This step determines the number of manufacturing plants to open as well as the allocation of each customer demand to plants. The results of the two steps are tied together to identify the initial feasible configuration of the multi-plant cellular manufacturing system, with the allocation of customer demand and the corresponding total cost solution.

3.3.2 Detailed simulated annealing algorithm

To achieve a simulated annealing process, in addition to generating an initial solution, three other elements are needed: the objective function, the cooling schedule and the neighbourhood search.

The objective function to minimize is represented by equation (3.1) given in section 3, where intercellular movements costs are either ignored (phase 2) or integrated (phase 4), as shown in Figure 3.3. To deal with the constraints of the model, namely, the upper cell size, iterative generation is used during the perturbation process.

The cooling schedule is specified with an initial temperature and a decrement function of successive temperatures defined with: $T_{i+1} = \alpha * T_i, i = 0,1, \ldots,$ where α is a positive constant smaller than but close to 1 (Aarts and Lenstra, 2003).

The definition of a neighbourhood solution is problem-dependent, and is defined through a solution perturbation process. In the implementation of SA in our approach, the originality of the proposed perturbation process of a current solution lies in the improved random perturbation In fact, conventional SA is based on random perturbation (RP), which traps in local optimum and limits the search progress. To alleviate this drawback with SA, different adaptations were used, such as: multiple perturbation operators (Defersha and Chen, 2009), genetic algorithms operators to perturb neighbour solutions (Wu et al., 2009) or adaptive annealing schedules (Aarts and Lenstra, 2003). The main advantage of adding an improvement of a random perturbation (IRP) is that it diversifies the search space, guide moves to best solutions, and expedites the search process. In fact, the improvement process exploits the objective function structure and attempts to upgrade a part of the last perturbed solution cost.

The proposed SA approach uses two types of perturbation operators. While the move insertion of a part is specific to a configuration with independent cells (phase 2), the move insertion of an operation part is applied for configurations allowing interplant flows between opened manufacturing plants resulting from phase 3 (phase 4). The random perturbation process consists of a move insertion of a part in another cell and another plant (phase 2). Before the perturbed solution at a given transition is replaced by a neighbour solution with a best cost or with a non-improving cost accepted with the Metropolis rule (Kirkpatrick et al. (1983), an improvement routine is called to decrease the solution cost. Then, the algorithm continues the usual steps of generating neighbourhood solutions. The first step of this improvement routine is intended to decrease the total production cost (Eq. (3.2)). With the perturbed solution, we obtain a new part family, and consequently, a new machine cell. While the production cost is a component of the total cost, this refinement step aims to minimise the invested machine cost in the cell. This process is aimed at using available alternative routing for parts in the new family so as to minimize the total fixed and variable machine cost for designing the corresponding cell. It is defined as a dynamic selection of machines. The second refinement step aims to decrease the total cost of opening plants and shipping customer demand with a dynamic allocation of customer demand (Eqs. (3.6) and (3.7)). The perturbed configuration differs from the last perturbed one, with a new part family, and with a different structure from which we might generate a new configuration of cell locations with decreased total shipping costs. The result of this routine is identified as a improved random perturbation. With this refined perturbation process, the proposed approach ensures that the best solution in the searched neighbourhood is isolated.

Another feature of the proposed SA-based heuristic (phases 3 and 4) is that in order to improve the solution cost, it allows the solution to be re-annealed a number of times, using the last best solution found as an initial solution. This re-annealing process is performed after an attempt is made to improve the last best solution with a dynamic selection of machines at each cell of the multi-plant CMS, and with new cell locations, decreasing the total shipping cost to customers, which appears in the change of cell location configuration, as compared to the last best solution.

3.4 Experimentation

The aim of this section is to evaluate the multiphase approach designed to solve the integrated model. Through the computational results of examples run based on the literature data, and compared with the best or optimal solution approach, two types of analysis are performed:

- Efficiency of the proposed approach with regard to initial solution generation (random or heuristic), for configurations with independent cells in the multi-plant manufacturing system and to the proposed solution perturbation process.
- Analysis of the effect of integrating interplant flows in the design of the multi-plant cellular manufacturing systems linked to scattered customer zones.

The proposed approach was written using Matlab 7.8. In the SA components; the probability of accepting non-improving solutions is set to 0.5; the temperature decrement factor is 0.98; the maximum number of iterations used is 50, and the annealing process is halted if the last 10 solutions are unchanged. The linearized formulation described in Appendix 1 was implemented using the ILOG OPL Studio 3.5 modeling language, and problems listed in Table 3.3 were solved with standard mathematical programming software, namely, ILOG CPLEX 9.0. Both the experiments with the heuristic and the exact approach were conducted on a dual-core PC with a 2.6 GHz processor and 2 GB of RAM. With the exact solution approach, when the optimal solution was not found within a half hour, the running process was halted, and the best solution found recorded.

Table 3.3 shows the features of each problem. The shared data for all the problems are the range of the shipping cost, the fixed cost to open a manufacturing plant set to 25000, and the range of part demand of each customer zone. Problems are classified with respect to the number of parts to be manufactured, the potential manufacturing plants to open and the number of customer zones to satisfy. Furthermore, Table 3.3 indicates the upper cell size used to satisfy the constraints model equations (3.11) . Problems 2, 3, 6, 7, 8, 9 and 10 use routing data drawn from the literature. Problems 1, 4 and 5 are based on problem 2 data.

3.4.1 Multi-plant manufacturing system with independent cells

Table 3.4 shows the results using the proposed SA-based approach and the performances with respect to the random and the heuristic approaches used in generating the initial solution. This solution is compared to two types of solutions. The first is obtained with the exact solution approach, denoted by “OPT”, while the second is the result of the sequential approach, described in section 3, and denoted by “SEQ”. The first combination, namely, the random approach followed by the SA algorithm, is denoted by “RA+SA”, and the second one, the heuristic approach and the SA algorithm are denoted by “HA+SA”. The same annealing parameters are used for both combinations. As well, for both of them, five replications are performed for each problem. The best results (solution cost and runtime) are recorded. For each problem, columns (1) and (2) respectively give the optimal objective and the corresponding runtime using the exact approach, except for problems 9 and 10, which only records the best solutions.

For the “RA+SA” and “HA+SA” approaches, the objective, the optimality gap and the time are given consecutively in columns (3) to (8). The gap from optimality is computed as: $\mathrm{Opt.Gap}(\%) = ((\mathrm{Z} - \mathrm{Z_{OPT}})/\mathrm{Z_{OPT}}) * 100$, where Z is the solution cost generated either by “RA+SA” or “HA+SA” and $\mathrm{Z_{OPT}}$ is the optimal or the best solution found generated by the optimum procedure. Negative values mean that the solution quality of the heuristic approach is better than the exact method. The result of the comparison of the integrated approach and the sequential approach is shown in column (10) as a cost savings percentage. This percentage is computed using the best solution obtained with the integrated approach, achieved either with the proposed SA approach or the exact solution approach.

Tableau 3-3 Problem features

Problem	Source of part routing data	NP,NM,NO	Alternative routing range	Number of potential mfg. plants	Number of customer zones	Upper cell size
1	Beaulieu et al. (1997)	6,8,3	[1,3]	2	3	4
2	Beaulieu et al. (1997)	8,8,3	[1,3]	2	3	6
3	Beaulieu et al. (1997)	8,8,3	[1,3]	2	2	4
4	Beaulieu et al. (1997)	10,8,3	[1,3]	2	3	4
5	Beaulieu et al. (1997)	10,8,3	[1,3]	2	3	7
6	Wicks and Reasor (1999)	20,11,3	[1,2]	2	3	6
7	Wicks and Reasor (1998)	20,11,3	[1,2]	3	3	6
8	Wicks and Reasor (1998)	20,11,3	[1,2]	3	4	6
9	Viswanathan (1995)	15,15,10	[1,3]	2	3	14
10	Boe and Chang(1991)	35,20,8	[1]	3	4	10

Considering all the problems, as expected, the initial solutions generated heuristically enhance getting better solutions, compared with those generated randomly, especially when the number of potential manufacturing plants increases (problems 8, 9 and 10). Typically, the CPU time of both combinations increase with the size of the problem, especially with respect to the number of potential manufacturing plants and the number of customer zones to satisfy. With the same SA parameter settings, "RA+SA" take more runtime than "HA+SA" to generate a solution. The "HA+SA" approach obtains the best solutions in all the problems, and the solutions may be optimal or near-optimal. In three problems (1, 2 and 8), optimal solutions are found.

For problems 5 through 10, with "HA+SA", there is an average optimality gap of 2.63%. With regard to computational efficiency, for problems 6, 7, and 8 with two manufacturing plants and three customer zones, the proposed solution approach generates a good solution in an average time of less than 184 seconds, compared with the runtime for the optimal solution. The best optimality gap ranges from 0% and 3.91%. The best average runtime seen for a configuration with 35 parts, 3 manufacturing plants and five customer zones was about 470 seconds, which corresponds to the best solution cost compared with that obtained using the exact approach. These observations allow us to conclude that the proposed approach, with a good initial solution, for the integrated model, performs well in terms of solution quality and computational time.

As shown in Table 3.4, the percentage cost savings incurred with integration increases when the size of the problem increases. With all problems, the integrated model with either “OPT” or “HA+SA” produced less total cost than with the sequential approach “SEQ”. Specifically, for problems 1 to 6, the cost savings are computed with optimal solutions for both integrated and sequential approaches, with a maximum cost savings rate of 5.41%. These results demonstrate the accurate potential of integrated decisions respecting the allocation of customer demand to plants and designing multi-plant cellular manufacturing, which would be higher on larger problems. When the size of the problem increases, the exact approach is not efficient, and the magnitude of the cost savings may be approximated using the proposed solution approach. The maximum cost saving percentage of 9.94% is achieved by Boe and Cheng, (1991) problem, and is attributed mainly to opening fewer manufacturing plants, and consequently generating lower total cellular manufacturing cost. The performance of the proposed approach, discussed earlier, allows a confirmation of the consistency of the computed cost savings with integration.

Furthermore, the performance of the proposed perturbation process in the SA component of the proposed approach is demonstrated through a comparison with a conventional random perturbation of a solution, applied alone, as shown in Figures 3.4 and 3.5. The two approaches use the respective solution perturbation with the same SA parameters and the same initial solution. The best performances in terms of solution quality and computation time are clearly achieved with the proposed perturbation process.

Tableau 3-4 Computational results for “OPT”, “RA+SA”, ”HA+SA” and “SEQ” approaches

Pb	Integrated approach								Sequential approach “SEQ”.	Cost Savings-1 (%) (10)
	“OPT”		“RA+SA”			"HA+SA"				
	OBJ (1)	Time (sec.) (2)	OBJ (3)	O-gap (%) (4)	Time (sec.) (5)	OBJ (6)	O-gap (%) (7)	Time (sec.) (8)	OBJ (9)	
1	369685.30	0.55	369685.30	0.00	16.83	369685.30	0.00	10.39	369685.30	0.00
2	511669.00	0.66	512928.556	0.24	25.32	511669.00	0.00	20.23	523232.72	2.26
3	517038.70	4.78	519468.45	0.47	14.64	517038.70	0.00	20.03	521640.34	0.89
4	627480.89	7.28	627497.18	0.00	14.90	627623.15	0.02	21.43	643418.90	2.54
5	633260.78	8.25	640914.26	1.28	14.38	635324.38	0.33	30.10	655171.60	3.46
6	1275886.19	152.25	1294763.83	1.48	41.28	1284500.00	0.68	14.64	1344911.63	5.41
7	805045.94	378.09	805045.94	0.00	88.92	812681.42	0.95	50.82	857695.94[2]	6.54
8	828706.41	1802.3	858006.41	3.54	79.63	828706.41	0.00	149.31	889367.72[2]	7.32
9	1800041.73[1]	1806.76	1825599.80	1.81	199.36	1819000.00	1.05	47.43	1894183.91[2]	5.23
10	841748.35[1]	1805.82	879630.48	9.01	480.07	838452.48	-0.39	457.84	921798.62[2]	9.94

[1] Best solution found with “OPT” method; [2] Best solution found with “SEQ” method

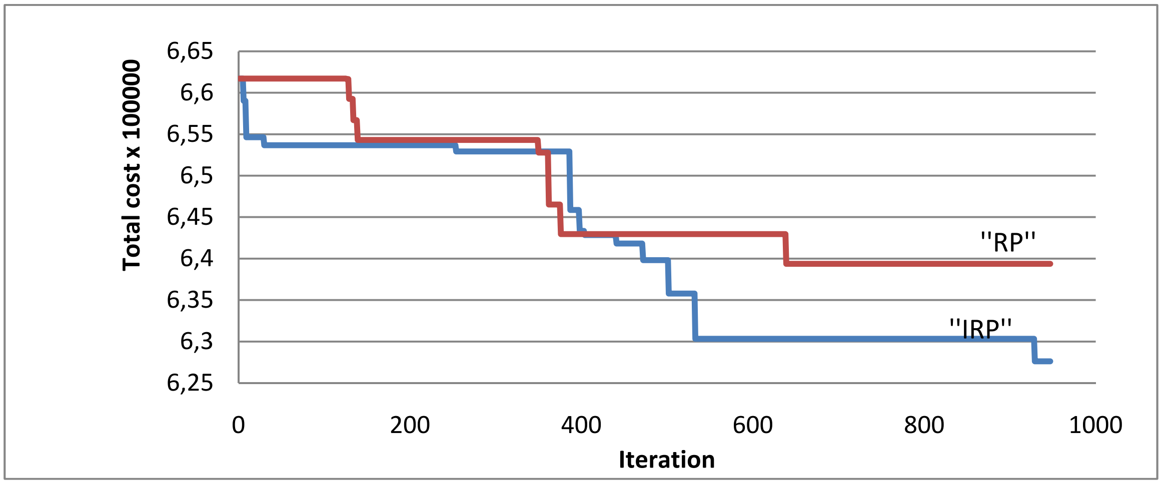

Figure 3-4 Total cost variation comparison with the random perturbation (RP) vs. improved random perturbation (IRP) in the solution approach, for test problem 6

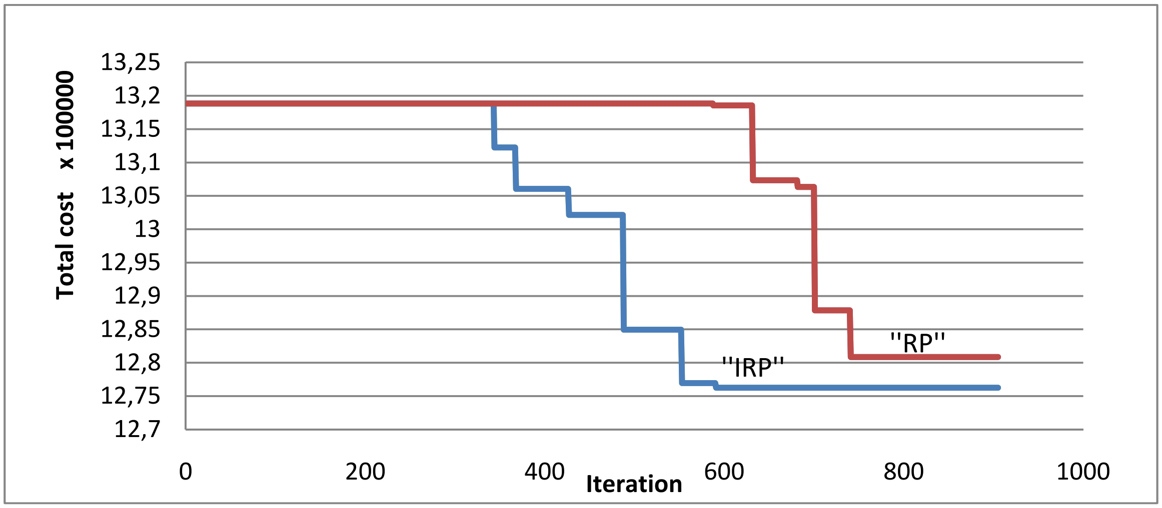

Figure 3-5 Total cost variation comparison with the random perturbation (RP) vs. improved random perturbation (IRP) in the solution approach, for test problem 4

3.4.2 Multi-plant manufacturing system with interplant flows

To introduce the interplant flow in the design of the multi-plant manufacturing system linked to scattered customers, we run phase 4, as shown in Figure 3.3, for the same examples of Table 3.3, using the result of phase 3 of the proposed approach. This input data correspond to the configuration of independent cells obtained with the "HA+SA" approach. The intercell costs ICC and ISC are set respectively to 10 and 20 for problems 1 through 5, and to 20 and 40 for problems 6 through 10.

Table 3.5 displays, for each problem, the best solution for a configuration without interplant flows, shown in column (3), which is used as an initial solution for phase 4 of the solution approach. The best solution cost and the runtime using the exact approach are in columns (1) and (2), respectively. The best of five replications of the solution cost, the optimality gap and the runtime, respectively, are given in columns (4) to (6). Particularly, for each best solution cost, the two types of intercellular costs (total cost of intra plant intercellular flows and total cost of interplant flows).

Considering problems 1 through 6, the approach generates a solution with an average optimality gap of 1.06%, in less than 140 seconds. Problem 7 exhibits the worst optimality gap, explained by the opening of one manufacturing plant and the intensification of intercellular flows in the same plant. For problems 8, 9 and 10, only the best obtained solutions are recorded. For problem 10, the multiphase approach generates the best solution compared with the solution obtained with the exact approach.

As shown in Table 3.5, the percentage of improvement of the initial solution (phase 3) with the phase 4 process varies from 0.14% to 4.35%. Specifically, for problems 2 to 6, 8 and 9, these improvements demonstrate the marginal effect of the integration of multistage completion of manufactured parts when the multi-plant CMS design is performed. An example of the detailed configuration with interplant flows is given in Table 3.6 for problem 5.

Tableau 3-5 Computational results for “OPT” and “HA+SA” approaches for configurations with interplant flows

Pb.	"OPT"		"HA+SA" –phase 4				Improv. (%) (7)	Cost Savings-2 (%)	Cost Savings-3 (%)
	OBJ (1)	Time (sec.) (2)	Initial solution OBJ (3)	OBJ (4)	O-gap (%) (5)	Time (sec.) (6)			
1	364623.31	3.34	369685.30	365305.60	0.19	2.39	1.18	1.20	1.39
	1040.000			990					
	0.000			0					
2	507333.11	26.17	511669.00	510947.88	0.71	1.02	0.14	2.40	3.13
	3420			860					
	2310			2340					
3	505313.30	18.53	517038.70	506760.86	0.29	15.44	1.99	2.94	3.23
	990.00			1900.00					
	2310.00			3450.00					
4	623405.16	13.08	627623.15	626212.42	0.45	13.74	0.22	2.75	3.21
	0.00			1160.00					
	1540.00			3450.00					
5	624232.49	90.06	635324.38	628011.09	0.61	22.17	1.15	4.32	4.96
	1040.00			1770.00					
	3620.00			2340.00					
6	1230595.13	425.52	1284500.00	1261893.83	2.48	99.93	1.76	6.58	9.29
	14680.00			7370.00					
	0.00			5010.00					
7	736059.29	53.52	812681.42	777120.94	5.58	125.22	4.38	10.37	16.53
	12320.00			16400.00					
	0.00			0.00					
8	780341.41	1233.16	828706.41	793456.62	1.68	116.13	4.25	12.09	13.97
	5700.00			14020.00					
	8560.00			10120.00					
9	1769366.17	1806.8	1819000.00	1800680.82	1.77	213.34	1.01	5.19	7.05
	21460.00			15700.00					
	16240.00			5320.00					
10	833356.35*	1917.2	838452.48	820249.35	-0.12	413.12	2.17	12.38	10.61
	21940.00			14440					
	3000.00			0					

The combined effect of integrating multi-plant CMS design and customer allocation decisions with the possibility of completing parts on more than one plant is highlighted by comparing both solutions obtained with “OPT” and with “HA+SA” in phase 4 with the solution of the sequential approach (see Table 5), as shown on the cost-savings columns in Table 3.5.

3.5 Conclusion

In this paper, we have outlined a mathematical model which examines a multi-plant cellular manufacturing system design integrated with a customer delivery process. The main decisions to be made under this model concern the selection of manufacturing plants to open, the allocation of customer demand and the internal CM configuration of each selected plant. The structure of the model handles various manufacturing design parameters, such as operation sequence, intercellular flows and multistage part completion, to enhance manufacturing and customer delivery flexibility. A linear model is proposed to solve small-sized examples. However, due to the complexity of the developed model, a multiphase solution approach is proposed using both constructive search and a modified simulated annealing algorithm, which embeds itself into a solution refinement procedure. Computational experiences show the potential of integrated decisions of allocation of customer demand to selected manufacturing and multi-plant CMS design, compared to a sequential process of decision making. It is also shown that the solution approach with the SA refined perturbation process performs well in terms of solution quality and computation time.

The proposed model could be extended to handle budget restrictions, which constitute a common constraint in a supply chain design model, and may specify machine investments with regard to the location of each potential manufacturing plant. Another extension of the model is to allow the satisfaction of customer demand from different manufacturing plants, which means that part demand can be split and manufactured on at least two plants.Future research will be oriented to improving the computational efficiency of the approach and integrating production planning decisions in dynamic multi-plant CM systems.

Tableau 3-6 Detailed configuration with interplant flows for problem 3 with two manufacturing plants and 3 customer zones

Mfg. Plants	**Part family**	**Parts**	**Operation part (op#)**	**Intercellular flows**	**Machine cells**	**Parts delivered**	**Customer zones satisfied**
1	1	4	[op1[	1a	M1,M2,M4	8	1 and 3
		8	[op1,op2,op3]				
2	2	3	[op1,op2,op3]		M3,M4, M7(2)	1,2,3,4,5, 6 and 7	1,2 and 3
		7	[op1,op2,op3]				
	3	1	[op1,op2[	1b	M5,M6		
		4	]op2,op3]	1a			
		6	]op3]	1b			
	4	1	]op3]	1b	M1,M2, M3(2)		
		2	[op1,op2,op3]				
		5	[op1,op2,op3]				
		6	[op1,op2[	1b			

1a: interplant flows; 1b: intra-plant flows

Appendix 1

In this appendix, we present a linearized mixed integer programming formulation of the proposed model. Three absolute terms lie in equations (3.3), (3.4) and (3.5).

The first absolute term is linearized through the binary variables $MOP_{ijcl} and\ NOP_{ijcl}$ and the second term of overall cost is rewritten as follows:

$$LZ_2 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\sum_{c=1}^{NC}(MOP_{ijcl} + NOP_{ijcl})$$

where the following constraints must be added to the original model

$$MOP_{ijcl} - NOP_{ijcl} = \sum_{m=1}^{NM} OP_{i(j+1)}^{mcl} - \sum_{m=1}^{NM} OP_{ij}^{mcl} \qquad \forall \text{ i, j,c,l}$$

The third and fourth terms in the objective function need the same type of binary variables for linearization $QOP_{ijl} \, and \; ROP_{ijl}$ and are rewritten respectively as follows:

$$LZ_3 = -\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left(QOP_{ijl} + ROP_{ijl}\right)$$

$$LZ_4 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left(QOP_{ijl} + ROP_{ijl}\right)$$

where an additional set of constraints must be satisfied.

$$QOP_{ijl} - ROP_{ijl} = \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP_{i(j+1)}^{mcl} - \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP_{ij}^{mcl} \qquad \forall \text{ i,j,l}$$

The linearized problem of Multi-CMS-SC (L- Multi-CMS-SC) is as follows

(L- Multi-CMS-SC) $\quad Min \ \left(\mathrm{Z}_1 + LZ_2 + LZ_3 + LZ_4 + \mathrm{Z}_5 + \mathrm{Z}_6\right)$

subject to

$$LZ_2 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\sum_{c=1}^{NC}(MOP_{ijcl} + NOP_{ijcl})$$

$$LZ_3 = -\frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left(QOP_{ijl} + ROP_{ijl}\right)$$

$$LZ_4 = \frac{1}{2}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC \bullet \left\lceil \frac{DO_{ij}}{B} \right\rceil \bullet \sum_{l=1}^{NL}\left(QOP_{ijl} + ROP_{ijl}\right)$$

$$MOP_{ijcl} - NOP_{ijcl} = \sum_{m=1}^{NM} OP_{i(j+1)}^{mcl} - \sum_{m=1}^{NM} OP_{ij}^{mcl} \qquad \forall \text{ i, j,c,l}$$

$$QOP_{ijl} - ROP_{ijl} = \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP_{i(j+1)}^{mcl} - \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP_{ij}^{mcl} \qquad \forall \text{ i,j,l}$$

$MOP_{ijcl}, NOP_{ijcl}, QOP_{ijl}, \ ROP_{ijl}$ binary variables

(3) through (9)

CHAPITRE 4

ARTICLE 3: DYNAMIC MULTI-PLANT CELLULAR MANUFACTURING SYSTEM DESIGN WITH SYSTEM CONFIGURATION AND PRODUCTION PLANNING DECISIONS

Abstract

This paper presents an integrated model for a dynamic multi-plant cellular manufacturing system with system reconfiguration and production planning decisions. The model is developed to support strategic and tactical decision making in terms of design of manufacturing plants on a cellular basis and planning production with variations in part mix and volume demand over a multi period planning horizon. The cost based and mixed integer non linear programming model sustain management to make decisions on manufacturing plant selection, dynamic cellular configuration, dynamic customer allocation, carried inventories, backordered demand, subcontracted production and part transfers between manufacturing plants. The manufacturing process is detailed with alternative routings, operation sequence, machine duplication and multi-stage operation completion. A numerical example, followed by a sensitivity analysis is presented to highlight the potential benefits of the dynamic configuration of manufacturing plants with corresponding dynamic multi-plant production plan decisions. Computational results show that a cellular manufacturing system designed on multiple plants with system reconfiguration and production planning decisions increases system flexibility in meeting dynamic demand, and generates significant cost reductions.

4.1 Introduction

Traditional cellular manufacturing design is performed on a single-facility plant in an attempt to define machine cells and part families, with each parts family to be manufactured in its corresponding machine cell, to meet a market demand. This market demand is assumed cumulative because in practice, many customers may need the same part. Proximity, spatial configuration and hierarchical design of facilities are very important since transportation costs represent a significant portion of total costs. Location decisions are therefore critical for systems integrating manufacturing and distribution activities. When the designer is faced with selecting more than one manufacturing plant facility, which should be configured on a cellular manufacturing basis in order to meet different customer part demands, traditional cellular manufacturing system (CMS) design models are inappropriate as they are plant-specific, and do not show the feature of part demand split on more than one customer. The transition from a CMS on a single plant to a CMS on multiple plants may be in response to a company's growth, which calls for a redesign or a reengineering of the manufacturing system in the near future. In fact, the selection of a new manufacturing plant will operate in conjunction with the existing plant to satisfy customer demand. Moreover, in the future, the company may want to meet demand through mixed strategies, including internal production, inventory, and subcontracting, at which time it should adapt the entire cellular configuration of the manufacturing plants, accordingly. As with the single-plant CMS problem, the design in the first period will not be effective for the entire planning horizon (Balakrishnan (2007)).

In today's business environment, product life cycles are short, and demand volumes and product mixes can vary frequently, issues which must be considered when designing cells. It cannot be assumed that a given cell design will remain effective for a considerable period. Ignoring new product introduction and volume fluctuations would necessitate subsequent ad hoc reconfigurations of the CMS, leading to disruptions and unplanned costs (Balakrishnan (2007). Demand fluctuations may be addressed through holding inventory and/or subcontracting a partial demand. However, when this issue is coupled with variable part mixes, carrying inventory and subcontracting options alone may not be sufficient (Defersha and Chen (2008)). Therefore, a dynamic reconfiguration of the manufacturing system may be responsive to frequent changes in volume and part mix. The effectiveness of such decisions depends on the ease which they can be achieved. A lack of integration of these reconfiguration and production planning decisions may lead to less effective layouts over the periods and to unexpected ad hoc reconfiguration costs. In this paper, we thus focus on dynamic multi-plant cellular manufacturing design, with system reconfiguration integrated with production planning decisions in order to meet demand of scattered customers. As the change may also appear in customer mix alongside those in part volume and part mix, the system design will also require a dynamic allocation of customer demand. Consequently, this paper investigates the problem through an integrated model which considers a multi-plant manufacturing system set to satisfy variable part demand coupled with changes in customer mix over a given planning horizon. The model covers a broad range of manufacturing design parameters and focuses on increasing system flexibility through multi-stage part completion and fractional customer demand allocation. It not only determines the dynamic cellular configuration of the manufacturing system, but also selects the manufacturing plants to open, determines the allocation of customer demand, and generates production, inventory and subcontracting decisions, over periods of the planning horizon.

The remainder of the paper is organized as follows. Section 4.2 presents a review of the literature on dynamic cellular manufacturing with production planning decisions and related research, through supply chain design models. Section 4.3 describes the assumptions used in our modeling approach, in which a mixed-integer non-linear programming formulation is presented. Section 4.4 reports on the computational experience through a base case example, involving the solution of a proposed linear model, followed by a sensitivity analysis presented to demonstrate the effect of some parameters on the behaviour of the system studied when the integrated model is used. Finally, Section 4.5 presents our conclusion, and suggests directions for future research.

4.2 Literature review

CMS design under static conditions for long planning periods addresses the cell formation problem (i.e., identification of parts families and machine groups) for a single time period, with a known and constant product mix and demand. However, for a more realistic dynamic situation, a multi-period planning horizon, with a different product mix and demand in each period, must be considered. This occurs in seasonally or monthly production circumstances, and as a result, a cell configuration in a given period may not be optimal in another period. Balakrishnan and Cheng (2007) present a broad review of the dynamic CMS (DCMS) problem, with an emphasis on multi-period planning and uncertainty. They cover research done in the area, and give taxonomy of existing models. To address the problem, several authors, including Chen(1998), Wicks and Reasor (1999), Mungwattana (2000) and Balakrishnan and Cheng (2005), Tavakkoli-Moghaddam et al. (2005), Pillai and Subbarao (2008), have proposed models and solution procedures, which take into account dynamic cell reconfigurations over multiple time periods.

The question of integrating production planning decisions in DCMS models has also been investigated. Chen (2001) proposed a non-linear programming model integrating inventory and production planning in a cellular manufacturing design under dynamic demand and involving a variable product mix, using a decomposition-based heuristic algorithm. Defersha and Chen (2006) developed a comprehensive mathematical model to design cellular manufacturing systems under dynamic demand; the model integrated tool consumption, lot splitting, work load balancing, inventory and subcontracting costs, and distinguished between installing and uninstalling machine costs during system reconfigurations. Subsequently, the same authors, Defersha and Chen (2008), proposed a model also integrating production lot sizing and product quality in the design of cellular systems in a dynamic environment. The model developed aimed to minimise operation, inventory and setup costs. The authors used a linear programming embedded genetic algorithm to solve the problem. Ah Koon et al. (2009) suggested a model similar to that developed by Defersha and Chen (2006), however addressing machine breakdowns with increasing routing flexibility through contingency routings and production planning decisions. Linearization approaches were proposed to analyse the model performance. Recently, Safaei et al. (2009) proposed an integrated mathematical model of multi-period cell formation and production planning in a dynamic cellular manufacturing system (DCMS) with the aim of minimizing machine inter/intra-cell movement, reconfiguration, partial subcontracting, inventory carrying costs and backorder costs.

The main assumption of the abovementioned researches is that customer demand is assigned to an open manufacturing plant. However, in today’s manufacturing environment, when a company needs to meet demand for multiple customers from different plants, the traditional CMS cannot accurately represent all incurred costs. In fact, the manufacturing environment is evolving from a single to a multi-plant operation, with plants acting as a networked manufacturing system when parts require processes in different plants (Lin and Yin-Yann, 2007) or allow material flows between them. In a multi-plant manufacturing system with scattered customers, production performance and distribution performance depend on the assignment of parts and of customers to plants. Decisions are more challenging when manufacturing plants must also be selected. In this integrated system which defines a supply chain, trade-offs must nevertheless be made when tackling facility location, manufacturing, supply and distribution costs. Each of these costs depends on different alternatives, and integrating these elements of a supply chain constitutes a major challenge for a company in today’s increasingly competitive markets.

Through supply chain design literature, many authors attempt to integrate more details of the production stage, characterise selection of manufacturing plants according to different production costs (Talluri and Baker, 2002; Arntzen, 1995) or specify a sequence of operations for a product for which an operation should be assigned to a partner already specified (Pan, 2010). Cohen and Moon (1991) specified production cost functions in a MIP model to determine the optimal assignment of product lines and volumes to a set of capacitated plants. Dogan and Goetschalck (1999) integrated the design of strategic supply chain networks and the determination of tactical production-distribution allocations, in the case of customer demands with seasonal variations. The authors’ model used part processing times and limited capacities expressed both at the machine and at the plant levels. Talluri and Baker (2002) developed a multi-phase mathematical programming approach for effective supply chain design based on a combination of multi-criteria efficiency models. The authors used alternative manufacturers obtained from alternative cellular plant layouts with different performance measures. Moon and Kim (2002) analysed a multi-plant supply chain integrating process planning and scheduling. Hsu and Li (2009) introduces different alternatives of manufacturing plants in the design of a global supply chain identified by capital cost and variable cost for each product at each manufacturing plant. Tsiakis and

Papageorgiou (2008) identifies the production cost as the product of the production rate of each product at each plant, with the unit production cost. Paquet et al. (2008) attempt to explicitly introduce the manufacturing process in the design of a manufacturing network, with the products identified by states to be manufactured in specific mission production centres. Although the research attempts to introduce more details on processing parts and to address operational issues integrated into strategic decisions at the manufacturing level, consideration of manufacturing facility configuration with location decisions is still not addressed. In fact, in configurations such as cellular manufacturing systems, production costs are strongly dependent on the structure of each manufacturing cell, and further, if the configuration is performed in a multi-plant manufacturing system, the multi-plant production cost is also dependent on cell locations within the multi-plant manufacturing system. However, the cellular manufacturing design does not require just detailed data on the parts manufacturing process, but also defined capacities at the machine, cell, and plant levels as well as each customer's part demand.

Decisions that are also related to supply chain design models cover production planning. This aspect is addressed, with an integrated perspective, in Thanh et al. (2008) and Hsu and Li (2009). To plan the expansion of a company that has to face increasing demands, Thanh et al. (2008) propose a mixed integer linear program for the design and planning of a production-distribution system. The program integrates strategic and tactical decisions: opening, closing or expansion of facilities, supplier selection, flows along the supply chain with different carrying inventories and subcontracting options. Hsu and Li (2009) focused on plant capacity and production planning issues in the wafer fabrication industry. They showed that capacity utilization as well as the production amount in the short run, and the capacity of multiple plants, in the long run, are related, and influence the total cost. Another important aspect of the supply chain network is related to flows between manufacturing plants. The review by Melo et al. (2008) emphasized the lack of research addressing intra-layer material flows simultaneously with the location problem. Some authors have addressed this question, including Vila et al. (2006) and particularly, Aghezzaf (2007), who addressed the capacitated supply network model, which allows both resource transfer and material transfer.

Earlier, Sambasivan and Yahiya (2005) used this feature of material transfer in the multi-plant capacitated lot sizing problem where the manufacturing plants already exist. However, a distinguishing feature of our problem in designing a multi-plant CMS is the integration of both inter plant flow and the transfer of parts between plants to be shipped to customer zones from a different manufacturing plant where the parts are manufactured.

The major feature characterising current manufacturing design systems models is the lack of details on manufacturing operations and manufacturing configurations. Specifically, when a cellular manufacturing project is intended for multiple plants over a specified planning horizon, the integration of these details determines the selection of manufacturing plants over the periods as well as the interactions of system reconfigurations with production planning decisions. The designed configuration of such a dynamic networked system is meant to ensure that it is responsive to fluctuations in customer demand. These interactions could be changed at the levels of manufacturing plant and machine cells activation or structure, parts family structure, cell locations, part routings selection and production planning decisions. This research aims precisely to investigate such interactions.

The model to be presented in the following section thus extends beyond the dynamic CMS design on a single plant and manufacturing network design models literature described above by considering broader context decisions. In fact, our model will include a dynamic planning horizon, dynamic system reconfiguration and production planning decisions (i.e., internal production, inventory, backordered demand and subcontracting, and parts transfer between plants). This paper proposes a model that extends previous models in Benhalla et al., (2007) with contributions to dynamic reconfiguration, coupled with multi-plant production planning decisions. Dynamic reconfiguration implies that from one period to the next, parts families may vary, as may machine cells locations and structures as well. Accordingly, a part demand may be shipped to a customer using a different routing (i.e., it may be shipped from a different plant, where the part was manufactured). Moreover, shipped demand to customers may originate from mixed alternatives of internal production, inventory, transferred parts, and subcontracting. The model attempts to balance the activation cost of manufacturing plants, the machine investment costs with reconfiguration and production planning costs.

4.3 Problem formulation

The system studied (Figure 4.1) consists of a manufacturing system of NL potential production facilities which may manufacture any of NP parts required by NK scattered customer zones, with part demand defined over a planning horizon of H periods: $dc_{ik}^{h}:\ i=1,..NP,\ k=1,..NK,\ h=1,..H$. The manufacturing capacity is defined at the machine, machine cell and plant levels. To optimize the total design cost of the multi-plant cellular manufacturing system ($\left\{CMS_{l}^{h}\right\}: l=1,..NL, h=1,..H$), with system reconfiguration and production planning decisions, the design model integrates the balance of machine capacity with different strategies to satisfy customer demand; the strategies include internal production, carried inventory, backorder, and/or subcontracting. Furthermore, the designed manufacturing network allows a fractional allocation of customer demand and the transfer of parts, within a specified period, between plants (tr_{i}^{h}), when necessary, to meet customer demand.

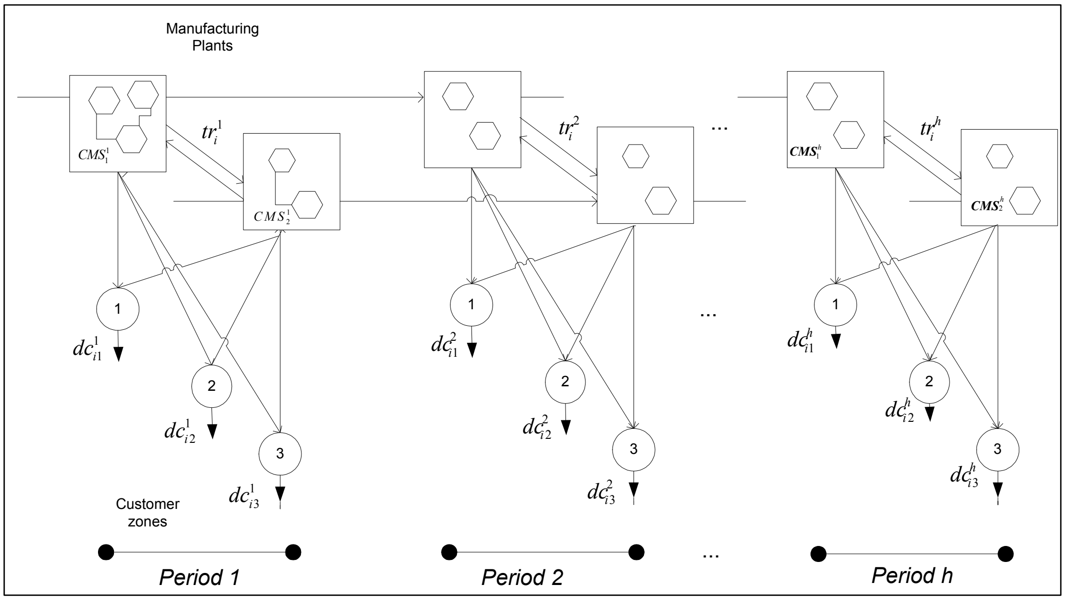

Figure 4-1 A multi-plant manufacturing system representing the problem

The following section develops a mathematical model for the problem when customer demand is dynamic and deterministic. The main assumptions, the different notations and the decision variables, under which the model is formulated, are detailed.

4.3.1 Assumptions

1) The period in the planning horizon may be three months, six months or one year.
2) The cumulative demand for a part is split between different customer zones. The demand for each part and each customer zone in each period is known and deterministic. Customer demand can be satisfied through mixed strategies: internal production, subcontracting or held inventory. Backorders are allowed. In the last period, all customer demand must be satisfied.
3) Each part is defined by a sequence of operations. Each operation part may be performed on different machine types with different and known processing times.
4) Installing or removing costs of a unit of machine type from a cell between periods are known and set at different values (Defersha and Chen, 2006).
5) Two types of intercellular flows between cells in the manufacturing system are allowed. Parts may be completed by sharing resources in the same manufacturing plant or in a different manufacturing plant, with different unit costs.

4.3.2 Notation and definition of decision variables

Model indices

h	Index of time periods ($h = 1,..,H$)
i	Index of parts $(i = 1,..,NP)$
l	Index of manufacturing plants $(l = 1,...,NL)$
m	Index of machine types $(m = 1,..,NM)$

j	Index of operations of part i $\left(j = 1,..,NO_i \right)$
c	Index of manufacturing cells $\left(c = 1,..,NC \right)$
k	Index of customer zones $\left(k = 1,..,NK \right)$

Model parameters

H	Number of time periods in the planning horizon
NP	Number of parts
NO_i	Number of operations of part i
NM	Number of machine types
NC	Number of manufacturing cells
NL	Number of manufacturing plants
NK	Number of customer zones
dc_{ik}^{h}	Demand of customer zone k for part i in period h
t_{ijm}	Process time to complete operation j on part i on a candidate machine m
$a_{ijm} = 1$	if a machine of type m can be used to process operation j on part i, = 0 otherwise
B	Batch size for inter-plant and intercellular flow
MUT_m	Maximum allowable utilization ratio of machine of type m
UT_m	Uptime ratio of machine of type m
A_m	Time capacity of machine of type m over the planning horizon
UB	Upper bound cell size

Costs

fc_m	Fixed cost of machine type m at each period
vc_m	Variable cost of one fully loaded machine of type m at each period
f_i	Fixed cost to open a plant l at each period

icc	Material handling cost for a batch transferred between two cells
isc	Transportation cost for a batch between two manufacturing plants
ϕ_m^1	Cost incurred to add one machine of type m
ϕ_m^2	Cost incurred to remove one machine of type m
φ_i^+	Inventory carrying cost per unit per time period of part i
φ_i^-	Backorder cost per unit per time period of part i
η_i	Unit cost of subcontracting part i
γ_{ilk}	Unit cost to ship part i from manufacturing plant l to customer zone k
$\tau_{ill'}$	Unit cost to transfer part i from plant l to plant l' at the end of period h
M	Large positive number

Model decision variables

N_{mcl}^h	Number of machines of type m in cell c in manufacturing plant l during period h
FN_{mcl}^h	Fraction of machine of type m needed for cell c in manufacturing plant l during period h
K_{mcl}^{h+}	Number of machines of type m to add for cell c in manufacturing plant l during period h
K_{mcl}^{h-}	Number of machines type m to remove from cell c in manufacturing plant l during period h
OP_{ij}^{mclh}	=1; if operation j on part i is performed on machine of type m in cell c of the manufacturing plant l during period h , 0 otherwise.
PQ_{ih}	Produced quantity of part i during period h
YP_{ih}	=1; If $PQ_{ih} > 0$, 0 otherwise
PQ'_{ilh}	Produced quantity of part i in manufacturing plant l during period h

SQ_{ilh}	Subcontracted quantity of part i to manufacturing plant l during period h
I^{+}_{ilh}	Inventory level of part i in manufacturing plant l during period h
I^{-}_{ilh}	backorder of part i in manufacturing plant l during period h
$tr^{h}_{ill'}$	Amount of part i transferred from plant l to plant l' at the end of period h;
SD^{h}_{ilk}	Shipped demand of part i from plant l for customer zone k at period h
W_{ilh}	Artificial variable indicating if part i is completed in plant l at period h

4.3.3 Mathematical model

Min

$$\begin{aligned}
&\left(\sum_{h=1}^{H}\left(\sum_{l=1}^{NL}\left(\sum_{c=1}^{NC}\left(\sum_{m=1}^{NM}\left(fc_m \bullet N^{h}_{mcl} + vc_m \bullet FN^{h}_{mcl}\right)\right)\right)\right)\right)\\
&+\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i} ICC\bullet\left\lceil \frac{PQ_{ih}}{B}\right\rceil \bullet\sum_{l=1}^{NL}\sum_{c=1}^{NC}\left|\sum_{m=1}^{NM} OP^{mclh}_{ij} - \sum_{m=1}^{NM} OP^{mclh}_{i,j+1}\right|\\
&-\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i} ICC\bullet\left\lceil \frac{PQ_{ih}}{B}\right\rceil \bullet\sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP^{mclh}_{ij} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP^{mclh}_{i,j+1}\right|\\
&+\frac{1}{2}\sum_{\mathrm{h}=1}^{\mathrm{H}}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i} ISC\bullet\left\lceil \frac{PQ_{ih}}{B}\right\rceil \bullet\sum_{l=1}^{NL}\left|\sum_{m=1}^{NM}\sum_{c=1}^{NC} OP^{mclh}_{ij} - \sum_{m=1}^{NM}\sum_{c=1}^{NC} OP^{mclh}_{i,j+1}\right|\\
&+\sum_{h=1}^{H}\sum_{l=1}^{NL} f_l \bullet Z_{lh} + \sum_{h=1}^{H}\sum_{l=1}^{NL}\sum_{m=1}^{NM}\left(\phi^{1}_{m}\bullet \mathrm{K}^{h+}_{mcl} + \phi^{2}_{m}\bullet \mathrm{K}^{h-}_{mcl}\right)\\
&+\sum_{h=1}^{H}\sum_{l=1}^{NL}\sum_{i=1}^{NP}(\varphi^{+}_{i}\bullet I^{+}_{ilh} + \varphi^{-}_{i}\bullet I^{-}_{ilh}) + \sum_{h=1}^{H}\sum_{i=1}^{NP}\eta_i \bullet SQ_{ilh}\\
&+\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{l=1}^{NL}\sum_{k=1}^{NC}\gamma_{ilk}\bullet SD^{h}_{ilk} + \sum_{h=1}^{H}\sum_{l\neq l'}^{NL}\sum_{i=1}^{NP}\tau_{ill'}\bullet tr^{h}_{ill'}
\end{aligned} \tag{4.1}$$

Subject to

$$\sum_{l=1}^{NL}\sum_{c=1}^{NC}\sum_{m=1}^{NM} a_{ijm} * OP^{mclh}_{ij} = YP_{ih} \quad \forall i,j,h \tag{4.2}$$

$$Z_{lh} \leq Z_{l,h+1} \qquad \forall l,h \tag{4.3}$$

$$\sum_{c=1}^{NC}\sum_{m=1}^{NM} OP_{ij}^{mclh} \leq Z_{lh} \qquad \forall i,j,l,h \tag{4.4}$$

$$FN_{mcl}^{h} = \left(\sum_{i=1}^{NP}\sum_{j=1}^{NO_i} PQ_{ih} \bullet t_{ijm} \bullet OP_{ij}^{mclh} \right) / A_m \bullet UT_m \qquad \forall m,c,l,h \tag{4.5}$$

$$\sum_{i=1}^{NP}\sum_{j=1}^{NO_i} PQ_{ih} \bullet t_{ijm} \bullet OP_{ij}^{mclh} \leq MUT_m \bullet A_m \bullet N_{mcl}^{h} \qquad \forall m,c,l,h \tag{4.6}$$

$$\sum_{m=1}^{NL} N_{mcl}^{h} \leq UB \bullet Z_{lh} \qquad \forall c,l,h \tag{4.7}$$

$$N_{mcl}^{h} + \mathrm{K}_{mcl}^{h+} - \mathrm{K}_{mcl}^{h-} = N_{mcl}^{h+1} \qquad \forall m,c,l,h \tag{4.8}$$

$$\sum_{l=1}^{NL} SD_{ilk}^{h} = dc_{ik}^{h} \quad \forall i,k,h \tag{4.9}$$

$$\begin{aligned} I_{ilh}^{+} &= I_{il,h-1}^{+} + I_{ilh}^{-} - I_{il,h-1}^{-} + \sum_{\substack{l'=1\\ l\neq l'}}^{NL} tr_{il'l}^{h} - \sum_{\substack{l'=1\\ l\neq l'}}^{NL} tr_{ill'}^{h} \\ &+ PQ_{ih} \bullet W_{ilh} + SQ_{il,h-l} - \sum_{k=1}^{NK} SD_{ilk}^{h} \qquad \forall i,l,h \end{aligned} \tag{4.10}$$

$$\begin{aligned} I_{ilH}^{+} &= 0 \quad \forall\ (i,l), \\ I_{ilH}^{-} &= 0 \quad \forall\ (i,l) \end{aligned} \tag{4.11}$$

$$PQ_{ih} \leq M \bullet YP_{ih} \qquad \forall i,h \tag{4.12}$$

$$SQ_{ilh} \leq M \bullet Z_{lh} \qquad \forall i,h; \tag{4.13}$$

$$\begin{aligned} & OP_{ij}^{mclh} \in \{0,1\} \ \forall\ (i,j,m,c,l,h), \\ & Z_{lh} \in \{0,1\} \ \forall\ (l,h), \\ & YP_{ih} \in \{0,1\} \ \forall\ (i,h), \\ & PQ_{ilh}, SQ_{ilh}, I_{ilh}^{+}, I_{ilh}^{-} \geq 0 \text{ and integer } \forall\ (i,l,h), \\ & N_{mcl}^{h}, \mathrm{K}_{mcl}^{h+}, \mathrm{K}_{mcl}^{h-} \geq 0 \text{ and integer } \forall\ (m,c,l,h). \end{aligned} \tag{4.14}$$

The objective function consists of the sum of ten cost terms. These costs are conflicting, and the optimization of the total cost is aimed at simultaneously determining the selection of manufacturing plants to open, the optimal allocation of customer demand to plants, the optimal configuration of the multi-plant CMS and the optimal production plan. Each of these elements, addressed alone, is combinatorial. Therefore, to balance the designed capacity (open plants, number of machines) with the strategies to store parts for future demand or subcontract partial demand based on competitive part assignment to selected plants, the model under study seeks a solution between more combinations than are present in DCMS.

The first term represents the sum of the constant and variable machine cost over the planning horizon. The constant cost is computed using all the machines required in all the cells located at all the manufacturing plants over the considered planning horizon. The variable cost depends on the machine utilization ratio, and is the sum of the operating costs for all the machines needed in all the cells in all the selected manufacturing plants over the planning horizon. The sum of the second term and the third term is the batch intercellular cost for flows between cells located in the same manufacturing plant. The amount of these flows is computed as the difference between all inter-cell flow types in the entire manufacturing system and the inter-plant flows. However, the fourth term is the sum of all inter-plant flow costs incurred between cells located in different manufacturing plants. This cost is proportional to the number of batches moved between two cells, irrespective of whether the move occurs in the same plant or between different manufacturing plants. The fifth term stands for the sum of all the fixed costs of opening a manufacturing plant during a period in the horizon. The sixth term is the reconfiguration cost, the summing costs of added machines and removed machines in all cells at all manufacturing plants. Unit costs ϕ_m^1 and ϕ_m^2 introduce the feasibility of adding or removing machines, ϕ_m^1 defines the cost of installing new machine in a cell and ϕ_m^2 defines the cost of uninstalling a new machine in a cell; to avoid reconfiguration costs in the optimal solution, these costs may be set very high. The seventh term sums the total inventory carrying cost and the backordered demand cost. The eighth term represents the total cost of subcontracting partial part demands incurred in the planning horizon; we assume that the subcontracting cost includes the cost of transportation to the manufacturing plant. The nineth term is the total distribution cost of all customer zones' demands over the planning horizon. The total cost of transferring parts between plants over the planning horizon is introduced in the last term.

The constraints (4.2) ensure that each part operation is assigned to one machine, one cell and one manufacturing plant if the part is manufactured during a given period. Constraints (4.3) enforce that a manufacturing plant cannot be closed in the subsequent period if it is open in the current period. Constraints (4.4) ensure that each part operation is assigned to one machine and one cell and one manufacturing plant only if the manufacturing plant is open, which will allow the avoidance of interplant flows. Constraints (4.5) define the machine fraction needed to satisfy part demand.

Constraints (4.6) ensure that machine capacities satisfy internal production requirements. Constraints (4.7) specify the cell size upper bound. Constraint (4.8) ensures the balance of machines between two successive periods for each cell in each manufacturing plant. In other words, the number of machines in the current period is equal to the number of machines in the previous period plus the new machines being installed minus the machines being moved. Constraints (4.9) ensure, for each part, the balance of each customer demand with the total shipments to the customer zone, over a given period. Constraints (4.10) show the balance of inventories at each manufacturing plant between two successive periods; it guarantees that the total shipments to all customer zones in each period, are satisfied from internal manufacturing and/or subcontracted manufacturing, and /or inventory carried over the previous period, and/or from transferred parts between plants. Backorders are also allowed, and the amount $(I^{+}_{ilh} - I^{-}_{ilh})$ represents the net inventory of part i at manufacturing plant l at the end of period h .The term $PQ_{ih} \bullet W_{ilh}$ in (4.10) identifies the produced quantity of part i if it is completed in the manufacturing plant l during the period h . Constraints (4.11) indicate that inventory and backorder levels of each part in the last period are set to zero, which means that all customer demand must be satisfied during the planning horizon. Constraints (4.12) are linked to constraints (4.2), and define internal production quantities when the production option occurs during period h. Constraints (4.13) specify that the subcontracting option is not allowed unless the manufacturing plant l is open. Binary and non-negativity constraints on decision variables are enforced through constraint set (4.14).

4.3.4 Linearization

The model is a nonlinear mixed integer programming model because of the nonlinear terms in the objective function terms and in the constraints (4.5), (4.6) and (4.10). A simultaneous occurrence of a product of integer variables with 0-1 variables and absolute terms can be found the second and third terms of (4.1) Some additional variables should be defined in order to linearize the model.

To remove absolute terms, we introduce binary variables and new constraints. The first absolute term is linearized through the binary variables $MOP_{ijcl}^{h} and\ NOP_{ijcl}^{h}$ and the corresponding cost is rewritten as follows:

$$\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC\bullet\left\lceil\frac{PQ_{ih}}{B}\right\rceil\bullet\sum_{l=1}^{NL}\sum_{c=1}^{NC}(MOP_{ijcl}^{h}+NOP_{ijcl}^{h}) \tag{4.15}$$

where the following constraints must be added to the original model

$$MOP_{ijcl}^{h}-NOP_{ijcl}^{h}=\sum_{m=1}^{NM}OP_{i,j+1}^{mclh}-\sum_{m=1}^{NM}OP_{i,j}^{mclh} \qquad \forall\ (i,j,c,l,h\ ) \tag{4.16}$$

The third and fourth terms in the objective function need the same type of binary variables for linearization $QOP_{ijl}^{h} and\ ROP_{ijl}^{h}$ and are rewritten respectively as follows:

$$-\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC\bullet\left\lceil\frac{PQ_{ij}}{B}\right\rceil\bullet\sum_{l=1}^{NL}\left(QOP_{ijl}^{h}+ROP_{ijl}^{h}\right) \tag{4.17}$$

$$\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC\bullet\left\lceil\frac{PQ_{ij}}{B}\right\rceil\bullet\sum_{l=1}^{NL}\left(QOP_{ijl}^{h}+ROP_{ijl}^{h}\right) \tag{4.18}$$

where an additional set of constraints must be satisfied

$$QOP^{h}_{ijl} - ROP^{h}_{ijl} = \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP^{mclh}_{i,j+1} - \sum_{c=1}^{NC}\sum_{m=1}^{NL} OP^{mclh}_{i,j} \qquad \forall\,(i,j,l,h) \tag{4.19}$$

To remove the product of decisions variable in (1-b) and (1-c), we introduce new variables Q^{1}_{ijclh} and the corresponding objectives become:

$$\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC\bullet\left\lceil \frac{Q1^{lh}_{ijc}}{B}\right\rceil \tag{4.20}$$

The following constraints are then added to the model:

$$\begin{aligned} Q^{1}_{ijclh} &\geq PQ_{ih} - M(1 - MOP^{h}_{ijcl} - NOP^{h}_{ijcl}) \quad \forall(i,j,c,l,h) \\ Q^{1}_{ijclh} &\leq PQ_{ih} + M(1 - MOP^{h}_{ijcl} - NOP^{h}_{ijcl}) \quad \forall(i,j,c,l,h) \end{aligned} \tag{4.21}$$

Eq. (4.20) forces $Q^{1}_{ijclh} = PQ_{ih}$ if operations j and $j+1$ are performed on different cells, otherwise Q^{1}_{ijclh} is equal to zero.

Similarly, absolute terms in the third and fourth terms will be rewritten respectively as follows:

$$-\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ICC\bullet\left\lceil \frac{Q^{2}_{ijlh}}{B}\right\rceil \tag{4.22}$$

$$\frac{1}{2}\sum_{h=1}^{H}\sum_{i=1}^{NP}\sum_{j=1}^{NO_i-1} ISC\bullet\left\lceil \frac{Q^{2}_{ijlh}}{B}\right\rceil \tag{4.23}$$

And new constraints are added.

$$\begin{aligned} Q_{ijlh}^{2} &\geq PQ_{ih} - M(1 - QOP_{ijl}^{h} - ROP_{ijl}^{h}) \quad \forall (i,j,l,h) \\ Q_{ijlh}^{2} &\leq PQ_{ih} + M(1 - QOP_{ijl}^{h} - ROP_{ijl}^{h}) \quad \forall (i,j,l,h) \end{aligned} \tag{4.24}$$

Eq. (23) forces $Q_{ijlh}^{2} = PQ_{ih}$ if operations j and $j+1$ are performed on different manufacturing plants, otherwise Q_{ijlh}^{2} is equal to zero.

Similarly, the nonlinear term $PQ_{ih} \bullet OP_{ij}^{mclh}$ used to compute the variable machine cost, introduced in the constraints sets (4) and (5) is removed through a new variable Q_{ijmclh}^{3} allowing the corresponding constraints to be rewritten as follows:

$$FN_{mcl}^{h} = \left(\sum_{i=1}^{NP} \sum_{j=1}^{NO} Q_{ijmclh}^{3} \bullet t_{ijm} \right) / \, A_m \bullet UT_m \quad \forall m,c,l,h \tag{4.25}$$

With new constraints:

$$\begin{aligned} Q_{ijmclh}^{3} &\geq PQ_{ih} - M(1 - OP_{i,j}^{mclh}) \quad \forall (i,j,m,c,l,h) \\ Q_{ijmclh}^{3} &\leq PQ_{ih} + M(1 - OP_{i,j}^{mclh}) \quad \forall (i,j,c,m,l,h) \end{aligned} \tag{4.26}$$

Likewise, Eq. (4.27) forces $Q_{ijmclh}^{3} = PQ_{ih}$ if operation j on part i is performed on machine m of cell c at the manufacturing plant l, otherwise Q_{ijclh}^{3} is equal to zero.

Consequently, the constraints set (4.6) will be rewritten:

$$\sum_{i=1}^{NP} \sum_{j=1}^{NO} Q_{ijclh}^{3} \bullet t_{ijm} \leq MUT_m \bullet A_m \bullet N_{mcl}^{h} \qquad \forall (m,c,l,h) \tag{4.27}$$

Similarly the nonlinear term $PQ_{ih} \bullet W_{ilh}$ in constraint (4.9) is removed by adding integer variables Q_{ilh}^{4} where $Q_{ilh}^{4} = PQ_{ih} \bullet W_{ilh}$ which must satisfy the following constraints:

$$\begin{aligned} Q^4_{ilh} &\geq PQ_{ih} - M(1-W_{ilh}) \quad \forall(i,l,h) \\ Q^4_{ilh} &\leq PQ_{ih} + M(1-W_{ilh}) \quad \forall(i,l,h) \end{aligned} \tag{4.28}$$

The linear integrated model is now:

Min

$$\begin{aligned} &\left(\left(\sum_{h=1}^{H}\left(\sum_{l=1}^{NL}\left(\sum_{c=1}^{NC}\left(\sum_{m=1}^{NM}\left(fc_m \bullet N^h_{mcl} + vc_m \bullet FN^h_{mcl}\right)\right)\right)\right)\right)\right) \\ &+ \text{Eq.(22)+Eq.(24)+Eq.(25)} \\ &+ \text{Eq.(1-d)+Eq.(1-e)+Eq.(1-f)+Eq.(1-g)+Eq.(1-h)} \end{aligned} \tag{4.29}$$

Subject to

Eqs (2)-(4), (7)-(15), (17), (20), (22), (25)-(29)

$MOP^h_{ijcl}, NOP^h_{ijcl} \in \{0,1\} \quad \forall\ (i,j,c,l,h)$

$QOP^h_{ijl}, ROP^h_{ijl} \in \{0,1\} \quad \forall\ (i,j,l,h)$

$Q^1_{ijclh} \geq 0$ and integer $\forall\ (i,j,c,l,h)$

$Q^2_{ijlh} \geq 0$ and integer $\forall\ (i,j,l,h)$

$Q^3_{ijmclh} \geq 0$ and integer $\forall\ (i,j,m,c,l,h)$

$Q^4_{ilh} \geq 0$ and integer $\forall\ (i,l,h)$

The complexity of the model is related principally to four criteria: the planning horizon, the size of the manufacturing network, the number of machine cells to be formed and the upper cell size, and the part routing data. The second is determined by the number of plants and the number of customer zones; the third is related to cellular design parameters in each plant, namely, the maximum number of cells to design and the maximum machine cell size; the fourth criteria may be evaluated with the number of parts, the number of operations and the number of machines. Accordingly, the number of decision variables and of constraints of the mathematical model will depend on the four criteria, and can be evaluated using equations (4.31) and (4.32), respectively.

$$nb_v = H \bullet \begin{pmatrix} 4\left(NM \bullet NC \bullet NL\right) + 2\left(NP \bullet NO \bullet NM \bullet NC \bullet NL\right) + \\ 3\left(NP \bullet NO \bullet NC \bullet NL\right) + 3\left(NP \bullet NO \bullet NL\right) + \\ 3\left(NP \bullet NL\right) + \left(NP \bullet NL \bullet NK\right) + NL + NP \end{pmatrix} \tag{4.30}$$

$$nb_c = H \bullet \begin{pmatrix} NP \bullet NO + \left(NP \bullet NO \bullet NL\right) + \left(NM \bullet NC \bullet NL\right) + \\ 3\left(NP \bullet NL\right) + 3\left(NP \bullet NO \bullet NC \bullet NL\right) + \\ 2\left(NP \bullet NO \bullet NM \bullet NC \bullet NL\right) + \\ 3\left(NP \bullet NO \bullet NL\right) + \left(NM \bullet NC \bullet NL\right) + \\ \left(NC \bullet NL\right) + \left(NP \bullet NK\right) \end{pmatrix} + \left(H - 1\right) \bullet NL \tag{4.31}$$

Through empirical experimentation and considering the model features, some constraints were added to the model acting as supplied cuts, and result in a significant reduction in computational time. The addition of these constraints to the linear model accelerates the realization of better feasible solutions. First, as the model allows partial subcontracting, the first constraint added is related to the minimum number of manufacturing plants to open in the first period, and is defined by equation (4.33). Second, a new set of constraints is added, which requires a new parameter: the total demand of a part over a given period ($d_{ih} = \sum_{k=1}^{NK} dc_{ik}^{h}$). The set is defined with equations (4.34), derived from constraints (4.10), and sets the flow conservation of a part over all the plants, for each period. In other words, the total demand of a part during a period must be satisfied through total inventory, total production and/or total subcontracting levels, at all manufacturing plants. This set of constraints is redundant in reality, but contributes to significantly improving the first value of the lower bound, and speeds up the running time.

$$\sum_{l=1}^{NL} Z_{l1} \geq 1 \tag{4.32}$$

$$\sum_{l=1}^{NL} I_{ilh}^{+} = \sum_{l=1}^{NL} I_{il,h-1}^{+} + \sum_{l=1}^{NL} I_{ilh}^{-} - \sum_{l=1}^{NL} I_{il,h-1}^{-} + PQ_{ih} + \sum_{l=1}^{NL} SQ_{il,h-l} - d_{ih} \quad \forall i,h \tag{4.33}$$

Moreover, through empirical experimentation, the tuning of selected CPLEX parameter settings significantly reduces computational runtime. The following parameters were set to values different from the default settings in order to obtain the best feasible solutions of the integrated model.

1. MIP emphasis indicator is set to *hidden feasible*, which indicates a search for high quality feasible solutions.
2. Variable selection strategy is set to *branch variable with maximum infeasibility*.
3. Probe strategy is set to 3, the maximum probing level on variables before branching.

4.4 Numerical examples

To investigate the effect of system configuration and production planning decisions in the multi-plant cellular manufacturing design, we consider a manufacturing system with two potential plants and three customer zones. The manufacturing network to design aims to satisfy customer demand, which is known on three periods, with changes in part mix and demand volume. Each manufacturing plant may be designed with two machine cells, having an upper cell size of 5 machines. Eight different parts are manufactured requiring five different machines types. The planning horizon equals three periods. Part demand is thus defined for each period and each customer zone. Each part requires three operations with a known sequence. For each operation, two alternative machines are allowed. However, intercellular flows are allowed with a batch cost of 20 and 40, respectively, for intercellular moves in the same manufacturing plant and for inter-plant flows. The batch size is set to 50 units; the transfer cost of parts between plants is set to 1 per unit. The fixed cost to open a manufacturing plant at each period is set to 10000. Table 4.1 shows the unit carrying cost per period, the unit subcontracting cost and the unit backorder cost per period for each part, respectively. Table 4.2 shows parts routing data.Table 4.3 gives, for each machine type, the periodic time capacity, the fixed machine cost, the variable machine cost and relocation costs. For each part, the unit delivery cost is defined, and is linked to the cost of delivery from a manufacturing plant to a customer zone. Table 4.4 shows the customer zone demand over the planning horizon.

Tableau 4-1 Part costs data ($)

Parts	**Costs related to**		
	Carrying inventory	**Subcontracting**	**Backorder**
1	0.2	13	20
2	0.8	16	20
3	0.9	14	20
4	0.2	14	20
5	0.9	14	20
6	0.9	15	20
7	0.9	14	20
8	0.3	16	20

Tableau 4-2 Part routing data

	P1			**P2**			**P3**			**P4**			**P5**			**P6**			**P7**			**P8**		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
M1	10		12	16				14	20	20	16	20		14	10									12
M2					18								20			10	8		20	8			8	
M3		6	20			16	6					12						16			16	24		16
M4											20		26	16										
M5	14	8				10		10	16		16					16			16			16		

Tableau 4-3 Machine data costs (\$)

Machines	A_m	fc_m	vc_m	ϕ_m^1	ϕ_m^2
M1	500	1150	1200	100	200
M2	500	850	900	100	200
M3	500	1000	1100	100	200
M4	500	1100	1150	100	200
M5	500	900	950	100	200

Tableau 4-4 Parts demand data (units)

Parts	**Customer zone k demand in period h , d_{ik}^h**					
	$h=1$		$h=2$		$h=3$	
	$k=1$	$k=2$	$k=1$	$k=2$	$k=1$	$k=2$
1	0	0	800	1400	0	800
2	0	1900	0	900	0	1640
3	400	1200	400	1400	0	0
4	280	120	800	1100	480	520
5	400	600	400	1400	400	800
6	0	0	400	500	600	600
7	380	480	560	800	480	600
8	440	520	0	0	600	920

For this example, we introduce model features (system reconfiguration, holding inventory and subcontracting, parts transfer between plants) in four combinations.

1- The first configuration ($Config^1$) represents the multi-plant CMS configuration which ignores all the features; in other words, the same configuration is generated for all the periods and the production quantities equal the total part demand at each period.
2- The second configuration ($Config^2$) considers relocation of machines.
3- The third configuration ($Config^3$) considers relocation of machines and production planning decisions only.
4- The fourth configuration ($Config^4$) is built with all the features, namely, system reconfiguration, production planning decisions with parts transfers.

These assumptions of the target configurations are satisfied through the following constraints:

Elimination of system reconfiguration

$$\mathrm{K}_{mcl}^{h+} = 0; \mathrm{K}_{mcl}^{h-} = 0; \quad \forall m, c, l, h \tag{4.34}$$

Elimination of carrying inventory option

$$I_{ilh}^{+} = 0; \quad \forall i, l, h \tag{4.35}$$

Elimination of backordered demand option

$$I_{ilh}^{-} = 0; \quad \forall i, l, h \tag{4.36}$$

Elimination of subcontracting option

$$SQ_{ilh} = 0; \ \forall i, h \tag{4.37}$$

Elimination of parts transfers between plants

$$tr_{ill'h} = 0; \ \forall i, h, l, l' \tag{4.38}$$

With these base case example settings, the estimated complexity is evaluated, using equations (4.31) and (4.32), with 3390 variables, 2104 binary variables and 4720 constraints. A detailed analysis of the results of this base case example is provided in section 4.4.1. Besides analysing this base case example, we will perform a sensitivity analysis in section 4.2, where some model parameters are varied one at a time.

The different configurations are modeled using ILOG-OPL, and solved with ILOG CPLEX 9.0 (ILOG 2000) on a 2.25 MHz dual-core computer with 1.00 GB of RAM. The first and second configurations are solved to optimality, with the default settings of CPLEX parameters and the added constraints. For the third and fourth configurations, the best feasible solutions are recorded after a running time limit of 3 hours, using the selected CPLEX parameter settings and the added constraints described earlier.

4.4.1 Base case example

The detailed components costs for the four configurations are given in Table 4.5. Figure 4.2 describes the evolution of the corresponding multi-plant CMS configuration $Config^3$ detailed through part families structures, machine cells and selected part routings. The corresponding detailed multi-plant production planning decisions for $Config^4$ are shown in Table 4.6, where the production quantity, the inventory level and the subcontracted quantity are specified for each opened plant at each period. Mainly, the origin and the amount of the customer demand delivered are indicated. Although the solution obtained is not optimal, the simultaneous integration of multi-plant reconfiguration and multi-plant production planning decisions generates significant percentage cost savings of 6.88% versus a multi-plant configuration, which ignores these decisions. From the cost components analysis, the comparison of $Config^1$ and $Config^2$ shows that dynamic reconfiguration has reduced machine cost, but at the same time, has also affected the total cost to deliver demand to customers, which generate cost savings of about 1.93%. For the configuration $Config^3$, three strategies were used in order to satisfy all customer zones demands: internal production, carrying inventory and subcontracting. As shown in Table 4.6, part 5 uses the three strategies simultaneously; however, demand for parts 6, 7 and 8 is only satisfied with the periodic internal production. From Table 4.5, when the manufacturing network ($Config^4$) introduces the strategy of parts transfer between plants to satisfy customer demand, the percentage of cost savings rises to 7.37%.

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These savings are explained by a decrease in total machine costs and the relocation cost, as well as by a decrease in distribution costs, which jointly compensate for the additional cost of transferring parts between plants.

Tableau 4-5 Cost components for the four configurations

	$Config^1$	$Config^2$	$Config^3$	$Config^4$
Constraints added	(4.35) to (4.39)	(4.36) to (4.39)	(4.39)	None
Total cost	192339.67	188616,33	179115,03	178167.65
Total machine cost	42259,667	40116,33	36198,223	36008,85
Opening plant cost	60000	60000	60000	60000
Distribution cost	90080	87000	79760	78720
Reconfiguration cost	0	1500	1600	800
Inventory holding cost	0	0	1318,8	874,8
Backorder cost	0	0	0	0
Subcontracting cost	0	0	238	238
Transfer cost	0	0	0	1526
% cost savings		1.93	6,88	7,37

From Table 4.6, parts 1, 3 and 4 share the same production planning pattern. For example, part 1 is manufactured in different plants for periods 1 and 2.

- In period 1, it is assigned to cell 1 in plant 2; an inventory of 2071 units is carried.
- In period 2, the part is manufactured in cell 2 of plant 1 and an inventory of 671 units is carried.

These inventories will be used to satisfy 100% of customer zone 1 demand of period 2 (1400 units) from plant 2, however customer zone 2 demand at period 3 is satisfied jointly from carried inventory of plant 2 (129 units) and from internal production of the third period (671 units). At period 2, demand of customer zone 2 is entirely satisfied from plant 1. Particularly, Customer zone 2 demand for part 2 for the third period is satisfied from the two manufacturing plants: 120 units from held inventory in plant 2 and 1520 units from internal production in plant 1.

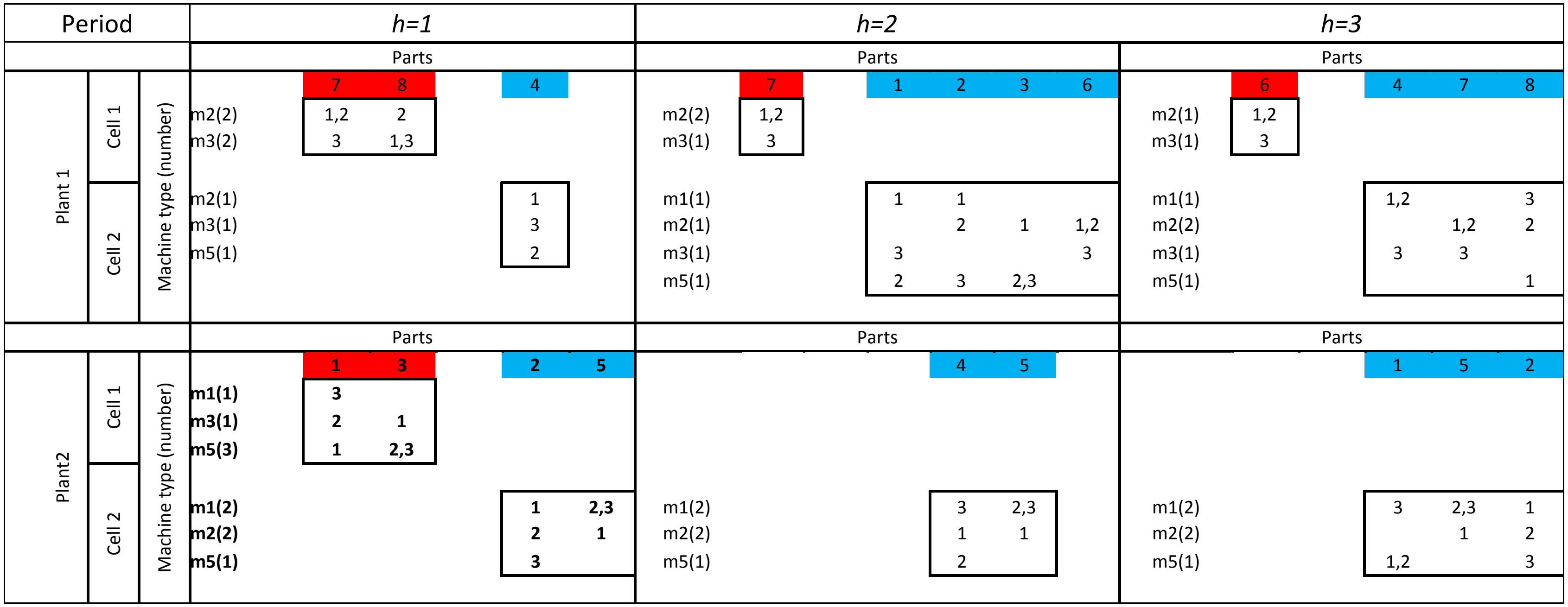
With the demand variation, the machine cells are either eliminated, shrink or enlarged. Besides that, as shown in Table 4.6, the partitions of parts and accordingly customer demand allocation change from period to period. For instance, for period 1, parts 4, 8 and 7 are assigned to plant 1 and parts 1, 2, 3 and 5 are assigned to plant 2, a partition which will change in subsequent periods. As an example, part 6 assigned to the second cell in the second manufacturing plant at the second period (with parts 3 and 5) is manufactured at the third period in the second cell of the first manufacturing plant within a new part family. Parts 1 and 4 use at least 2 different part routings from period 1 to period 3 explained by the fact that these each of these parts have six alternatives to be manufactured. From Table 4.5 it can be concluded that dynamic customer demand allocation contributes significantly in cost savings as a subset of parts (5, 6, 7 and 8) have fixed assigned plant over periods and the other parts are manufactured in different plants. With regard to the evolution of cell configuration in the opened manufacturing plants, all the machines of cell 1 designed in period 1 in plant 2 are relocated generating a cell configuration with a single cell in this plant for the subsequent periods.

As shown in Table 4.7, when the transfer of parts between plants is allowed, the multi plant CMS and the corresponding production planning decisions are altered compared to those when ignoring part transfers (Table 4.6). Both of the two manufacturing plants are activated over the three periods. The distinguishing feature is that the system design exercises less changing the manufacturing plant of a part through the three periods; only parts 1, 3 and 4 are manufactured in different plants over the planning horizon. The designed system makes it mandatory to use the excess machine capacity on a plant to manufacture parts to be transferred afterwards to another plant from which customer demand is satisfied.

For this example, a feasible solution of the integrated model outlines significant savings for multi-plant cellular manufacturing design that simultaneously considers dynamic reconfiguration and production planning decisions when the part demand is dynamic. An investigation of multi-plant CMS design with production planning decisions and system reconfiguration reveals that flexibility of customer demand satisfaction generated from manufacturing flexibility over the planning horizon is an important consideration. Naturally, it is expected that such collaborative manufacturing system design will require a suitable coordination in production planning decisions between the different manufacturing plants, which must align part quality requirements to be more responsive to customer demand.

4.4.2 Sensitivity analysis

To discuss the effect of some input parameter variations on the behaviour of the designed system, we conducted a sensitivity analysis on the model, introducing system reconfiguration and production planning decisions. The model parameters are primarily part demand, machine costs, and the ratio between unit backorder cost and unit holding cost. We modify the demand and machine costs parameters one at time from the base case, and for all parts. One common observation from all tests is that the holding inventory option gets used, and with system reconfiguration, represents a potential strategy for addressing changes in demand and part mixes. This is because unit carrying cost is still competitive as compared to machine costs, and the use of excess capacity in periods, to satisfy demand in future periods, contributes to improving the machine loading rate.



Period			*h=1*		
			Parts		
		Machine type (number)	7	8	4
Plant 1	Cell 1	m2(2)	1,2	2	
		m3(2)	3	1,3	
	Cell 2	m2(1)			1
		m3(1)			3
		m5(1)			2

			Parts			
		Machine type (number)	**1**	**3**	**2**	**5**
Plant2	Cell 1	**m1(1)**	**3**			
		m3(1)	**2**	**1**		
		m5(3)	**1**	**2,3**		
	Cell 2	**m1(2)**			**1**	**2,3**
		m2(2)			**2**	**1**
		m5(1)			**3**	

Period			*h=2*				
			Parts				
		Machine type (number)	7	1	2	3	6
Plant 1	Cell 1	m2(2)	1,2				
		m3(1)	3				
	Cell 2	m1(1)		1	1		
		m2(1)			2	1	1,2
		m3(1)		3			3
		m5(1)		2	3	2,3	

			Parts	
		Machine type (number)	4	5
Plant2	Cell 1			
	Cell 2	m1(2)	3	2,3
		m2(2)	1	1
		m5(1)	2	

Period			*h=3*			
			Parts			
		Machine type (number)	6	4	7	8
Plant 1	Cell 1	m2(1)	1,2			
		m3(1)	3			
	Cell 2	m1(1)		1,2		3
		m2(2)			1,2	2
		m3(1)		3	3	
		m5(1)				1

			Parts		
		Machine type (number)	1	5	2
Plant2	Cell 1				
	Cell 2	m1(2)	3	2,3	1
		m2(2)		1	2
		m5(1)	1,2		3

Figure 4-2 Evolution of the multi-plant CMS (Config^3), using the integrated model

Tableau 4-6 Best feasible solution of the multi-plant CMS design with production palnning decisions (Config³)

		Part 1			Part 2			Part 3			Part 4		
	Period	1	2	3	1	2	3	1	2	3	1	2	3
Deliv. Demand from plant	1		800			900	120		400		400	800	480
	2		1400	800	1900		1520	1600	400			1100	520
Total demand			2200	800	1900	900	1640	1600	800		400	1900	1000
Internal Prod. of plant	1		800			1020			400		1200		480
	2	2071		129	1900		1520	2000				1620	
Inventory level of plant	1					120					800		
	2	2071	671					400				520	
Subcontracted Qty of plant	1												
	2												

(Tableau 4.6 continued)

		Part 5			Part 6			Part 7			Part 8		
	Period	1	2	3	1	2	3	1	2	3	1	2	3
Deliv. Demand from plant	1					400	1200	860	1360	1080	960		1520
	2	1000	800	1200									
Total demand		1000	800	1200		400	1200	860	1360	1080	960		1520
Internal Prod. of plant	1					400	1200	860	1360	1080	960		1520
	2	983	828	1172									
Inventory level of plant	1												
	2		28										
Subcontracted Qty of plant	1												
	2	17											

Tableau 4-7 Best feasible solution of the multi-plant CMS design with production palnning decisions and parts transfer (Config^4)

		Part 1			Part 2			Part 3			Part 4		
	Period	1	2	3	1	2	3	1	2	3	1	2	3
Deliv. demand from plant	1		800					400	400		280	800	480
	2		1400	800	1900	900	1640	1200	400		120	1100	520
Total demand			2200	800	1900	900	1640	1600	800		400	1900	1000
Internal Prod. of plant	1		973						400		967		480
	2	1227		800	1900	965	1575	2000				1853	
Transferred parts	1--2		173								120		
parts	2--1							400				233	
Inventory level of plant	1										567		
	2	1227				65		400				520	
Subcontracted qty of plant	1												
	2												

(Tableau 4.7 continued)

		Part 5			Part 6			Part 7			Part 8		
	Period	1	2	3	1	2	3	1	2	3	1	2	3
Deliv. demand from plant	1	17				400	600	860	1360	1080	960		1520
	2	983	800	1200			600						
Total demand		1000	800	1200		400	1200	860	1360	1080	960		1520
Internal Prod. of plant	1							860	1360	1080	960		1520
	2	983	800	1200		400	1200						
Transferred parts	1--2												
parts	2--1						600						
Inventory level of plant	1												
	2												
Subcontracted qty of plant	1	17											
	2												

The effects of demand variation on total cost and on its components are presented in Figures 4.3, 4.4 and 4.5. As demand increases, more manufacturing plants are activated through periods, and more machine cells are designed, which increases the total machine cost. This increase is compensated through variations in both the total inventory cost and in the total distribution cost. As an example, when a 10% decrease is set to all parts, only one manufacturing plant is activated in the first period, as shown in Figure 4.3, and less inventory is held (see Figure 4.5), as compared to the base case results, which is explained by the designed machine capacity and the machine relocation, which are balanced to satisfy customer demand at each period. When a 10% increase is set, Figure 4.4 shows that the total machine cost and the total distribution cost increase, which is intuitively predictable: the lack in plant capacity in period 1 is adjusted with a new cell formed in periods 2 and 3, which was inexistent in the base case solution (see Figure 4.2). As shown in Figure 4.5, these system adjustments are coupled with different machine cells structures and less exercised carrying inventory option. Moreover, when demand increases (or decreases) by 5%, the total inventory cost varies slightly. This stability is attributed to the most profitable loading rate of

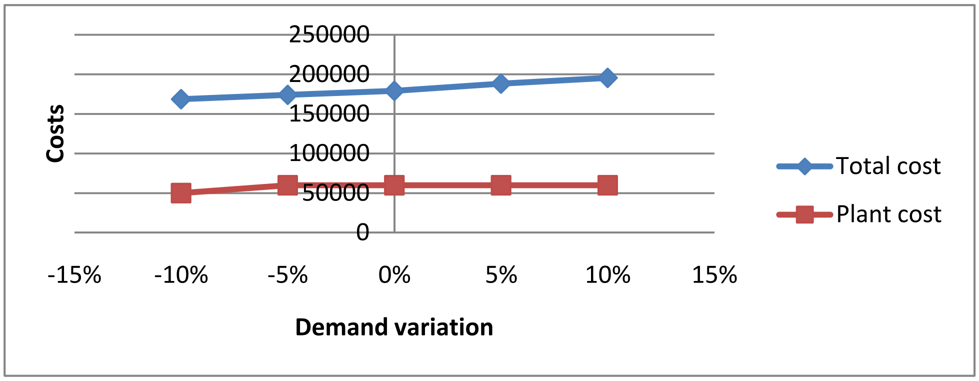


Figure 4-3 Effects of demand variation on the total cost and on open plant cost components

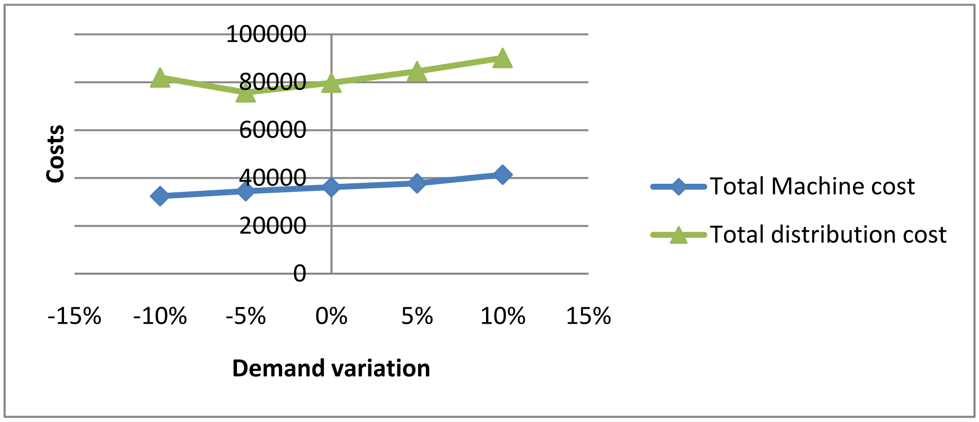


Figure 4-4 Effects of demand variation on the Total machine costand on the total distribution cost

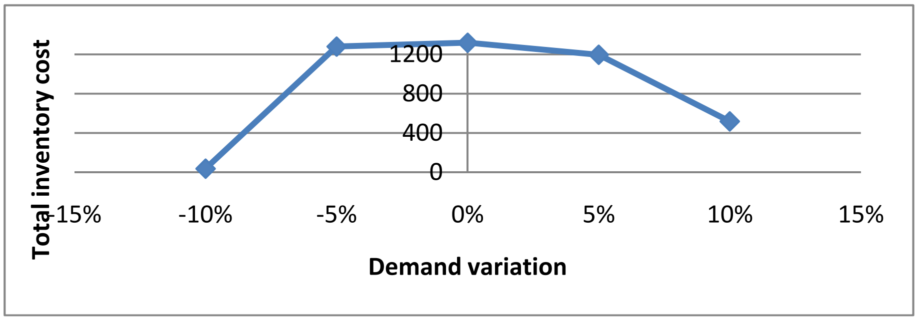


Figure 4-5 Effects of demand variation on the total inventory cost

machine cells, which allows the satisfaction of demand for future periods, and with regard to the slow evolution of the total machine cost.

Figure 4.6 shows that as the machine costs increase, the total design cost increases significantly, and the total distribution cost varies slightly. The most noticeable point is that the inventory strategy is more exercised, and accordingly, the total inventory cost increases, as depicted in Figure 4.7. In this context, the designed system increased the inventory cost with optimizing machine loading through periods, to satisfy future customer demand with held inventory.

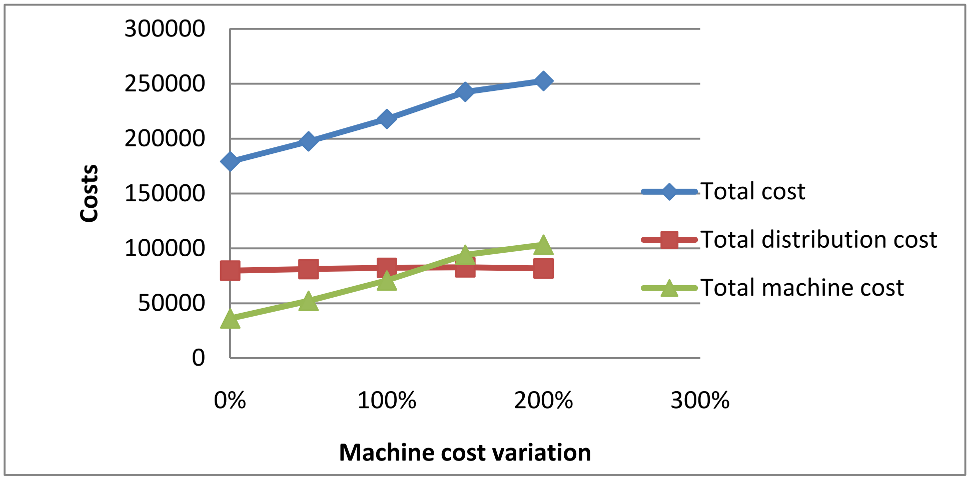


Figure 4-6 Effect of machine cost variation on the total cost components

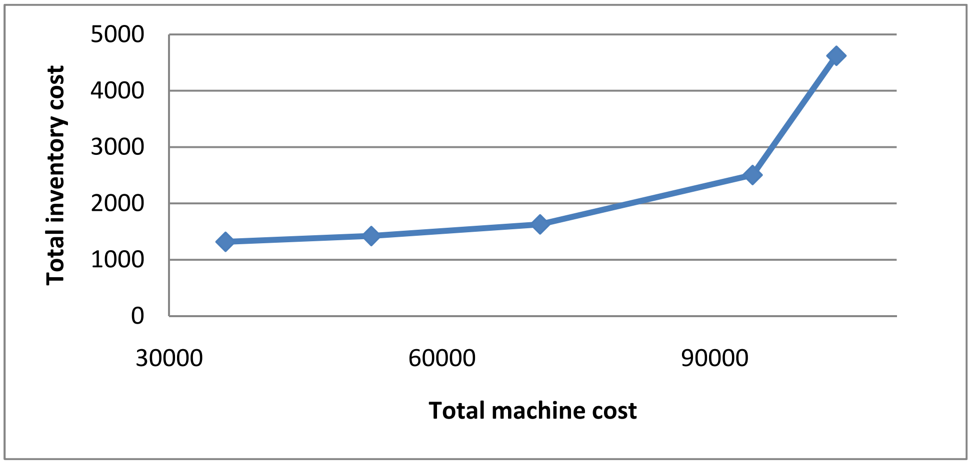


Figure 4-7 The total inventory cost as a function of the total machine cost

Figure 4.8 shows that the total design cost varies slightly when the ratio between the unit backorder cost and the unit carrying inventory cost $(\varphi_i^- / \varphi_i^+)$ decreases. The system maintains two manufacturing plants open for the three periods; however, when this ratio decreases to 2, the total plant cost decreases, whereas the total distribution cost increases. This is explained by the fact that activating a smaller number of manufacturing plants in the first period ordered, with the option to backorder some customer demand parts for this period to the subsequent period, compensates for the increase in the total distribution cost. In the first period, the system behaves as a single cellular manufacturing system, and then evolves to a two-plant CMS, opening another manufacturing plant. This scenario indicates managerial insight into considering multiple objectives for deciding which final system design will be adopted.

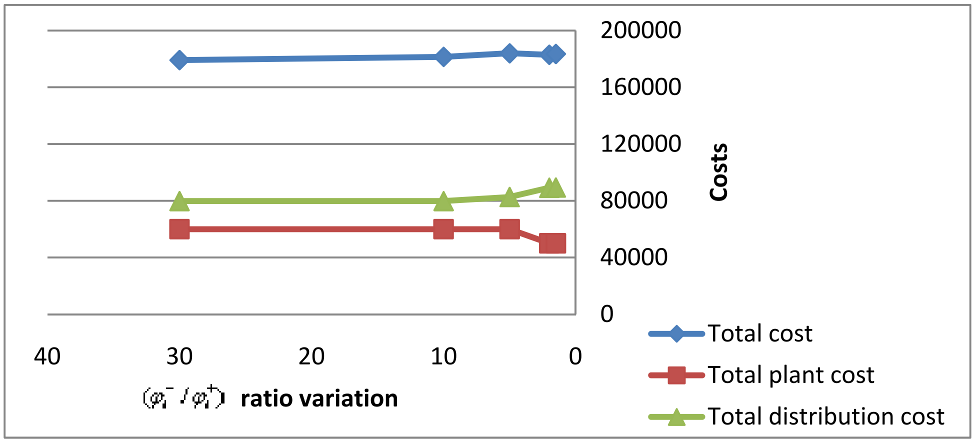


Figure 4-8 Sensitivity of the total cost components to $(\varphi_i^- / \varphi_i^+)$ ratio variation

4.5 Conclusion

In this paper, an integrated mathematical model for designing a dynamic multi-plant CMS design is proposed. The main contribution is to have extended the classical single plant CMS design to a manufacturing system intended on multiple plants to meet customer demand over a planning horizon. The original features of the model lie in the integration of dynamic customer allocation, part transfers between plants, multi-plant production planning decisions and many manufacturing aspects well integrated in CMS design. Experiments on small-sized examples solved with a proposed linear model show significant savings when considering dynamic configurations simultaneously with production planning decisions. The addition of the parts transfer feature between manufacturing plants also improves the total design cost, as a means of consolidating customer demand shipments from a single plant. Results also show also that the part mix, customer mix and demand change over periods affect system configuration, production planning decisions and customer delivery routing decisions. The cost savings are significant enough to justify the multi-plant CMS design with an integrated model. Although, the proposed linear model, appended with user defined cuts was efficient to solve small sized examples, it is computationally more complex for real instances problems and therefore needs to design appropriate heuristics to propose near optimal solutions in a reasonable time.

The model could be refined with new cost components, such as the relocation cost of machines between manufacturing plants and might consider the manufacturing plants closing option after a specified number of periods. The increase of dependence of the manufacturing plants, to satisfy customer demand will require more coordination effort and therefore the design process of the multi-plant CMS should comply with this qualitative criterion.

CONCLUSION

Une grande partie de la recherche sur la conception des systèmes manufacturiers cellulaires s'appuie sur l'hypothèse que la demande client est affectée à un seul site de production. Par ailleurs, la conception des chaînes d'approvisionnement, de nature stratégique, ne représente pas la configuration du système de production comme une variable de décision. Toutefois, quand un système manufacturier cellulaire évolue sur plusieurs sites de production, de surcroit pouvant être intereliés, les décisions quant à l'affectation des demandes clients aux sites de production et aux choix de fournisseurs doivent être intégrées aux décisions de conception multi-site de SMC.

Dans cette thèse, nous avons présenté des modèles mathématiques intégrant la conception de systèmes manufacturiers cellulaires multi-site dans un contexte de chaîne d'approvisionnement. Ces modèles n'introduisent pas seulement les décisions liées aux liens amont et aval d'un système de production (fournisseurs ou clients) mais incluent aussi l'hypothèse de partage de ressources entre les sites du système de production. Ces modèles concourent avec une vision pratique de la conception de SMC évoluant sur plusieurs sites dans un environnement de chaîne d'approvisionnement où la conception intégrée est devenu un enjeu crucial.

Nous avons investigué en premier les bénéfices liés à la conception multi- site d'un système cellulaire, permettant les flux entre les sites, utilisant un modèle mathématique développé, et linéarisé. Ce modèle a été étendu pour inclure les décisions quant au processus d'approvisionnement en matières premières. Les résultats des exemples illustratifs, résolus avec le solveur CPLEX, démontrent les gains potentiels induits par l'accroissement de la flexibilité de routage des opérations sur les sites de production et par une conception intégrant le processus de sélection pour l'approvisionnement en matières premières à la conception multi site d'un système de production.

Par rapport au processus de livraison de demandes client, nous avons développé un modèle mathématique non linéaire, qui détermine simultanément la sélection des sites de production, configure chaque site selon une structure cellulaire et identifie l'affectation des demandes client. Le modèle introduit aussi une originalité quant à la réalisation de produits sur plus d'un site et couvre des paramètres pratiques de la production cellulaire. Un modèle linéarisé est proposé pour résoudre des problèmes de petites tailles. Le modèle est de nature combinatoire et sa complexité est accrue par rapport aux aspects liés aux : sites de production potentiels, de zones clients, de produits et processus opératoires. Pour résoudre des problèmes de plus grandes tailles, une approche de décision en plusieurs phases est développée, basée sur le recuit simulé, se caractérisant par un processus de perturbation original. Les résultats expérimentaux ont démontré des gains significatifs des décisions intégrées utilisant le modèle et l'approche développés, comparées aux décisions avec une approche séquentielle. De plus, l'efficacité de l'approche par recuit simulé appuyée par une perturbation aléatoire et affinée de solution a été clairement mise en relief, en termes de qualité de solution et de temps de résolution.

Dans une perspective d'intégrer l'aspect dynamique lié à la variation de la demande et la variété des produits, une extention du modèle introduit dans le chapitre 3 est réalisée. Nous avons développé un modèle intégré pour la conception d'un système de production multi-site dans un contexte dynamique où les décisions relatives au plan de production et à la reconfiguration du système sont introduites avec l'hypothèse de la demande de produits connue sur plusieurs périodes. Le modèle a pour but de sélectionner les sites de production à ouvrir, de configurer chaque site selon une structure cellulaire et de déterminer un planning de production et un plan de reconfiguration des sites de production, et ce pour chaque période de l'horizon de planification. L'objectif à optimiser inclut les coûts reliés à la sélection des sites, les coûts de reconfiguration, les coûts de livraison de demande aux clients, les coûts pour maintenir des stocks, les coûts de pénurie, les coûts de soustraitance ainsi que les coûts de transferts de produits entre sites de production. Une analyse de sensibilité conduite sur un exemple de base a démontré les bénéfices potentiels induits par une reconfiguartion dynamique des sites de production cellulaires couplée aux décisions de production, de stockage ou de soustraitance. Dans ce contexte multi-site soumis à une demande variable, la possibilité de transferts de produits entre les sites de production a permis d'accroître la flexibilité de routage des demandes clients et de générer des réductions de coûts significatives.

RECOMMANDATIONS

Les recommandations pour de futures recherches sont résumées dans les points suivants :

- Intégration de l'hypothèse de production d'un produit sur plus d'un site de production. En effet, permettre que la demande d'un produit soit réalisée dans des cellules de production localisées dans des sites différents (suppléant les hypothèses des modèles présentés aux chapitres 2, 3 et 4) offre la possibilité d'utiliser au mieux les ressources machines des cellules formées et d'apporter plus de flexibilité pour la satisfaction des demandes client.

- Parallélization du processus de résolution par recuit simulé introduit dans le chapitre 3. Les techniques de parallélisation ont prouvé leur efficacité dans un contexte de formation de cellules sur un seul site. L'exploration simultanée de plusieurs voisinages (phase 2 de notre approche) permettra d'amélioer l'efficacité de l'approche et d'offrir un moyen de comparer des alternatives d'un SMC multi-site selon les paramètres de conception (sites de production et données clients). Cette parllélisation pourra être aussi adaptée comme une phase de résolution pour le modèle dynamique (chapitre 4).

- Développement de modèles de simulation d'un SMC multi-site incluant le processus d'approvisionnement ou le processus de livraison (contextes des chapitres 2, 3 et 4). Afin d'analyser l'aspect dynamique et stochastique des variables du système étudié, les modèles de simulation serviront à relaxer des hypothèses que les approches analytiques ne permettent pas telles que l'aspect stochastique et dynamique de la demande client. Précisément, les facteurs aléatoires peuvent se manifester par des perturbations à l'intérieur des sites de production comme la capacité de production (taille des cellules, capacité des machines) jumelés à d'autres perturbations entre les fournisseurs et les producteurs ou entre les sites producteurs et les clients. Grâce aux modèles de simulation, il sera aussi possible de quantifier les effets de sites de production reliés (modèles des chapitres 2,3 et 4).

- Décision multi-critère pour la conception de SMC multi-site dans un contexte de chaîne d'approvisionnement. Dans le cadre de cette thèse, le coût a été utilisé comme mesure de performance. Or, la conception des sites de production ou la sélection des fournisseurs, considérés séparément, sont des processus multi-critère avec des aspects aussi bien quantitatif que qualitatif et appellent à considérer des approches multi-critère telles que l'optimisation à plusieurs objectifs (*goal programming*) ou la méthode AHP (*Analytic Hierarchy Process*). Ghodsypour et O'Brien (2001) ont démontré l'applicabilité de AHP pour réduire le nombre de fournisseurs et gérer le partenariat avec les fournisseurs. Par rapport aux contextes étudiés dans cette thèse, AHP va permettre aux décideurs de classer des configuations qui associent plusieurs points de vue (fournisseurs, producteurs et clients). Des paramètres tels que les les stratégies de production, les stratégies de maintenance, les préférences de clients, l'importance des clients selon des critères de variété et de volume de demande, de profitabilité, le niveau de risque liés aux clients ou aux fournisseurs et les modes de livraison aux clients introduisent des critères qualitatifs qui permettent de mieux évaluer la performance des systèmes étudiés.

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