UNIVERSIDAD POLITÉCNICA DE VALENCIA

Departamento de Organización de Empresas

Modelos y Algoritmos basados en el concepto Stroke para la Planificación y Programación de Operaciones con Alternativas en Redes de Suministro

TESIS DOCTORAL

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À Audrey, Yohann, Elisa, mes parents et grand-parents

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Cuando empecé mi proyecto final de carrera en Ford España, SA a principio del 2009, sin saberlo, comenzó mi trayectoria como investigador que se hizo realidad cuando conseguí un contrato pre-doctoral. Reflexionando sobre el proceso seguido para la elaboración de esta tesis doctoral, reconozco que ha supuesto sacrificios y decisiones difícilmente entendibles para muchos. Pero la valoración de todas las alternativas, en este contexto complejo, incierto (y por ello cambiante), fue lo que me motivó para demostrar que no hay que rendirse durante una crisis, sino que hay que superarse para provocar su suerte. Mis decisiones y esfuerzos tienen como resultado un trabajo de investigación. Pero no me cabe la menor duda, que no hubiera tenido este final sin el apoyo y la confianza incondicional de las personas que me rodearon durante estos tres últimos años. Así que para mí es todo un privilegio y un deber dar las gracias a quienes me apoyaron y aguantaron a lo largo de la elaboración de esta tesis.

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Valencia, Noviembre 2012 Julien Maheut

Título: Modelos y Algoritmos basados en el concepto Stroke para la Planificación y Programación de Operaciones con Alternativas en Redes de Suministro

PRESENTADA POR: D. Julien Maheut

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Resumen:

En la segunda mitad del siglo XX se comenzó a desarrollar la gestión de materiales de productos multinivel. En ese momento, se decidió que lo verdaderamente relevante, era la gestión de los materiales. De este modo, los modelos de datos que se desarrollaron a partir de entonces, se enfocaron en estructurar con detalle las relaciones entre materiales. La herramienta/metodología para gestionarlos pasó a denominarse *Material Requirement Planning (MRP)*. Posteriormente, cuando el MRP fue entendido, y la tecnología comenzó a permitirlo, los modelos de datos evolucionaron y se incorporó la información necesaria para la gestión de los recursos.

En estas estructuras de datos, tanto los materiales como los recursos que hacían falta para fabricar un producto final se asociaban a éste último. Esta forma de asociar todos los productos necesarios (producto hijos) y los recursos a inmovilizar para la obtención de un único producto denominado "producto padre" se denominó estructura *Gozinto*. Este origen, probablemente, marcó un "efecto candado" (*lock-in)* en la manera de abordar la planificación de los requerimientos de Materiales y de Recursos y, sobre todo, de las operaciones en su sentido más genérico.

Durante la implantación de algunas herramientas de planificación en empresas y a partir de la revisión del estado del arte sobre dichas herramientas, hemos detectado varias oportunidades de investigación. De entre ellas nos hemos centrado en entender cuales son los requisitos necesarios para que las herramientas de planificación y programación de las operaciones pudieran ser flexibles y adaptadas a cualquier sector industrial.

Para ello, en esta tesis vamos a estudiar la evolución de las estructuras de datos y propondremos una nueva estructura de datos más genérica, basada en el concepto de *stroke* que extiende el concepto de lista de materiales más allá de las estructuras tradicionales presentes en las herramientas comerciales existentes. Esto nos permitirá dar soporte a la planificación y programación de manera más generalizada, pudiendo abarcar cualquier operación, incluso sus alternativas en entorno multi-planta. Al mismo tiempo se podrán desarrollar los modelos de programación matemática, algoritmos y los mecanismos de coordinación necesarios para resolver los modelos e implantarlos en herramientas integradas para su uso industrial.

Esta tesis se plantea como una colección de 10 artículos científicos, el orden en que están situados en la tesis permite mantener una secuencia lógica construida a posteriori y no según el orden cronológico en el que fueron escritos.

Title: Models and algorithms based on the Stroke concept for Planning and Scheduling Alternative Operations in Supply Networks

PRESENTED BY: MR. Julien Maheut

DIRECTED BY: PhD. D. José Pedro Garcia-Sabater

Abstract:

In the second half of the 20th century the management of multi-product materials began to be a concern. At that time, it was decided that the truly relevant, was the management of materials. Thus, data models which were developed thereafter focused in structure the relations between materials with detail. The tool/methodology to manage materials took the name of Material Requirement Planning (MRP). Later, when the MRP was understood and when the technology began to allow it, the data models evolved and the information necessary for the management of resources was incorporated.

In these data structures, both the materials and resources that were needed to manufacture an end-product were associated with the end-product. This way to associate all the necessary products (child items) to consume and the resources to immobilize for obtaining a single end-product called "parent item" was called Gozinto structure. This source probably marked a lock-in on the approach to the planning of material requirements and resources and, above all, of the operations in its most generic sense.

During the implementation of some planning tools in companies and from the review of the state of the art about these tools, we have identified several gaps/opportunities for research. Among them we have focused on understanding what are the requirements for the operations' planning and scheduling tools could be flexible and adapted to any industry.

To this end, in this thesis, the evolution of the data structures is reviewed and a new generic data structure based on the stroke concept that extends the concept of BOM beyond traditional structures present in the existing commercial tools is proposed. This will allow us to support the planning and schedule tasks more widely covering any operation, including its alternatives in multi-plant context. At the same time mathematical programming models, algorithms and coordination mechanisms needed to solve models has been developed and implanted into integrated tools for industrial use.

This thesis is presented as a collection of 10 scientific papers, the order they are located in the thesis can maintain a logical sequence and subsequently are not in the chronological order in which they were written.

Títol: Models i Algoritmes basats en el concepte Stroke per a la Planificació i Programació d’Operacions amb Alternatives en Xarxes de Subministrament

PRESENTADA PER: D. Julien Maheut

DIRIGIDA PER: DR. D. José Pedro Garcia-Sabater

Resum:

En la segona meitat del segle XX es va començar a desenvolupar la gestió de materials de productes multinivell. En eixe moment, es va decidir que el verdaderament rellevant era la gestió dels materials. D’aquesta manera, els models de dades que es van desevolupar a partir d´eixe moment, es van enfocar a estructurar amb detall les relacions entre materials. La ferramenta/metodologia per a gestionar-los va passar a denominar-se Material Requirement Planning (MRP). Posteriorment, quan el MRP va ser entès, i la tecnologia va començar a permetre-ho, els models de dades van evolucionar i es va incorporar la informació necessària per a la gestió dels recursos.

En aquestes estructures de dades, tant els materials com els recursos que es necessitaven per a fabricar un producte final s’associaven a este últim. Aquesta forma d’associar tots els productes necessaris (productes fills) i els recursos a immobilitzar per a l’obtenció d’un únic producte denominat “producte pare” es va denominar estructura Gozinto. Aquest origen, probablement, va marcar un “efecte cadenat” (lock-in) en la manera d’abordar la planificació dels requeriments de Materials i de Recursos i, sobretot, de les operacions en el seu sentit més genèric.

Durant la implantació d’algunes ferramentes de planificació en empreses i a partir de la revisió de l’estat de l’art sobre les dites ferramentes, hem detectat diverses oportunitats d’investigació. D’entre elles ens hem centrat a entendre quins són els requisits necessaris per què les ferramentes de planificació i programació de les operacions pogueren ser flexibles i adaptades a qualsevol sector industrial.

Per a tal fi, en aquesta tesi estudiarem l’evolució de les estructures de dades i proposarem una nova estructura de dades més genèrica, basada en el concepte de *stroke* que estén el concepte de llista de materials més enllà de les estructures tradicionals presents en les ferramentes comercials existents. Açò ens permetrà donar suport a la planificació i programació de manera més generalitzada, podent comprendre qualsevol operació, inclús les seues alternatives en entorn multi-planta. Al mateix temps es podran desenvolupar els models de programació matemàtica, algoritmes i els mecanismes de coordinació necessaris per a resoldre els models i implantar-los en ferramentes integrades per al seu ús industrial.

Esta tesi es planteja com una col·lecció de 10 articles científics, l’ordre en què estan situats en la tesi permet mantenir una seqüència lògica construïda a posteriori i no segons l’ordre cronològic en què van ser escrits.

Titre : Modèles et algorithmes basés sur le concept du *stroke* pour la planification et l´ordonnancement des opérations alternatives dans les réseaux d'approvisionnement

PRESENTÉ PAR: Mr. Julien Maheut

DIRIGÉ PAR: Prof. Dr. José Pedro Garcia-Sabater

Résumé:

Durant la seconde moitié du XXe siècle a commencé à se développer la gestion des produits multi-niveaux. A cette époque, la gestion des produits était vraiment critique. Ainsi, les modèles de données développés par la suite ont évolué afin de structurer avec plus de détails les relations entre les produits. L'outil/méthode associé(e) a ainsi été nommé *Material Requirement Planning* (MRP). Plus tard, quand le MRP a été compris et que la technologie a commencé à le permettre, les modèles de données se sont perfectionnés et les informations nécessaires à la gestion des ressources s´ajoutèrent à ces modèles.

Dans ces structures de données, les données relatives aux composants et aux ressources nécessaires pour fabriquer un produit final sont associées à ce même produit final. Cette façon d'associer tous les composants (*child item*) et ressources nécessaires pour l'obtention d'un unique produit (*parent item*) a été appelée structure de *Gozinto*. Cette origine a probablement marqué un « effet de verrouillage » (lock-in) dans la manière d´aborder la problématique associée à la planification des besoins en produits et ressources et, surtout, de la planification des opérations au sens général du terme.

Lors de l´implantation de certains outils de planification en entreprises et durant le recensement des technologies, outils et méthodes existant sur ces types d'outils dans la littérature scientifique, nous avons identifié plusieurs opportunités de recherche. Parmi ces *gaps*, nous nous sommes concentrés sur la compréhension des exigences et fonctionnalités nécessaires aux outils de planification et de séquençage des opérations pour qu'ils soient plus flexibles et puissent s'adapter au mieux aux différents secteurs industriels.

Pour cela, dans cette thèse doctorale, nous allons étudier l'évolution des structures de données et en proposer une nouvelle plus générique, basée sur le concept du *stroke* qui étend le concept de Bordereau Matière (BOM) au-delà des structures traditionnelles présentes dans les outils commerciaux existants. Cela nous permettra de planifier et ordonnancer un plus grand nombre d´opérations, y compris leurs alternatives possibles, dans un contexte multi-usines. Dans le même temps, des modèles de programmation mathématique, des algorithmes et des mécanismes de coordination nécessaires pour résoudre les modèles sont proposés et implantés dans des outils intégrés pour une utilisation industrielle.

Cette thèse est présentée comme une collection de 10 articles scientifiques. L'ordre dans lequel ces articles sont présentés dans ce document respecte un ordre logique qui facilite la compréhension des recherches effectuées et mais ne représente pas l'ordre chronologique dans lequel ils ont été écrits.

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Introducción general a la tesis doctoral

Esta tesis doctoral aborda el problema de la planificación y programación de las operaciones en entorno multi-planta proponiendo un nuevo modelo de datos para permitir la consideración de las alternativas de operaciones. Este proyecto de tesis doctoral y las publicaciones científicas incluidas en este documento, surgen como resultado del continuo y extenso contacto del director de la tesis, Prof. Dr. D. José Pédro García Sabater y más recientemente del autor de esta tesis, D. Julien Maheut, con empresas del sector automovilístico y empresas del sector de bienes de consumo. También se pudo llevar a cabo con la participación activa de ambos en diversos proyectos de transferencia de tecnología y proyectos de investigación tanto de ámbito nacional como europeo.

Durante la implantación de algunas herramientas de planificación en empresas y a partir de la revisión del estado del arte realizado para las publicaciones científicas de sobre dichas herramientas, hemos detectado varios huecos de investigación. De ellos nos hemos centrado en entender cuales son los requisitos necesarios para que las herramientas de planificación y programación de las operaciones pudieran ser flexibles y adaptadas a cualquier sector industrial.

Para ello, en esta tesis vamos a estudiar la evolución de las estructuras de datos existentes y propondremos una nueva estructura de datos más genérica, basada en el concepto de stroke que extiende el concepto de lista de materiales más allá de las estructuras tradicionales presentes en las herramientas comerciales existentes. Esto nos permitirá dar soporte a la planificación y programación de manera más generalizada, pudiendo abarcar cualquier operación, incluso sus alternativas en entorno multi-planta. Al mismo tiempo se podrán desarrollar los modelos de programación matemática, algoritmos y los mecanismos de coordinación necesarios para resolver los modelos e implantarlos en herramientas integradas para su uso industrial.

Esta tesis se plantea como una colección de artículos científicos, el orden en que están situados en la tesis permite mantener una secuencia lógica y no el orden cronológico en el que fueron escritos. El Capítulo 1 revisa la literatura necesaria para introducir todos los objetivos abordados en esta tesis doctoral. Los demás capítulos son un compendio de algunos de los trabajos de investigación publicados, aceptados o en proceso de revisión, que se han elaborado a lo largo de los 30 meses de investigación del doctorando. Del 0 al Capítulo 10, se recoge un artículo publicado en una revista indexada JCR (0), un artículo aceptado en una revista indexada JCR en proceso de publicación (0), un artículo enviado a una revista indexada JCR en proceso de primera revisión (Capítulo 5), un artículo publicado en una revista indexada Scopus (Capítulo 3), un artículo aceptado en una revista indexada Scopus en proceso de publicación (Capítulo 6), un artículo publicado en una revista indexada Scimago (Capítulo 7), un artículo aceptado en una revista indexada Scimago en proceso de segunda revisión (Capítulo 9), un capítulo de libro publicado en un libro editado por Springer (Capítulo 8) y un capítulo de libro en proceso de publicación en un libro de la editorial Springer (Capítulo 10). El Capítulo 11 concluye el trabajo de investigación realizado y plantea algunas de las futuras líneas de investigación.

Capítulo 1 Modelos de datos para Herramientas de Planificación de Operaciones: situación actual y nuevas oportunidades

Abstract. La planificación de las operaciones en las empresas y más generalmente en las cadenas de suministro se apoya en diferentes modelos de datos conocidos como Listas de Materiales, Listas de Operaciones, etc. La actividad práctica y la literatura se han ido enriqueciendo durante 60 años presentando nuevos modelos de datos para adaptarse a las necesidades de los diferentes tipos de industria y de paradigma de producción. En este capítulo, se propone una clasificación de los diferentes modelos de datos para representar las listas de materiales. Además se clasificarán los modelos de datos existentes en la industria para apoyar las diferentes tareas que se ejecutan a lo largo del ciclo de vida de los productos manufacturados. Para ello se abordará una revisión de la literatura sobre los modelos de datos más recientes para soportar la planificación de las operaciones en dentro de una organización y en un entorno multi-plantas. Por último, se plantea una discusión sobre las necesidades prácticas de las empresas para planificar las operaciones (tanto de compra, producción como de transporte) que finalizará con la propuesta de un modo diferente de estructurar las listas de materiales y operaciones que permite tener en cuenta muchas de las necesidades no cubiertas por las estructuras convencionales.

Keywords: Planificación de Operaciones, Modelo de datos, Listas de Materiales, Lista de Operaciones

I. Introducción

I. 1. Evolución de las herramientas de planificación de las operaciones

Planificar es el proceso racional de tomar decisiones, de acuerdo a unos criterios para conseguir un conjunto de objetivos en función unas previsiones en un momento y entorno dado. Hasta los años 50, planificar la producción en el entorno industrial se limitaba a decidir la cantidad de productos acabados a producir en cada periodo para poder cubrir la demanda en cualquier caso, sin manejar de forma científica previsiones de demanda (Olson y Kesharwani, 2011).

Debido a la simplicidad estructural de los productos, a la relativa predictibilidad de su demanda y a la falta de sistemas automáticos, las tareas de planificación eran suficientemente sencillas para ser realizadas manualmente (Mok et al., 2011). Durante los 20 años siguientes, las empresas se enfrentaron a un aumento continuo en la complejidad de los productos a manufacturar, y sobre todo la necesidad de entregar en el plazo adecuado los productos (Caridi y Sianesi, 1999; Erens y Hegge, 1994). Planificar manualmente la producción de productos con listas de materiales grandes era cada vez más difícil. Además, mantener un control sobre sobre los inventarios en materia prima y productos semi-elaborados no había sido un aspecto problemático, puesto que en épocas de demanda siempre creciente, tener materia prima es la restricción básica de cualquier director industrial. Al aumentar los precios de la materia prima, controlarse el crecimiento de la demanda y con una la presión por parte del entorno, las empresas tuvieron que mejorar sus resultados, y uno de los caminos fue controlando sus inventarios. El modo de controlar los inventarios de materia prima es papel del departamento de compras así que se empezó a planificar las compras junto con la producción de productos terminados con el fin de maximizar sus beneficios.

Aprovechando el nacimiento de la informática y con el objetivo de planificar la producción y las compras, nació la lógica MRP (*Material Requirements Planning*). La lógica MRP permite, en función de unas previsiones de demanda en productos finales, gestionar las necesidades en productos con demanda dependiente (Orlicky, 1975). Está lógica necesita basarse en unos modelos de datos para aprehender la realidad, capturar la información relativa a las estructuras de productos y tomar las decisiones adecuadas. Las listas de materiales multi-nivel suponían la generación de necesidades de productos con demanda dependiente y la escasez de estos productos podía tener como consecuencia problemas para servir los clientes a tiempo. Por ello la dificultad de la gestión se había trasladado a la gestión de materiales.

Dado que la mayor complejidad se encontraba fundamentalmente en los procesos industriales basados en procesos de ensamblaje, el modelo de datos para estructurar las listas de productos ensamblados quedó como el estándar para planificar los materiales. Esta forma estándar para estructurar las listas de materiales se llamó entonces lista de materiales (*Bill of Materials*, BOM) de ensamblaje o listas convergentes. Este modelo de datos consiste en usar dos tablas: una tabla para los ítems padres (*parent items*) y otra para los items hijos (*child items*). Estas dos tablas tienen los mismos campos: el identificador del producto final, el nivel al cual el producto pertenece, la posición en el nivel. Si el ítem es de tipo hijo, entonces se le añade los campos de la posición del ítem padre si existe, un booleano para si el producto tiene un ítem hijo (Guoli et al., 2003) y también la cantidad para realizar una unidad del ítem padre. El uso de estas tablas puede provocar redundancias difícilmente localizables. Por este motivo, el modelo de almacenamiento más cómodo y visual es el grafo Gozinto, adaptación lingüística de "*the part that goes into*" (Vazsonyi, 1954). Este modelo de datos permite evitar eficientemente redundancia ya que cada objeto (producto) aparece solamente una vez (Guoli et al., 2003). El grafo Gozinto se limita a establecer las relaciones entre dos productos con lo cual es necesario únicamente una tabla en la cual se establece el ítem padre, el ítem hijo y la cantidad de ítem hijos necesarios para producir una unidad del ítem padre (Fig. 1-1).

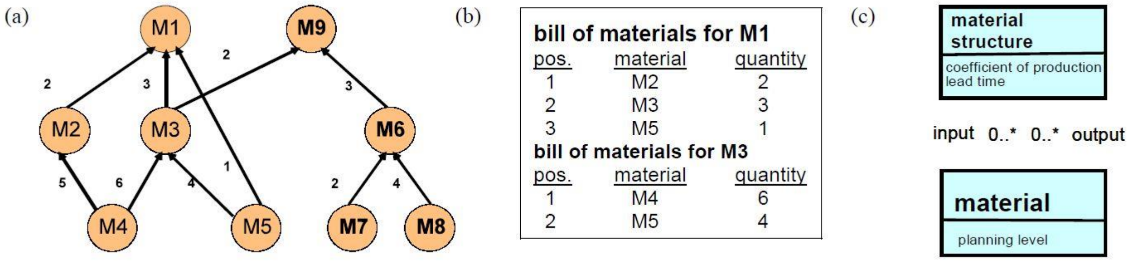

Fig. 1-1 (a) Grafo Gozinto (b) Lista de Materiales (c) Diagrama de clase correspondiente (Loos, 2001)

Estos dos modelos de datos estándares permiten gestionar de forma estándar la producción en la mayor parte de las empresas. El modo de establecer los planes de producción se basa en un algoritmo simple. Dicho algoritmo fija periodo a periodo las necesidades de producción de cada producto (ítem padre) y establece los niveles necesarios a obtener de cada uno de los sub-productos (ítems hijos) como se explica en detalle en (Wight, 1984).

Los sistemas MRP tuvieron éxito en unos pocos años como demuestra el número creciente de implementación de tales sistemas en EEUU (Orlicky, 1975) entre 1970 y 1975. El uso de dichos sistemas permitió a las empresas manejar complejidades crecientes tanto de producto como de demanda. Al tener bajo control las necesidades de productos y materias primas, , las empresas descubrieron otra limitación de los MRP: no tenían en cuenta la capacidad finita de sus recursos (Wight, 1984). La no consideración sobre los niveles de producción admisibles podía llevar a planes no factibles. Por esta razón, se incorporó al modelo de datos la consideración los recursos y limitaciones de capacidad para los recursos productivos. La nueva estructura llamada Lista de Recursos (*Bill of Resources*, BOR) recoge la información sobre las capacidades de los diferentes recursos (por ejemplo las máquinas). A este modelo de datos, se le asignó un mecanismo de comprobación de capacidad que se denominó CRP (*Capacity Requirements Planning*). Después de la ejecución del MRP, los datos de producción en cada recurso comprobaban si se disponía de capacidad productiva suficiente en cada uno de ellos mediante algoritmos, tal y como se explica en Daniel et al. (1997).

Si no se dispone de la capacidad necesaria, se modifican los planes de producción iterativamente para ajustarse a la capacidad disponible de los recursos(Chung y Snyder, 2000; Taal y Wortmann, 1997) . Este era un mecanismo de bucle cerrado para la planificación conjunta de la producción y del uso de los recursos al que se denominó MRPII (*Manufacturing Resource Planning*) como explica (Wight, 1984).

El modo de resolver el problema no tenía en cuenta ningún tipo de coste financiero y se limitaba a encontrar una solución factible respetando las fechas de entrega y las capacidades. Esta limitación se ve abordada por primera vez en 1983 con la primera formulación matemática capaz de resolver el problema del MRPII (Billington et al., 1983). Este modelo permitía a la empresa no solamente planificar sus necesidades sino también optimizar económicamente sus planes de producción y compras.

Para poder utilizar estos modelos que aprehendían cada vez más elementos de la realidad, las empresas necesitaron gestionar más información. Para cubrir esta necesidad, y viendo cómo crecía la capacidad computacional y de almacenamiento de datos, se desarrollaron los denominados ERPs (*Enterprise Resources Planning, ERP)*. Estos sistemas contienen el MRPII pero también incorporan módulos para capturar información relativa a las finanzas, contabilidad, recursos humanos, marketing, etc. (Caridi y Sianesi, 1999). Kumar y Van Hillegersberg (2000) definen los sistemas ERP como paquetes de sistemas de información configurables que integran información y procesos basados en la información a lo largo y a través de las diferentes áreas funcionales de una organización.

Una vez capturado ese siguiente nivel, y al disponer de herramientas y modelos de datos estándar, y como consecuencia de la necesidad de integrar y coordinarse entre los miembros de las cadenas de suministro, aparecen los programas SCM (*Supply Chain Management)*. Los sistemas SCM ya no se limitan a integrar y 'optimizar' los procesos de negocio internos de una organización como los sistemas ERP, sino que también 'optimizan' las interacciones de la organización con sus *partners* de negocios arriba y abajo de la cadena de suministro según Tarn et al. (2002).

Estos sistemas permiten la planificación de la cadena de suministro, pero también tienen la ventaja de ser estandarizados y de permitir una integración de los diferentes sistemas para los miembros de una misma cadena de suministro. Dicha integración de información se entiende como la utilización de definiciones y códigos comunes para toda la organización. Esto implicó entre otros aspectos operativos, la utilización de una cantidad limitada o una única base de datos común para toda la compañía y una posible interoperabilidad entre las aplicaciones.

La interoperabilidad se considera alcanzado si la interacción puede, al menos, tener lugar en los tres niveles: datos empresariales, aplicaciones y negocios a través de la arquitectura del modelo de empresa y teniendo en cuenta la semántica (Poler et al., 2007). Pero, en lo que respecta a la planificación de materiales y de recursos, las empresas han tenido que adaptarse a los estándares fijados por los suministradores de soluciones ERP y SCM (Olson y Kesharwani, 2011). Como cada empresa tiene problemáticas distintas en cuanto a sus recursos y procesos el módulo de planificación de producción basado en el MRPII no puede resolver algunas de las necesidades particulares de las empresas. Esta necesidad es cubierta por desarrollos realizados por empresas especializadas bajo el nombre de Sistemas Avanzados de Planificación y Programación (*Advanced Planning & Scheduling System, APS).* Los APS son un tipo particular de Sistemas de Apoyo a la Decisión (*Decision Support System,* DSS) (1999). Estos sistemas permiten a las empresas suplir las deficiencias/ineficiencias de los ERP ofreciéndoles una herramienta diseñada a medida para resolver a problemas de planificación.

Por otro lado, los sistemas SCM evolucionaron en los ERPII (*Money Resource planning*) o también denominados MRPIII (Schollaert, 1994). A diferencia del MRPII, La evolución de estos sistemas permitió enfocar la planificación en términos de recursos económicos (Mula et al., 2012a). Sin embargo, estas herramientas seguían basándose en la lógica del MRPII que generalmente tiene en cuenta defectuosamente las limitaciones en el uso de recursos.

En entorno del año 2000, las empresas que desarrollaban sistemas APS y DSS fueron adquiridas por los suministradores de ERP (Olson y Kesharwani, 2011). Con estas compras, los desarrolladores de ERPs estandarizaron los modelos de datos y la estructura de los programas de los sistemas avanzados para que pudieran integrarse con sus ERPs. Todos los sistemas existentes han permitido mejorar fundamentalmente el funcionamiento de las empresas y más generalmente de las cadenas de suministro (Fleischmann y Meyr, 2003).

I. 2. Situación actual

La mayoría de las empresas manufactureras dispone hoy día de su ERP, y cuando se requiere una planificación detallada de la capacidad los suministradores de ERP intentan vender sus *add-ons* como los APS para optimizar sus operaciones (Albrecht et al., 2006). Los APS ahora permiten planificar no solamente la producción y las compras sino también permiten planificar el transporte, la programación de producción, el diseño de las cadenas de suministro (David et al., 2006).

En general, la experiencia nos muestra, las empresas no quedan satisfechas con el funcionamiento de los APS adquiridos. La razón puede ser simple: la estandarización que requiere el uso de estos programas, es en general incompatible con una complejidad creciente con dos orígenes: la que requiere la adecuación de las empresas a los mercados en los que actúan y la que genera el propio sistema que, cuando ve controlada una parte de su complejidad pasa a generar más complejidad.

Por ello, la mayor parte de las empresas finalmente planifican su producción, sus compras o transporte, utilizando hojas Excel ya que los ERPs o APSs son demasiados rígidos para adaptarse a sus realidades industriales (Hahn et al., 2000; Olson y Kesharwani, 2011). A pesar de su nombre, los APS no parecen ser herramientas que se puedan aplicar en todos los casos (Mok et al., 2011).

Las empresas necesitan herramientas flexibles que se adecúen a sus procesos y operaciones y no al revés. Algunos autores como Olson (2011) van más allá y relatan que algunos profesionales dicen públicamente que estos sistemas APS permiten mejoras pero son demasiado rígidos por ser herramientas muy enfocadas para los departamentos de IT, los compradores de estos programas, y que no ven las necesidades de los stackholders. Como dice Stadtler (2002), a pesar de que los APS estén diseñados para ser aplicables a un cierto número de industrias, los problemas decisionales pueden variar mucho de un sector a sector. De hecho, la literatura sobre modelos para optimizar los planes de compras, producción y transporte es importante, y presenta siempre nuevas variantes para resolver problemáticas industriales concretas y más complejas (Alvarez, 2007; Bilgen y Günther, 2009; Sarmiento y Nagi, 1999; Zhi-Long y Vairaktarakis, 2005).

Para profundizar en estas razones, se propone estudiar algunos de los aspectos relevantes de la literatura que pueden justificar la falta de uso de dichas herramientas estandarizadas. Para esto, en la sección II. , se propone una clasificación de los diferentes modelos de datos para la gestión de los materiales en la industria. En la sección III. , se estudiará como como los modelos de datos para la gestión de los materiales se han extendido en los procesos de negocios a lo largo de una organización y de una cadena de suministro para resolver problemas de planificación más detallados. En la sección IV. , se discutirá sobre las necesidades para las industrias de considerar otros modelos de datos para planificar con más detalles las operaciones. En la sección V. se introducirá la estructura de la tesis doctoral y de los objetivos de investigación perseguidos en la tesis doctoral.

II. Propuesta de una clasificación de los diferentes modelos de datos para gestionar los materiales en la industria

Para planificar los recursos y materiales necesarios para atender la demanda los modelos de datos enfocados a los materiales han evolucionado a lo largo de los últimos 50 años. Para poder entender esta evolución se propone, en este apartado, una clasificación de los diferentes modelos de datos utilizados. Para esto, se estudiará la necesidad de considerar diferentes modelos de datos para la industria en el primer apartado y se propondrá una clasificación a continuación.

II. 1. Necesidad de considerar diferentes tipos de listas de materiales en función del tipo de estructura del producto final

La gestión de las listas de materiales es uno de los factores más críticos para generar planes más reales, entendiendo como más reales aquellos planes más cercanos lo que cada día se debe hacer. Desde los años 60, las empresas manufactureras han sufrido un aumento considerable de complejidad en la gestión de sus listas de materiales (Serdarasan y Tanyas, 2012). Este aumento considera diferentes factores: (1) el aumento en la cantidad de productos a gestionar dentro los productos ensamblados (como por ejemplo el automóvil o el sector aeronáutico), (2) la cantidad de productos diferentes a servir a los clientes debido a un aumento de la personalización, (3) la necesidad de planificar, a mínimos costes, cada vez más productos con estructuras y características diferentes.

En la literatura, los BOMs tienen diferentes nombres en función de las industrias consideradas: una receta (*recipe*), una formula (*formula*), una lista de ingredientes (*ingredient list*), una lista de ítems (*parts list*), unas especificaciones de embalaje (*packaging specifications*), para nombrar unos pocos (Lee et al., 2012). Estos tipos de estructura aparecen para cubrir las necesidades de los dos tipos básicos de industria: la industria de procesos y la manufactura discreta (Fransoo y Rutten, 1994).

Dado que apoyarse en un modelo de datos ofrece muchas ventajas, las listas de materiales se han implementado de forma consensuada en las empresas. La tendencia global ha sido la de generar tipos de listas diferentes entre empresas e incluso entre las diferentes unidades de negocio de una misma empresa. Seguramente el origen de los diferentes tipos de BOM existentes se debe a las necesidades tan diferentes existentes entre los dos grandes tipos de industrias: la industria “discreta” y la industria “de procesos” (Crama et al., 2001).

Mientras que en la manufactura “discreta” el objetivo de la lista de materiales es representar la estructura del producto, en la industria de procesos la lista de materiales sirve también para representar los procesos técnicos para representar el input y el output de material (Wu, 2001).

No hemos sido capaces de encontrar una propuesta clara para clasificar los diferentes tipos de listas de materiales. Así que a continuación, se hace una propuesta para clasificar los BOMs en función de los siguientes criterios:

- La profundidad del BOM: El BOM mono-nivel y el BOM multi-nivel
- Las relaciones del BOM: El BOM plano y el BOM profundo
- La estructura del BOM: El BOM de tipo ‘A’, de tipo ‘V’ o de tipo ‘X’
- La flexibilidad del BOM: El BOM fijo y el BOM alternativo
- Las operaciones que se ejecutan: El BOM de ensamblaje, el BOM de desensamblaje, el BOM genérico y el BOM cíclico
- La naturaleza de los materiales del BOM: los productos tradicionales, los embalajes, los productos fantasmas
- El nivel de agregación de los datos: El BOM tradicional y el BOM agregado

II. 2. El BOM mono-nivel y el BOM multi-nivel

Un BOM mono-nivel implica que un conjunto de materia prima se transforma en un conjunto de productos acabados. Por ejemplo, un BOM mono-nivel podría ser un producto inyectado en una prensa como un vaso de plástico. De forma genérica, un BOM mono-nivel es aquella representación de la estructura de materiales que considere solamente dos niveles y puede que ser una decisión de representación más bien que la estructura del producto terminado.

Un BOM multi-nivel es aquel que considera más de dos niveles de productos. En general, la mayor parte de los productos ensamblados son multi-nivel. Un BOM multi-nivel implica, al menos, la existencia de una materia prima, un conjunto de productos semi-acabados, sub-ensamblajes o embalajes, y la existencia de un conjunto de productos acabados.

Un BOM se puede caracterizar según la relación entre su profundidad y su anchura (Lea y Fredendall, 2002). Según Benton y Srivasta (1985), por profundidad se entiende el número máximo de niveles de productos, mientras que por anchura se entiende la cantidad inmediata de ítems hijos diferentes para cada ítem padre.

Autores como Caridi y Sianesi (1999) definen estos parámetros bajo el concepto de complejidad del BOM. Lo seguro es que la estructura plana o profunda del BOM permite saber si un producto dado necesita más actividades de soporte (p.e planificación, ingeniería, aprovisionamiento, etc.) que otro según se comenta en el trabajo de Lea y Fredendall (2002).

II. 3. Las estructuras de BOM de tipo A, de tipo V, y de tipo X

La literatura suele caracterizar un producto en función de la estructura de su grafo gozinto o del árbol asociado a un determinado producto (Grubbström, 1995). Una de las posibles clasificaciones consiste en caracterizar las listas de materiales según tres tipos de estructura: los BOMs de tipo 'A', de tipo 'V' y de tipo 'X'. Algunos autores como Perez Pereales et al. (2002) proponen esta clasificación para caracterizar plantas sin explicitar el origen de esta. A diferencia de estos últimos autores que se enfocan en el sector del automóvil, a continuación se caracterizará el tipo de estructura asociado a un determinado conjunto de productos acabados para que la caracterización sea más genérica.

Los productos con un BOM de tipo 'A', llamado también BOM convergente (2004), son aquellos que se obtienen un único producto en base a muchos componentes. Los productos con listas de materiales de tipo A tienen una forma de pirámide y son típicas para los productos ensamblados. Las empresas ensambladoras de automóviles o de máquinas herramientas por ejemplo, solían tener este tipo de listas. Sin embargo, con la personalización en masa, estas listas han evolucionado hacia estructuras de tipo 'X'.

Los productos con un BOM de tipo 'V' son aquellos que las variantes que exige el mercado se generan a partir de un número muy reducido de materias primas. A medida que se va avanzando por el proceso de producción, los productos se transforman en distintos productos acabados. En la industria, estos tipos de listas de materiales son frecuentes en la industria agro-alimentaria, la industria siderúrgica, la industria de refinería del petróleo, etc. Estas estructuras divergentes pueden surgir también cuando aparecen los denominados co-productos y by-productos (Segerstedt, 1996b). Estas estructura de listas se suelen representar de modo inverso al de la estructura convencional en 'A' (Inderfurth y Langella, 2006). Spengler et al. (1997) introducen el fenómeno para el proceso de desmantelamiento de edificios, y proponen un modelo de datos basados en las precedencias para planificar las operaciones.

Una variante de listas divergentes es el de *product binning* (Lyon et al., 2001) donde se obtienen diferentes calidades de producto al realizar la misma operación, pero siempre tras un análisis del resultado.

Los productos con un BOM de tipo 'X' se caracterizan por tener un alto grado de personalización resultado de la combinación de un número relativamente bajo de sub-ensamblajes o componentes. También, estos sub-ensamblajes deben caracterizarse por tener un BOM de tipo 'A'. Rusk (1990) denomina esta estructura 'reloj de arena' (*hourglass*) por su forma de doble trapecio. Kim (2007) define esta estructura como propia del sector del automóvil ya que las combinaciones posibles de configuraciones debido a las opciones, los cambios de ingeniería y la impredecibilidad de estos últimos la hacen interesante.

II. 4. El BOM fijo y el BOM alternativo

El tipo de estructura más frecuente en la fabricación discreta es el BOM fijo (*fixed BOM*). Un BOM fijo implica que un producto final tiene una estructura de materiales única y fija. La idea básica de estas listas de materiales convencionales es relacionar un ítem padre (un producto de ensamblaje generalmente) con un conjunto de ítems hijos (sub-ensamblajes o componentes).

En contraposición al BOM fijo han aparecido variantes. Estas listas de materiales alternativas tienen diferentes nombres en la literatura. Para caracterizarlas, al no haber encontrado ninguna clasificación satisfactoria, se propone clasificarlas según:

1. La flexibilidad sobre las cantidades de ítems hijos
2. La flexibilidad para sustituir un ítem por otro

El nombre concreto de las listas de materiales, considerando una cantidad variable de ítems-hijos, es el BOM flexible (*flexible BOM*) y fue introducido por Ram et al. (2006). Según estos autores, el BOM flexible fue utilizado por la NASA para resolver una problemática de preparación de comida para los astronautas, en el cual la cantidad de ítems-hijos para preparar una receta podía variar en función de la disponibilidad de estos. Ram et al. (2006) aplican este concepto de BOM flexible al MRP incorporando la existencia de rangos mínimos de cantidad de ítem hijos a incorporar en un ítem padre. De este modo, se permite de este modo responder a inesperadas roturas de stock al usar el MRP para planificar los productos con demanda dependiente. Este tipo de BOM no se puede aplicar en todos los sectores. Por ejemplo, Lin et al. (2009) sugieren que la existencia de productos alternativos puede ser una decisión del fabricante, fundamentalmente como resultado del *product binning*.

El segundo tipo de BOM alternativo se puede caracterizar por la posible sustitución de ítems hijos por otros. Seguramente, uno de los primeros en introducir esta estructura de BOM alternativo fue Escudero (1994) bajo el concepto de *alternate (sic) BOM* para considerar componentes de sustitución. En este trabajo, se propone un algoritmo en la herramienta *Capacitated Multi-level Implosion Tool*. En ella, no solamente se considera limitaciones de capacidad para los recursos productivos, sino que también considera la existencia de productos substitutivos en listas de materiales complejas. A continuación, Balakrishnan y Geunes (2000) introdujeron los conceptos de componentes comunes y componentes de sustitución para resolver el problema de planificación considerando la sustitución de unos productos con otros de más alta funcionalidad. Esta sustitución es llamada también *"upgrading"* en la industria electrónica según Lang (2010). Otro problema presente en la literatura coge el nombre de Planificación de Requerimientos con sustitución (*Requirement Planning with Substitution*, RPS) en (Balakrishnan y Geunes, 2000; Geunes, 2003). El modo de resolver este problema se basa en la agregación de familias de producto. Dentro de cada familia, algunos componentes pueden ser sustituidos por otros pero no se presenta ningún modelo de datos en estos trabajos. Lyon et al. (Lyon et al., 2001) proponen otro tipo de listas de materiales alternativas dentro del módulo llamado *Alternative BOM material-resource-planning.* En este módulo, se considera un problema de *binning* para un *downgrading* de substitución y una estructura alternativa de BOM debido a procesos alternativos de producción para un mismo ítem. En paralelo a la literatura, las empresas vendedoras de ERP desarrollaron sus propias listas de materiales flexibles. En el caso de SAP®, el BOM múltiple (*Multiple BOM*) es un objeto técnico, consistiendo en diferentes combinaciones de material, que se represente para un número de BOMs alternativos. Estos BOMs alternativos según la ayuda se usan para la planificación de producción y difieren solamente ligeramente en la cantidad de algunos materiales en algunos ítems (2012).

II. 5. Las listas puras: de ensamblaje o desensamblaje y las listas mixtas: genéricas o cíclicas

Se pueden caracterizar las listas de materiales según las operaciones que se llevan a cabo para la obtención de los productos finales. Por este motivo, en la literatura, diferentes tipos de listas de materiales se caracterizan en función de los tipos de procesos involucrados.

Probablemente, la lista más frecuente es la lista de materiales dicha de "ensamblaje" (*Assembling BOM,* ABOM). Bajo este concepto, se entiende que la lista de material es de tipo 'A' en su estructura.

En los años 90, apareció otro tipo de lista asociada a las operaciones de desensamblaje y reciclaje con el nombre de lista de materiales de desensamblaje (*Disassembly BOM*, DBOM). Los DBOMs son versiones agregadas de los BOMs de ensamblaje ya que no todos los detalles sobre los ítems son necesarios para el desensamblaje, sino que se necesita información sobre la estructura de fijación, y los fijadores (Das y Naik, 2001). Posiblemente, Das y Naik (2001) fueron los primeros en introducir el DBOM aunque la consideración del desensamblaje se debe a los trabajos previos de Wallace (1993), Johnson (1995) y Shyamsundar (1997).

Por otra parte, la literatura considera los BOMs genéricos. Estos son típicos de las industrias de procesos como la industria química dónde los procesos generan frecuentemente co-productos o by-productos además del producto primario que se manufactura. Un ejemplo típico es la elaboración de los productos petrolíferos, en los cuales múltiples grados de lubricantes y fueles son producidos así como productos que no se pueden usar (by-productos en este caso). Según el APICS[1], el termino co-producto se asocia a aquel producto "*que se suele manufacturar conjuntamente o secuencialmente debido a similitudes de productos o procesos*". Esta palabra se usa para describir múltiples productos que son producidos simultáneamente durante la ejecución de un proceso. Se utilizan a menudo para aumentar el rendimiento en las operaciones de corte. También se conocen como productos secundarios, y son comunes en el proceso de fabricación como en plantas químicas. Aunque el concepto de co-productos es bastante simple, la lógica de programación para la planificación y el procesamiento de los subproductos es muy complicada." Por otra parte, y según el APICS[2], los by-productos son aquellos "*productos de valor producidos como residuos o incidentales al proceso productivo. El ratio de sub-producto al producto primario es generalmente predecible. Los Sub-productos pueden ser reciclados, vendidos como tal o ser utilizados para otros fines.*" Pantelides (1994) presenta una estructura en forma de Grafo bipartito denominada *State Task Network* (STN). El STN se podría denominar "co-product BOM" ya que es una extensión natural del BOM tradicional en el cual básicamente se añade una tabla "co-product" ligada al ítem padre (el producto principal). Posteriormente, el STN fue ampliado a *Resource Task Network* (RTN) en el trabajo de Barbosa-Pavoa y Pantelides (1997) siendo muy utilizada en trabajos relacionados con la programación de producción en la industria química.

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[1] http://www.apics.org/dictionary/dictionary-information?ID=806

[2] http://www.apics.org/dictionary/dictionary-information?ID=483

Sin embargo, y a pesar de ser una temática específica de la industria de procesos, la industria discreta comenzó a considerar dichos sub-productos. En el caso de la industria automóvil, las piezas de las carrocerías se hacen en una planta de estampación donde a partir de pocas materias primas, se pueden obtener muchos productos que pueden ser co-productos o by-productos (Deuermeyer y Pierskalla, 1978). Otro caso donde se caracteriza esos productos se puede encontrar en (Weidema, 1999). Sin embargo, Vidal Carreras et al. (2012) introducen la planificación “deliberada” de dichos productos.

El último tema de lista de materiales concierne el uso de los embalajes. Existen varios tipos de embalajes en cuanto a sus geometrías, sus usos, pesos, etc. Los embalajes, como podría ser el caso de los contenedores en la planificación portuaria, tienden a considerarse cada vez más como productos a planificar en sí mismos.

En el caso de los embalajes no-retornables (como los embalajes de cartón) en la mayor parte de las empresas, los modelos de datos pueden consideran (o no) estos productos. Sin embargo, no existe un circuito de recirculación del embalaje. En algunas industrias como es el caso del automóvil, es muy frecuente usar embalajes duraderos para transportar las piezas (ya sea a su cliente o a otra planta de la compañía). También es frecuente para las empresas que únicamente secuencian los productos, desempaquetar los productos de una embalaje duradero y empaquetarlos en otras unidades de carga (otro embalaje duradero) para entregar el producto Justo en Secuencia. En estos casos, la estructura del producto es cíclica ya que el embalaje se reutiliza. En el momento de escribir este documento no hemos encontrado literatura que introduzca un modelo de datos capaz de representar estas estructuras.

II. 6. Los BOMS y la naturaleza de los materiales

Una lista de materiales, como ya se definió anteriormente, es un modelo de datos que representar unas relaciones entre productos. Sin embargo, la naturaleza de los productos puede también caracterizar un BOM.

Se suele asociar a un BOM un producto. Este producto se entiende como componente, ensamblaje, sub-ensamblaje, material, ítem ubicado físicamente en un sitio. Por una razón seguramente económica, pero también de complejidad debido a la cantidad de productos a gestionar, los BOMs se han enfocado siempre en los productos físicos con valor añadido.

Debido a las necesidades de considerar todos los materiales posibles, en los BOMs se han incorporado productos que antes no se consideraban. Wu et al. (2009) por ejemplo consideran dos tipos de BOM para el aprovisionamiento: el BOM de materia prima (*raw materials BOM*) y el BOM de paquetes (*packing BOM*). Este segundo es según los autores necesarios para planificar las necesidades de cajas, instrucciones, PVC que se usan para empaquetar el producto final. A pesar de su nombre distinto, los autores consideran que estos productos son iguales al producto principal en la lista de materiales. Solamente se denominan de modo diferente para poder gestionarlos de forma separada durante la explosión del MRPII.

Existen también otro tipo de materiales que se considera en las listas de materiales. Son los ítems fantasmas (*phantom ítems*). Según Balakrishnan y Geunes (2000), para resolver el RPS, cuando el número de elementos alternativos que simultáneamente se pueden considerar es elevado, es interesante utilizar el concepto de productos fantasmas. Clement et al. (1995) definen los *phantom items* de la manera siguiente: "*Los Phantom ítems no se producen nunca y tampoco se almacenan*". Luszczak (2012), en su trabajo sobre el programa Microsoft Dynamics AX 2012®, explica que los productos fantasmas se pueden planificar pero no generan ordenes de fabricación en sí-mismo ya que no existen. En este caso, se genera una orden de fabricación solamente para los ítems hijos del ítem fantasma.

II. 7. El BOM detallado y el BOM agregado

En general, se entiende por lista de materiales, el modelo de datos que define los ítems o materia prima que va dentro de un producto(Garwood, 1988). Cox et al. (1995) amplían la definición enfatizando en las relaciones entre los componentes y padres definiendo el BOM como el "listado de todos los sub-ensamblajes, productos intermedios, partes y materia prima que van dentro de un ítem padre de ensamblaje y ofreciendo un valor sobre la cantidad necesaria de cada uno para ensamblar un producto de ensamblaje".

En general, como dice Stonebraker (1996), en el caso de una competencia limitada, con poca presión por parte de la demanda, un BOM detallado tradicional es suficiente. Sin embargo, cuando los ciclos de vida de productos son reducidos, la flexibilidad en los procesos es más importante y que los tiempos de entrega se reducen, los sistemas de información necesitan migrar desde una visión tradicional del BOM hacia un versión agregada llamada Modular BOM. Como explica Stonebraker, a diferencia de un BOM detallado dónde los productos se gestionan desde el ítem de más alto nivel (producto final), en los BOMs modulares, los productos se gestionan a un nivel intermedio del BOM usando agrupaciones. Este tipo de BOM es sobre todo necesario en el caso de la personalización en masa. Gracias a este tipo de BOM, se reduce el número de listas segregando los ítems comunes y se eliminan las combinaciones de características de productos (Stonebraker y Keong Leong, 1994).

Para ir más allá del BOM modular, los productos se pueden en algunos casos agrupar en pseudo-ítems. Los pseudo-ítems fueron considerados primero por Mather (1982) para denotar un conjunto de partes físicos que dentro de un proceso de ensamblaje se usan siempre como un conjunto. En el caso de Bertrand et al. (2000), los autores manejan los pseudo-ítems para presentar el BOM jerárquico de pseudo-ítem. En este caso, los autores asignan un número de código a todos los pseudo-ítems de la misma forma que los productos tradicionales para facilitar el *picking* y reaprovisionamiento de estos.

III. Diferentes modelos de datos basados en los materiales en las empresas

Las listas de materiales también han evolucionado con los sistemas de información para satisfacer las necesidades de las diferentes unidades de negocio o departamentos de las empresas. La literatura presenta numerosos tipos de listas de materiales que no se distinguen en su estructura sino solamente en su área de aplicación y en la naturaleza de la información en las listas. La existencia de diferentes BOMs hizo que la literatura también ha abordado bastante la problemática relativa a la transformación de dichas listas.

III. 1. Modelos generados en las diferentes fases del ciclo de vida del producto

Un buen ejemplo de los diferentes tipos de presentes en la industria se presenta en la Fig. 1-2 en el caso del automóvil.

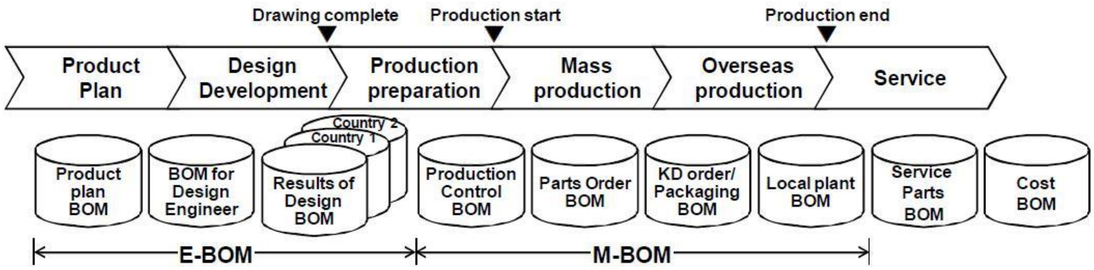

Fig. 1-2 Ejemplo extremo de los múltiples BOM de una empresa del sector del automóvil (fuente: Tozawa y Yotsukura (2009))

De la fase de diseño a la fase de ventas, existen diferentes tipos de BOM que se distinguen. Estas distinciones existen seguramente debido a las necesidades de cada unidad de negocio pero también debido a las diferentes fases del ciclo de vida de los productos. El primero de ellos es el BOM de ingeniería (*engineering BOM, EBOM)*. El EBOM se usa para representar la estructura del producto diseñado y sus funciones de producción.

Después, el BOM de diseño (*Design BOM*) es generado por el departamento de diseño. Este BOM estructura una información más detallada sobre la estructura del producto final (Qing-lan, 2008). En general, una vez establecido el BOM de diseño, se debe generar el BOM de proceso (*process BOM, PBOM)*. El PBOM usa el *Design BOM* y se le introduce datos de sub-ensamblajes, operaciones, tamaños, y los indicadores de rendimiento necesarios en el proceso según Han (2008).

Una vez terminados el EBOM y el PBOM, este se transforma en un BOM de producción (*manufacturing BOM,* MBOM) para ser usado por el sistema de planificación de producción.

Lee et al. (2012) dicen que en las industrias trabajando en MTO (*Made-To-Order*) y ATO (*Assembly To Order*), solamente se manejan el EBOM y el MBOM. De todos modos, la transformación entre el primero y el segundo consiste solamente en la incorporación de la secuencia de ensamblaje (Brun y Zorzini, 2009). Para hacer esta transformación, existen algoritmos como el de Chang et al. (1997) para transformar un tipo de lista de materiales hacia otro.

Sin embargo, la estructura de los productos objeto de planificación se han ido complicando, tanto por el desarrollo tecnológico como por las estrategias del tipo mass customization (Pine, 1993). De este modo la representación de la lista de materiales se ha ido convirtiendo en un problema cada vez más complicado (Hegge y Wortmann, 1991). Así se puede afirmar que la investigación respecto a cómo capturar, almacenar y manejar listas de materiales no está en absoluto acabada (Stapic et al., 2009).

Es interesante también destacar que Tozawa y Yotsukara (2009) relatan que Toyota no usa diferentes BOM en función del área de negocio, del ciclo de vida o incluso de la planta, sino que existe un único BOM llamado *Specification Management System*. Según estos autores, incluso si la separación entre el EBOM y el MBOM ofrece flexibilidad, es necesario integrar todos los BOMs en uno para que este se pueda transformar en una herramienta de comunicación potente.

III. 2. Modelos generados para facilitar la dirección y gestión

Han surgido otros tipos de listas de materiales para facilitar las tareas de dirección y gestión de operaciones. Por ejemplo, el concepto de BOM de coste (*cost* BOM, CBOM) apareció para facilitar las labores del departamento de contabilidad y finanzas. Este CBOM consiste en asignar de forma consensuada la estructura de coste asociada a la estructura del producto (Qing-lan, 2008).

Para el departamento de calidad, el BOM de calidad (*quality BOM,* QBOM*)* apareció para facilitar la dirección y gestión de la calidad total (Jiang et al., 2004).

El departamento de compras necesita también un modelo de datos para suplir las deficiencias de los BOMs tradicionales. Por este motivo, autores como Yao et al. (2009) introdujeron el BOM de aprovisionamiento (*Procurement* BOM, PBOM). El PBOM tiene como función estructurar los datos para la materia prima y auxiliar con el fin de determinar en función de las futuras necesidades en material en el tiempo, los lotes de aprovisionamiento a realizar.

III. 3. Modelos de datos integrados para el apoyo a la planificación de las operaciones

Con el fin de planificar las necesidades de recursos, se introdujo otro modelo de datos basado en los recursos con el nombre de Lista de Operaciones (*Bill of Operations*, BOO). En general, este modelo se suele llamar ruteo (*routing)*. Wunsch et al. (2007) justifican que el BOO es el modelo de datos fundamental para la ejecución de la producción. El BOO representa el modo de fabricar el producto y define todas las actividades que se tienen que ejecutar para obtener el producto pedido. El BOO contiene información sobre los varios segmentos de procesos (p.e. operaciones), que se interrelacionan entre ellos vía unas relaciones de precedencia, procedimientos en paralelos u opcionales y las relaciones jerárquicas. SAP por ejemplo lo denomina Lista de Operaciones de Producción (Cameron, 2012).

Sin embargo, al tratarse de otro modelo de datos en paralelo, para facilitar las tareas de planificación de producción a capacidad finita, Jiao et al. (2000) integraron el BOM y el BOO en un modelo de datos compacto denominado Lista Genérica de Materiales y Operaciones (*Generic Bill of Materials and Operations, GBOMO*).

Según los autores, esta unificación permite sincronizar múltiples perspectivas de variedad como la gestión de pedidos de los clientes (*customer ordering*), la ingeniería de productos y la planificación de operaciones.

Para integrar más funcionalidades necesarias para la planificación de operaciones, Zhang et al. (2012) propusieron un modelo de datos denominado Lista genérica de Funciones, Materiales y Operaciones (*Generic Bill of Functions, Materials, and Operations*, GBoFMO). El GBoFMO es una estructura conceptual general para una familia de productos desde el punto de vista de ventas, diseño y producción. Los autores usan esta estructura en el caso de la industria aeronáutica para el ensamblaje de avión. La estructura propuesta se limita a casos de lista de materiales de ensamblaje puras y como explican los autores, les falta probar la estructura propuesta en modelos de programación para demostrar sus implicaciones sobre la planificación y la configuración de los procesos. En paralelo a esta unificación, las industrias tuvieron que desarrollar otros modelos de datos para considerar más factores críticos para las tareas de planificación de operaciones.

III. 4. Hacia una integración en entorno multi-planta

Actualmente muchas de las compañías disponen de varias plantas geográficamente distribuidas. La gestión de los BOMs en un entorno distribuido añade un punto más de complejidad a los datos a mantener. En general, y en muchos casos, en un mismo sistema ERP, dos productos idénticos situados en dos plantas distintas no deberían tienen el mismo *part number*. Tozawa y Yotsukara (2009) dicen que hay que distinguir el origen de los diferentes ítems hijos de un mismo producto ensamblado a pesar de tener el mismo *part number* en sistemas con diferentes BOMs. En SAP® y Oracle®, los productos pueden tener un atributo de ubicación en sus módulos de optimización[3].

Esta consideración se debe tener presente en la planificación ya que como sugirieron de Kok y Fransoo en (de Kok y Fransoo, 2003) y posteriormente en (Pires et al., 2008) un producto en otro sitio, no es más que otro producto. Por esta razón, Tozawa y Yotsukara (2009) alaban el uso de un BOM integrado como el de Toyota, en este se distingue cada *part number* en función del país de origen (*mother country*) y del país (*local country*) dónde se encuentra inventariado.

Otro problema a resolver cuando la problemática industrial es multi-sitio es la consideración del transporte. En la literatura sobre planificación integrada con resolución mediante modelos de programación matemática, el problema se aborda introduciendo variables de transporte (ver Sousa et al. (2008) o Mula et al. (2010) por ejemplo). Sin embargo, la literatura no está muy desarrollada sobre los modelos de datos que permiten planificar estos transportes.

Pires et al. (2008) introducen el único modelo de datos encontrado en el cual se considera el transporte denominándolo Lista de Materiales y Movimientos (*Bill of Materials and Movements, BOMM*). Este BOMM que se aplica en el ámbito de las empresas virtuales (*Virtual Enterprise, VE*) es una de las piezas centrales para los sistemas de Planificación de Producción y control de las VE según la propuesta de Carvalho et al. (2005). Según estos autores sólo una estructura de materiales que incluya también la ubicación de los productos permitirá la coordinación de lo que denominan Sistemas Autónomos de Producción. El artículo plantea la estructura de materiales y movimientos como un ente dinámico y propone los diagramas IDEF0 de los procesos que permitirán modificar y mantener los BOMM a lo largo de la vida de la VE.

[3] http://help.sap.com/saphelp_nw73/helpdata/en/b6/61fc388861c403e10000000a114084/content.htm

IV. Discusión

En los apartados anteriores, se ha observado que la literatura presenta muchos modelos de datos para intentar proponer un soporte a la planificación de los materiales y, más recientemente, a las operaciones. Históricamente, la palabra "Operación" se ha asociado a cualquier actividad relacionada con el flujo de material. Por lo tanto, el significado de "Operaciones" se asignó primero a las tareas de producción y más tarde, se le incorporó el transporte, la distribución o el almacenamiento. Sin embargo, las operaciones no se deberían limitar a las actividades relacionadas directamente con el flujo del material, sino con todas las actividades que aportan valor al cliente y las actividades relacionadas con los recursos.

Como se ha visto anteriormente, muchos modelos de datos se han desarrollados de forma aislada para resolver algunos de los problemas de las empresas. Probablemente, el modo idóneo de estructurar los datos para la planificación de una cadena de suministro consistiría en usar un modelo único que pueda soportar la información y apoyar las operaciones de todos los dominios internos (o unidades de negocio) de todos los miembros de la cadena.

Posiblemente, al no existir un modelo integrado y único capaz de apoyar las tareas de planificación de las operaciones, las empresas se han orientado hacía una planificación de las operaciones basada en hojas de cálculo personalizadas. Durante la implantación de las herramientas, objeto de capítulos en esta tesis doctoral, los profesionales (Directores de Operaciones y de Planificación de Cadenas de Suministro) evocan que las razones suelen ser las siguientes:

- Los modelos de datos capturan la existencia del ruteo alternativo pero no son capaces de soportar una decisión basada en costes. El ruteo se asigna al producto que se obtiene. Si existen diferentes ruteos, existe una preferencia entre los dos ruteos. Y siempre se usará el ruteo preferente.
- Los modelos de datos soportan la consideración de los co-productos y by-productos pero se planifican de forma deliberada.
- Los modelos de datos no son capaces de considerar de forma adecuada el uso de los embalajes en un entorno multi-plantas. Este nuevo *asunto* es una preocupación muy importante para aquellas empresas que deben gestionar embalajes duraderos entre plantas.
- Los modelos de datos no soportan la planificación de las operaciones de transporte y la problemática asociada a los modos de transporte alternativo.
- Los modelos de datos no consideran en la planificación del aprovisionamiento considerando alternativas.
- La necesidad de considerar operaciones de ensamblaje alternativas sin considerar agregación por familias.
- La necesidad de considerar tareas de mantenimiento como parte integra de las operaciones.

Para tratar de averiguar los motivos y aportar soluciones, se plantean en esta tesis los siguientes objetivos:

1. Estudiar las necesidades de las empresas, proporcionando conocimientos empíricos sobre algunas características de la planificación de las operaciones en la industria.

2. Definir un nuevo modelo de datos para soportar la planificación de las operaciones considerando listas de materiales alternativas y operaciones alternativas en los contextos multi-plantas.
3. Proponer un modelo de programación matemática para resolver el problema genérico de planificación y de programación de las operaciones considerando Listas de Materiales alternativas, co-productos, by-productos y embalajes así como operaciones alternativas de transporte en un entorno multi-planta.
4. Desarrollar algoritmos para resolver problemas de planificación y programación de las operaciones en base al nuevo modelo de datos.
5. Implantar el nuevo modelo de datos en una herramienta de planificación.
6. Reflexionar sobre los requisitos e implicaciones a la hora de implementar herramientas basadas en este nuevo modelo de datos.
7. Desplegar y analizar las matrices asociadas al nuevo modelo de datos que facilitan la implementación de un modelo y una herramienta que se basen en el concepto de stroke.
8. Proponer mecanismos de coordinación para coordinar modelos de programación matemática en diferentes niveles de planificación así como en diferentes dominios de planificación.

V. Propuesta y Estructura de la tesis y los objetivos de investigación

Esta tesis doctoral gira alrededor del concepto stroke y su aplicación. Un stroke representa cualquier operación básica (en su sentido más genérico), tarea o actividad que puede transformar, transportar o consumir un conjunto de productos (medido preferentemente como SKU) para obtener o generar otro conjunto de productos (también medido preferentemente en SKU). Cada stroke puede utilizar o inmovilizar recursos en su ejecución.

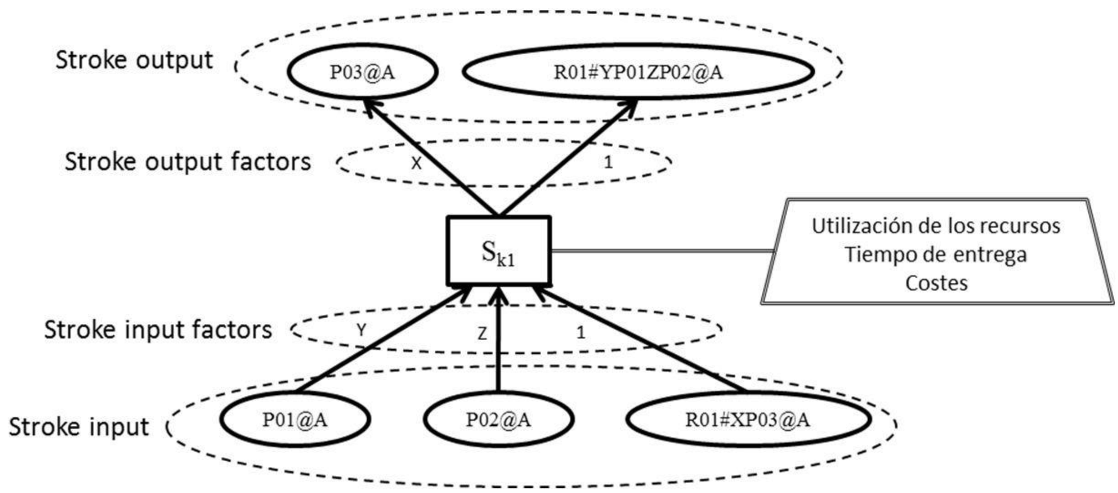

Fig. 1-3 Representación conceptual de un Stroke S_k

El uso del stroke supone la necesidad de estructurar los datos de una forma distinta a las estructuras presentes en los sistemas comerciales. El uso del stroke permite, por otra parte, hacer un modelado que pone la planificación y programación de las operaciones en nivel de igualdad a la de requerimientos de materiales. Además, con el stroke, se pretende considerar de una forma única y sencilla las estructuras conocidas de productos, las rutas alternativas, las alternativas de operación (ya sean de aprovisionamiento, de transformación, de venta o de transporte) que podría facilitar la integración de la planificación para redes de suministro multi-sitio y que podría resultar de aplicación en diferentes industrias.

La tesis está estructurada en capítulos que, aunque hayan sido publicados o estén en fase de publicación, se han maquetado para tener el mismo formato que el primer capítulo de modo que no tienen el formato de la revista y se respetan los derechos de *copyright*.

Por su estructura, los capítulos se pueden leer de forma independiente teniendo cada capítulo todos aquellos detalles necesarios para su perfecta comprensión (marco teórico, objetivos, resultados y conclusiones).

En este apartado se muestra una guía de los objetivos de la tesis y los capítulos donde se han abordado.

1. El primer objetivo es "estudiar las necesidades de las empresas, proporcionando conocimientos empíricos sobre algunas características de la planificación de las operaciones en la industria".

Dicho objetivo se aborda en el 0, 0, Capítulo 5, Capítulo 7, y el Capítulo 9.

Se puede observar en el 0 que los modelos de programación matemática se han enriquecido a lo largo de los años. En los Capítulos 4, 7 y 9, se revisa la literatura sobre las necesidades para la planificación de las operaciones en el sector del automóvil. En el Capítulo 5, se introduce una problemática de configuración de red de suministro y de programación de operaciones en el caso de una empresa ensambladora de máquinas herramientas.

2. Definir un nuevo modelo de datos para soportar la planificación de las operaciones considerando listas de materiales alternativas y operaciones alternativas en los contextos multi-plantas e implantarlo en una herramienta.

Este objetivo se introduce en el Capítulo 5. Se propone una base de datos relacional basada en el concepto Stroke como elemento central para poder considerar operaciones alternativas. La base de datos propuesta se ha implementado en un sistema de soporte a la decisión.

3. Proponer un modelo de programación matemática para resolver el problema genérico de planificación y de programación de las operaciones considerando Listas de Materiales alternativas, co-productos, by-productos y embalajes así como operaciones alternativas de transporte en un entorno multi-planta.

En esta tesis, diferentes capítulos proponen modelos de programación matemática. Para la planificación de las operaciones, el primer modelo genérico se describe íntegramente en el 0. En el Capítulo 3, se propone una ampliación del modelo genérico. El Capítulo 7 y el Capítulo 9 presentan otras variantes.

Por otra parte, en el Capítulo 8 se propone un modelo de programación matemática que tiene en cuenta específicamente características de programación de las operaciones.

4. Desarrollar algoritmos para resolver problemas de planificación y programación de las operaciones en base al nuevo modelo de datos.

En el Capítulo 8, se propone un modelo de programación lineal entera mixta. Para su implantación en una herramienta (ver Capítulo 5), la necesidad de trabajar sin usar un programa de resolución de modelos matemáticos, permitió el desarrollo (Capítulo 6) de un algoritmo para resolver el problema de programación de las operaciones en un entorno multi-plantas.

5. Implantar el nuevo modelo de datos en una herramienta de planificación.

Este objetivo se aborda en diferentes capítulos que introducen aplicaciones reales de desarrollo de herramientas diseñadas a medida. En el anexo del 0 y el Capítulo 9 se introduce la implantación del modelo de datos en FSegura. En el 0, se describe una herramienta de planificación implantada en una empresa del sector del automóvil dónde se usa el modelo de datos propuesto. Por otra parte, en el Capítulo 5, se describe también un sistema de apoyo a la decisión que se diseñó para una empresa del sector de bienes de equipo.

6. Reflexionar sobre los requisitos e implicaciones a la hora de implementar herramientas basadas en este nuevo modelo de datos.

Este objetivo se aborda en 2 capítulos. En el 0, se propone una reflexión sobre la implantación de una herramienta integrada de tipo APS en una empresa ensambladora de motores. En el Capítulo 9, se aborda también este objetivo en el caso de una aplicación para un proveedor del sector del automóvil.

7. Desplegar y analizar las matrices asociadas al nuevo modelo de datos que facilitan la implementación de un modelo y una herramienta que se basen en el concepto de stroke.

Este objetivo se aborda en el Capítulo 3 dónde se introduce, se despliega y analizan las matrices necesarias para facilitar la implementación de herramientas basadas en el concepto de stroke.

8. Proponer mecanismos de coordinación para coordinar modelos de programación matemática en diferentes niveles de planificación así como en diferentes dominios de planificación.

Este objetivo se aborda primero en el 0 dónde se propone un mecanismo de coordinación jerárquica implantado en la primera fase del desarrollo de la herramienta. En el Capítulo 10, se proponen los diferentes mecanismos implantados en la fase final de la implantación de la herramienta.

Capítulo 2 A new formulation technique to model Materials and Operations Planning: the Generic Materials and Operations Planning (GMOP) Problem

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Abstract. This paper presents a technique that mathematically models relationships between operations and materials, which amends the usual technique used to model Materials and Resources Requirement Planning through Mathematical Programming. This technique represents operations and materials requirement planning by extending the bill of materials concept beyond the Gozinto structure. This so-called Generic Materials and Operations Planning (GMOP) Problem is based on the “stroke” concept. The decision variables are the operations (strokes) each resource is capable of, and not materials or resources. This form extends modeling capacity to transformation operations, resource and product substitution, and material transportation. It considers most conventional bills of materials types (direct, alternative and reverse BOMs, alternative resources and routings) with the same data structure. It contemplates multi-level problem modeling, and even packaging and alternative transport modes. The same data structure represents these characteristics. The problem, its mathematical modeling approach and examples illustrating its use are provided.

Keywords: Alternative bill of materials; Alternative operations; Alternative routings; Generic Materials and Operations Planning; Material Requirement Planning; Packaging; Product substitution; Reverse bill of materials; Stroke; Supply chain management

I. Introduction

In the 1970's when multi-level materials management commenced, materials management was seen to be a relevant matter, and tools/methodologies became known as Material Requirement Planning (MRP). Later on, planning of the resources required to produce the materials was incorporated. In the proposed structures, all the materials and resources needed to manufacture a product were associated with it. This origin probably marked a lock-in (Arthur, 1989; David et al., 2006) to tackle Materials and Resources Requirement Planning.

This paper proposes an alternative modeling technique that places emphasis on planning what is known to be done rather than the result of the action (the product). The proposed modeling method is useful given its simplicity and generality. Furthermore, its proposal is feasible since the mathematical programming of problem-solving technology has considerably improved in the last 10 years (Bixby y Rothberg, 2007).

This need emerged from the planning tools design and production planning in the automobile sector. Given the pressure to continuously improve (Lamming, 1993), it is usual to come across manufacturing processes that do not strictly adapt to an assembly-type structure (Garcia-Sabater y Vidal-Carreras, 2010), and alternative products and resources, or deliberate co-production circumstances, may arise (Vidal-Carreras y Garcia-Sabater, 2009). These features, together with the relevance of alternative processes, ought to be taken into account in the planning process. This work specifies and analyzes in detail a modeling process which has been outlined in papers, like that of Calderon-Lama et al. (Calderon-Lama et al., 2009) or that by Garcia-Sabater et al. (Garcia-Sabater et al., 2009a), and has been implemented in different tools of current use.

The rest of the paper is arranged as so: the evolution of materials and operations planning has been briefly reviewed by considering resources constraints. Some works relating to Materials and Resources Planning under the name of Multi-level Capacitated Lot-Sizing Problem (MLCLSP), or others, have been analyzed. Special stress is placed on works which present variants in modeling instead of on those that present variants in ways of solving. Next, the proposal is presented and how this proposal includes the cited variants in a more compact formulation. Then there are two cases in which the concept has been successfully applied, along with some general observations to implement the tool in a practical context. Finally, some conclusions and future research lines are offered and proposed, and a simplified case study is provided as an appendix.

II. Materials and Operations Planning

II. 1. Introduction to the MRP logic and its evolution

Many authors indicate that Orlicky (1975) was the first to successfully apply the logic of the so-called MRP, although others like Mabert (2007) highlight former experiences in the 1950's. In any case, they all acknowledge that Orlicky greatly boosted the main technique known to plan the demand of materials of demand-dependent products.

Although MRP is a well-studied technique, it is relatively frequent to encounter firms that do not apply it at all or that do not apply it fully (Lin et al., 2009). More often than not, the generated plan is more descriptive of the activity itself than it is prescriptive (Shapiro, 2010).

II. 2. Basic MRP data

The basic input data in an MRP system are the Master Production Schedule (MPS), the Bill of Materials (BOM) and initial stock levels (Slack et al., 2010). Executing the planning process generates production and purchase orders that will feedback the next MRP execution. The quantity and quality of the information that the MRP requires to run is the main problem to be faced (Chase et al., 2004).

So, as the MPS plan attempts to satisfy due dates and customer demand, increases in demand uncertainty have mixed effects on the MPS due date performance (Enns, 2002). The problem of demand uncertainty has different origins, and this problem is tackled from various perspectives: improving forecast processes (Poler et al., 2008), optimizing safety stocks (Molinder, 1997), or developing solutions that consider uncertainty when planning (Mula et al., 2008).

Another equally important problem is that the inventory data lack certainty. As this is evidently an operative-type problem, firms of all sizes whose level of reliability between their Official Information System Data and reality is far too broad for a Materials Planning System to provide reliable results are frequently found. Improving the quality of the registered data (Kang y Gershwin, 2005) is probably the only reasonable way forward.

If the problem of both the MPS and stocks levels is considerable, then the BOM structure problem is no better. From the data structures viewpoint, this theme has been extensively covered. The structure of the products to be planned has been complicated by both technological development and mass customization-type strategies (Pine, 1993). Thus, representation of BOMs has become an ever increasingly complex problem (Hegge y Wortmann, 1991). So it may be stated that research into how to acquire, store and manage BOMs is far from complete (Stapic et al., 2009).

The basic structure of conventional BOM has always been to relate a parent item with one or several child items, which only takes place in pure convergent product structures (Perez Perales et al., 2002). Yet even in these cases, once one of the firm's subsystems has defined a structure (generally a structure used for new products design), an algorithm will have to be designed to transform one type of BOM into another (Chang et al., 1997); even Olsen et al. (1997) proposed that such a process is part of defining the BOM.

Concepts like the Generic Bill of Materials and Operations (GBOMO) by Jiao et al. (2000) and Phantom Items (Clement et al., 1995; Luszczak, 2009) are ways of structuring BOMs to facilitate the consideration of product variants, transportation processes and co-products or substitution products. However, merely considering "alternate BOMs" (Escudero, 1994) or "reverse BOMs" (Gupta y Taleb, 1994; Lambert y Gupta, 2002), as two examples, is a complicated issue.

II. 3. Considering resources and their capacity constraints

One of the most obvious constraints of classic MRP systems is not considering capacity limits. Although one work (Mize et al., 1971) had already considered this problem, its real circumstances had not actually been considered until MRPII had been introduced, whose authorship is attributed to O. (Wight, 1984). When it came about, MRPII was seen as a closed loop system because, after performing the materials explosion, the capacity leading to an adjustment of input data and to the subsequent launch of the MRP to restart the analysis was continually checked until an acceptable result was obtained (Voss y Woodruff, 2005). In this way, the database required to calculate materials requirements must be extended by incorporating routing (Plenert, 1999) and, of course, the capacity data. Thus to implement an MRPII system properly, both product structures and process structures are required (what is known as generic routing).

For different reasons, both structures have evolved separately in Enterprise Resource Planning (ERP). Tatsiopoulos (1996) indicates three reasons why this situation comes about: avoiding the inflation of part numbers, the existence or nonexistence of production stages with intermediate warehouses, and the need to maintain different attributes for materials and operations. Yet the same author points out that a unified structure is better understood in small firms than a separate structure.

II. 4. The MRPII Mathematical Formulation

Initially, those applications dedicated to MRP emerged mainly from perspectives based on data processing rather than from a mathematical or an optimization perspective. The development of operations planning applications that consider capacity constraints occupies a relatively common place in the literature (Drexl y Kimms, 1997). The consideration of multi-level systems creates numerous ways of covering capacity constraints and, should they be required, the need for not exceeding this capacity (Rong et al., 2006). Yet tackling the problem from the mathematical programming perspective is more likely to be a good mechanism, as suggested by Segerstedt (1996b), who indicates that formulas are the “supreme methods for communication”.

It is worth stressing that this author’s notion of assigning a BOM and a bill of resources to each product that is susceptible to being assembled has been maintained since it was proposed, and has not been since amended. The matrix linking each parent item with its child items required for its assembly appears in this formulation, and is in accordance with the Gozinto structure presented by Vazsonyi (1954). Mize et al. (1971) already presented a matrix-based calculation method, although the proposal of considering an MRP enabled by mathematical programming can be attributed to Billington et al. (1983). Obviously, existing technological constraints (both hardware and software) prevented these authors in 1983 from stating that the model itself was applicable. So their work proposes alternative methods to solve it.

This work included some concepts such as the lead time, which is also associated with the product, plus a yield for production and a bill of resources in a matrix form. Likewise, the objective function of the model contemplated in (Billington et al., 1983) incorporates stock holding and setup costs, as well as production costs relating to overtime and idle time.

Billington et al. briefly consider one of the most important problems in the practical formulation of any of these models; that of setting the coefficient values of the objective function. Later, Segerstedt (1996) considers a variant of the model and justifies why it is not to be put into practice by explicitly associating it with the user’s incapacity to understand marginal costs.

III. MLCLSP and the extensions required to adapt it to reality

The commonest name with which to consider the mathematical model that simultaneously solves the materials and operations planning problem is the MLCLSP. Other authors ascertain that this is a mathematical version of the more general Supply Chain Operations Planning problem (de Kok y Fransoo, 2003), or they include other adjectives when defining it; for example, dynamic (Buschkühl et al., 2009).

The model representing the problem is a simple one, but solving it in a reasonable time has always proved a complex matter. Therefore other authors like (Stadtler, 1996) have developed more sophisticated models which, using more constraints, help solve the mathematical programming model faster. Some authors like Pochet and Wolsey (2006) suggest that optimization tools cannot tackle real problems. Nevertheless, increased computing capacity of late, and not just in computers, but also optimization technology itself (Bixby y Rothberg, 2007), offers hope.

All in all, most works on the MLCLSP still assume that the BOM entails assembly products. A series of problem variants based on amending the structure of BOMs may also be found in both the practice and the literature. Some interesting ones are provided below.

III. 1. Gozinto Matrix and Resources Matrix

As previously mentioned, the conventional way of representing the BOM is the Gozinto Matrix (goes into) Aij in which products i (parent item) relate to products j (child items). The products structure is assumed to always be convergent. The values of matrix Aij are normally positive integers. BOMs are, therefore, represented in denominated direct BOMs.

In association with each product i, the quantity of resource *r* required to produce a unit of product i by means of matrix *Uir* is also constituted, and this structure was considered by Mize et al. (1971).

III. 2. Alternative products and resources

The existence of alternative components was contemplated by, for example, the work of Escudero (1994), which offers obvious advantages thanks to the addition of both risks in components availability and demand (Balakrishnan y Geunes, 2000). This problem is sometimes called Requirement Planning with Substitution (RPS) as, for example, in (Lang y Lang, 2010), which requires long computing times. Attempts have been made to overcome this computing cost problem by means of alternative and ever increasingly complex formulations (Geunes, 2003), even though the problem is not a multi-level one. Lang and Domschke (2010) propose extending this problem by considering the limited constraint for one resource, or for many.

Ram et al. (2006) propose an interesting variant is the so-called Flexible BOM in which the BOM depends on the availability of materials. However, these authors maintain that this concept cannot be applied to most production systems. Lin et al. (2009) suggest that the existence of alternative products could be the manufacturer's decision, basically as a result of product binning; however, it may seem inappropriate for certain clients who recognize the difference. In this way, the number of alternative products would grow in accordance with the alternative components employed. If as Balakrishnan and Geunes (2000) suggest the number of alternative elements which may be simultaneously considered for a given product is large, then the use of the phantom products concept is an interesting one: "Phantoms are items produced in the manufacturing process and thus are definable parent items, but they are not typically stocked" (Clement et al., 1995).

Lot-sizing problems, which include the suppliers' selection or multiple manufacturing alternatives, are also related with products substitution (Aissaoui et al., 2007) both in terms of considering them and how to solve them. Likewise, the lateral transshipments proposed by Tagaras (1999) are assimilable to products substitution.

One situation which, to the best of our knowledge, has not been modeled is that of considering different lead-times with different costs, but using the same resource; this would once again imply the use of alternative resources. Some authors suggest that the definition of lead time is exogenous to the problem (de Kok y Fransoo, 2003), and that it would be interesting to develop a costs models according to which a supplier could commit itself in a short time at a higher cost (with the same resources and the same resources utilisation).

III. 3. Reverse Bill of Materials

Reverse BOMs are needed when a product gives way to two products or more through the transformation process. One of the reasons behind this is that the so-called co-products, or by-products, appear. Segerstedt (1996a) terms these structures "divergent structures", and indicates that the way to model them is to assume that the aij value determines the amount of each i obtained from the transformation of j. This type of modeling is, however, very limited to specific kinds of divergent processes.

Another special type of problems with divergent structures occurs in the so-called Reverse MRP (Gupta y Taleb, 1994). This problem does not consider products that are not assembled, but those that are disassembled or separated into pieces. These structures tend to be represented inversely to the conventional structure (Inderfurth y Langella, 2006). Spengler et al. (1997) introduce the phenomenon for the dismantling process with buildings, and consider different activity alternatives that generate varying amounts of finished products. These authors propose an MILP model; however they believed that the commercial software programs available in 1997 could not solve it in a reasonable time. Apparently the reverse lot-sizing problem is considerably more complex than the direct lot-sizing problem (Barba-Gutierrez et al., 2008).

In general terms, direct BOMs are never mixed with reverse ones in mathematical problem modeling. Schutz et al. (2009) incorporate reverse BOMs along with direct ones and, in parallel, state that: "In addition, even when it comes to pure operational models, we do not know any alternative model that handles a combination of splitting processes and combining processes." In order to solve the problem of including them in the same model, two different matrices are established for each one. The direct ones are known as BOMs, while the reverse ones are called r-BOMs.

III. 4. Several inputs and outputs in the same process

Indeed, processes can be found in which one operation involves disassembly and assembly (or processes that may be considered simultaneous). These simultaneous assembly and disassembly processes are quite usual in the chemical industry. Pantelides (1994) presents a bipartite graph called the State Task Network, which was later extended to the Resource Task Network (Barbosa-Pavoa y Pantelides, 1997), and is widely used in scheduling-related works in the chemical industry.

Sousa et al. (2008) consider an integrated planning and scheduling model for a network of chemical products firms. Their proposal includes two solution stages using MILP models. Having considered the existence of this type of processes (with several inputs and outputs) in the chemical industry, the authors simplify them with a conventional Gozinto structure by contemplating their models which, incidentally, include transport between plants.

Co-production, a normal feature in the processes industry (Crama et al., 2001), is not often considered in the discrete production theory. In general, the existence of co-products (or by-products) is generally considered “non deliberate”, although it could well be “deliberate” (Vidal-Carreras y Garcia-Sabater, 2009); in other words, a decision is made to co-produce two or more products simultaneously in the same operation.

This co-production problem may also vary, this being the aforementioned product binning problem (Lyon et al., 2001), where various product qualities were obtained during the operation, but always after analyzing the result.

III. 5. Transport between plants

Transport between plants has been considered by a good number of authors, including (Sousa et al., 2008) and (Schutz et al., 2009). In general, the problem of incorporating new sites tends to be solved by including a new subindex with the variables. In any case, and as suggested by de Kok and Fransoo (de Kok y Fransoo, 2003), and by Pires et al. (2008) later, basically, a product at another site is just another product.

Caner Taskin and Tamer Ünal (2009) contemplate a planning model that simultaneously considers substitutable products, yield production, co-production and multisites. This work examines a multi-level problem, and the multisite concept is present, although sites eventually overlap. Thus, the problem in this work boils down to an alternative resources analysis (located at different sites).

Pires et al. (2008) work out the Bill of Materials and Movements (BOMM) in a Virtual Enterprise (VE) setting. In fact, the proposal put forward by Carvalho et al. (2005) states that this structure is defined as the central piece of VEs’ Production and Control Planning Systems. According to these authors, only one materials structure, which also includes products sites, will enable the coordination of the so-called Autonomous Production Systems. This paper considers the materials and movements structure to be a dynamic entity, and proposes the IDEF0 diagrams of the processes to amend and maintain the BOMM throughout the VE’s life. Moreover, this work does not consider coordination at all, but assumes that the proposed structure must be taken into account. A complementary problem appears with the alternative transports considered in, for example, (Calderon-Lama et al., 2009).

III. 6. Packagings

Should a product be packaged with different packagings, it might be defined as different entities; this fact is mentioned in (Pinto et al., 2007). Furthermore, Voss and Woodruff (Voss y Woodruff, 2005) consider SKUs (stock-keeping units) as the minimum unit to be planned. Carner Taskin and Tamer Ünal (2009) believe that a product packaged for one client is a different product if it is packaged for another client. Along these lines, changing packagings could be viewed as a substitution activity (Lang y Domschke, 2010). Thus, transferring one product between packagings must be considered another operation.

Our experience, based mainly in the automobile sector, reaches a higher level as it assumes that end product packagings are an input of the process and that, similarly, raw materials packagings become the output of the same operation. Having considered packagings, considering returnable packagings becomes unavoidable. However, returnable packagings pose a cyclic structure problem which, despite being habitual in the chemical industry (Scheer, 1994), is not usual in discrete manufacturing, which therefore poses problems in most approaches, as in (Ball et al., 2003; Sahling et al., 2009).

Once packagings have been considered to be different components of a specific product, the possibility of determining a transport plan for empty packaging becomes an obvious option, if required.

The Full Truck Load strategy may be adopted using the same argument in certain sectors that have imposed the use of complete packagings as a means of transport (Puig-Bernabeu et al., 2010). The use of complete packagings entails the appearance of over-deliveries (or negative backlogs); that is, those products delivered before they are required for complete packaging delivery.

IV. Modeling the GMOP problem

IV. 1. Definition for the concept of “Stroke”

To consider this proposal, it is compulsory to specify some basic assumptions. Not only the place where products are stored should be considered, as proposed in (Pires et al., 2008), but also the type of packaging to be used. The products contemplated in this approach should always be SKU which, within the frame of this work, are products defined with both their packaging and site. Such data can be ignored if there is no possibility or need to consider packagings or sites in a given problem.

The series of products that the operation input consists in will be known as “stroke input”. Kitting is the name given by Jiao et al. (2000) to a very similar stroke inputs concept. The series of products of an operation output will be called “stroke output”.

A stroke represents any operation that transforms (or transports) a series of products (preferably measured as SKUs) into another series of products (also preferably measured as SKUs). This operation and, therefore the stroke representing it, has an associated cost and due date, and consumes a certain amount of resources during the first of the due date planning periods; however, this aspect could be reconsidered in accordance with the specific case. Fig. 2-1 proposes a conceptual representation of a stroke. The due date in the proposed deterministic model is taken into account. Should it be a stochastic model, the approaches of Hnaien et al. (2008) could be employed to diminish the due date uncertainty problem.

Resources are associated with each stroke, but not with the product (or the series of products) obtained. In general terms, it is possible to obtain this data from the bill of routing (Tatsiopoulos, 1996).

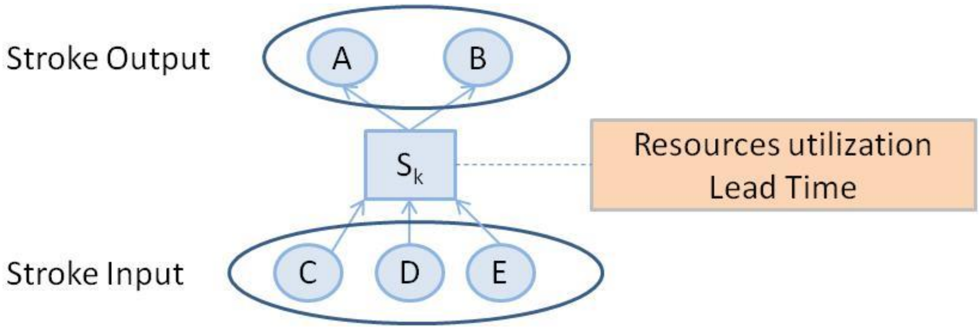


Fig. 2-1 Conceptual representation of a Sk Stroke

IV. 2. Mathematical formulation of the MLCLS problem using strokes: the GMOP model

This section contemplates the mathematical formulation of the problem model, and the name put forward for this model is the GMOP Problem. To mathematically formulate the problem, it is necessary to define the nomenclature presented in Tabla 2-1.

Tabla 2-1 Nomenclature

Indices	
i	*Index set of products (includes product, packaging and site)*
t	*Index set of planning periods*
r	*Index set of resources*
k	*Index set of strokes*
Parameters	
D_{it}	*Demand of product i for period t*
h_{it}	*Cost of storing a unit of product i in period t*
CO_{kt}	*Cost of stroke k in period t*
CS_{kt}	*Cost of the setup of stroke k in period t*
CB_{it}	*Cost of purchasing product i in period t*
SO_{ik}	*Number of units i that generates a stroke k*
SI_{ik}	*Number of units i that stroke k consumes*
LT_k	*Lead time of stroke k*

KAP_{rt}	*Capacity availability of resource r in period t (in time units)*
M	*A sufficiently large number*
TO_{kr}	*Capacity of the resource r required for performing one unit of stroke k (in time units)*
TS_{kr}	*Capacity required of resource r for setup of stroke k (in time units)*
Variables	
z_{kt}	*Amount of strokes k to be performed in period t*
δ_{kt}	*= 1 if stroke k is performed in period t (0 otherwise)*
w_{it}	*Purchase quantity for product i in period t*
x_{it}	*Stock level of product i on hand at the end of period t*

The linear GMOP programming model may be formulated as so:

$$Z:\min\sum_{t}\sum_{i}\left(h_{it}\cdot x_{it}+CB_{it}\cdot w_{it}\right)+\sum_{t}\sum_{k}\left(CS_{kt}\cdot\delta_{kt}+CO_{kt}\cdot z_{kt}\right) \quad (0.1)$$

Subject to:

$$x_{it}=x_{i,t-1}-D_{it}+w_{it}-\sum_{k}\left(SI_{ik}\cdot z_{kt}\right)+\sum_{k}\left(SO_{ik}\cdot z_{k,t-LT_k}\right) \quad \forall i,t \quad (0.2)$$

$$z_{k,t}-M\cdot\delta_{k,t}\leq 0 \quad \forall k,t \quad (0.3)$$

$$\sum_{k}\left(TS_{kr}\cdot\delta_{kt}\right)+\sum_{k}\left(TO_{kr}\cdot z_{kt}\right)\leq KAP_{rt} \quad \forall r,t \quad (0.4)$$

$$x_{it}\geq 0;\ w_{it}\geq 0 \quad \forall i,t \quad (0.5)$$

$$z_{k,t}\in\mathbb{Z}^{+};\ \delta_{k,t}\in\{0,1\} \quad \forall k,t \quad (0.6)$$

The objective function (0.1) attempts to minimize the costs involved in storing and purchasing materials, and in performing operations by considering both setup and storage costs. Constraint (0.2) is a stock continuity constraint where that obtained by the planned strokes is added to the stock of the former period, with the associated lead-time, or it is compared externally and demand is deducted since this is what is consumed in the planned strokes for the considered time instant. Constraint (0.3) is introduced to know if stroke k is produced in t by employing the capacity associated with the setup (setup forcing). Constraint (0.4) is a capacity constraint that limits the use of resource r in period t by considering both setup and operations times. Constraints (0.5) and (0.6) define the range of variables.

For simplicity reasons, the following have not been incorporated: the initial level of stocks, planned receipts of goods, details about the lead time consideration (a similar application can be found in (Clark y Armentano, 1993)). Moreover, other variants, such as the possibility of delays, over-deliveries, or the use of additional capacity, have not been specified.

IV. 3. How does the proposal solve the extensions to Materials and Operations Planning?

Next, the different transformations required between the classic Gozinto structures and the structures that the strokes use as a planning method are established. The so-called direct BOMs are conventional ones. One or several products give(s) way to a single product. In this case, the operation representing the stroke is of an assembly or transformation kind. Traditionally, this is the type of BOM that has been represented with a Gozinto Graph which, in the proposed mathematical representation, requires two similarly sized matrices based on the BOM (Fig. 2-2). To understand our proposal, the "Stroke graph" and the "Stroke matrices" associated with the same BOM are introduced.

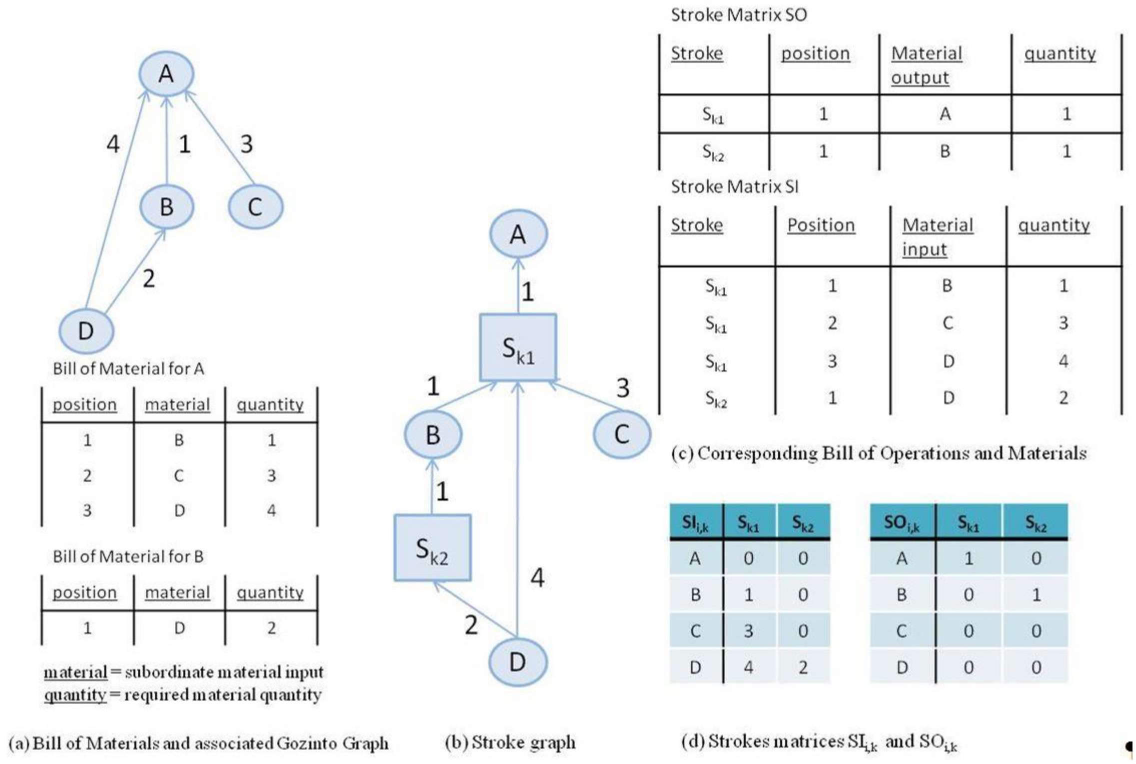
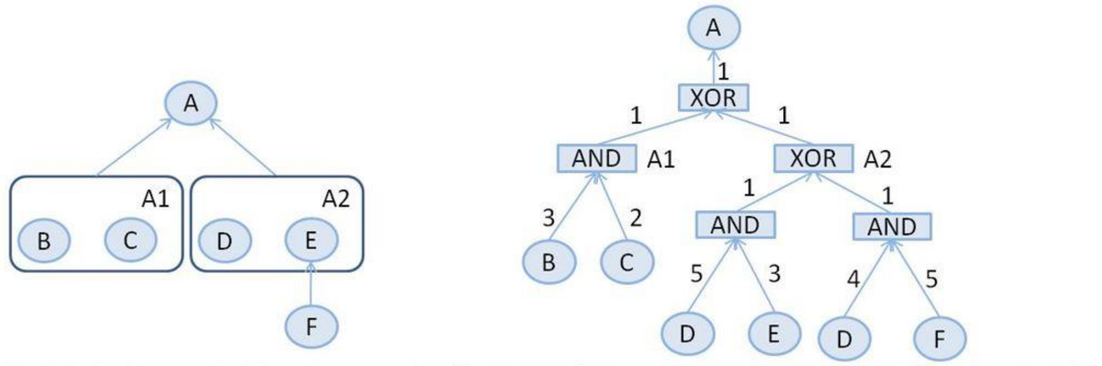
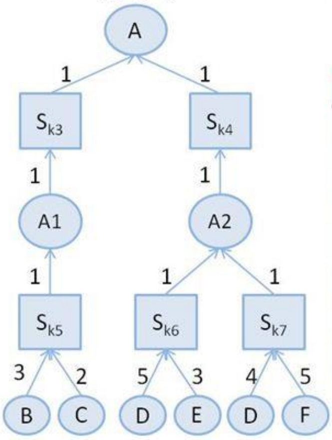


Fig. 2-2 Gozinto Graph vs. Stroke Graph and BOM vs. Stroke matrices

The fact that there are substitution components does not amend the formal structure of the problem; it is merely a matter of creating an additional operation. The same structure applies to the existence of alternative operations, or even to different ways (with different costs) of doing the same operation. Thus that which for Sahling et al. (2009) is a very useful future work for the case of parallel machines is actually included very simply in the representation. The structure conventionally employed to express products substitution is a substitution hypergraph (Lang y Lang, 2010). An example of a simple substitution hypergraph with six products, two assemblies and the corresponding Gozinto factors is depicted in Fig. 2-3.a. The corresponding AND-XOR graph representation (Ozturan, 2004) is also depicted in Fig. 2-3.b. The corresponding Stroke graph is proposed in Fig. 2-3.c and its associated matrices are presented in Fig. 2-3.d. It is worth mentioning that we do not consider "*abstract products*" (a similar concept to phantom items) here, but we contemplate two alternative operations (see S_{k6} and S_{k7}).



(a)Substitution hypergraph without abstract product (b) Corresponding AND-XOR graph representation without abstract product



(c) Stroke graph with Substitution and without abstract product

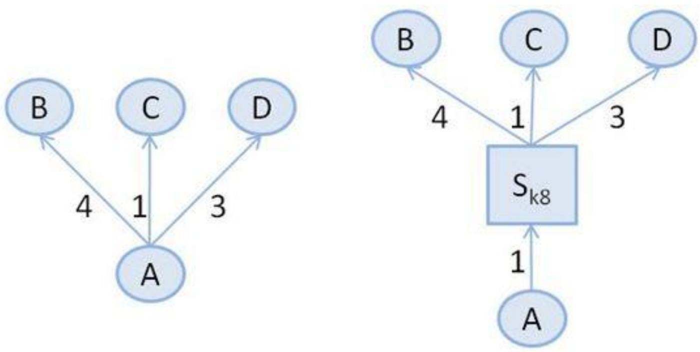
$SI_{i,k}$	S_{k3}	S_{k4}	S_{k5}	S_{k6}	S_{k7}
A	0	0	0	0	0
A1	1	0	0	0	0
A2	0	1	0	0	0
B	0	0	3	0	0
C	0	0	2	0	0
D	0	0	0	5	4
E	0	0	0	3	0
F	0	0	0	0	5

$SO_{i,k}$	S_{k3}	S_{k4}	S_{k5}	S_{k6}	S_{k7}
A	1	1	0	0	0
A1	0	0	1	0	0
A2	0	0	0	1	1
B	0	0	0	0	0
C	0	0	0	0	0
D	0	0	0	0	0
E	0	0	0	0	0
F	0	0	0	0	0

(d) Stroke matrices in case of products substitution and without abstract product

Fig. 2-3 Representations of alternative operations with substitution products

The so-called reverse or divergent structures may also be represented simply if the same concept is used (Fig. 2-4).



(a) Divergent Graph (b) Stroke graph

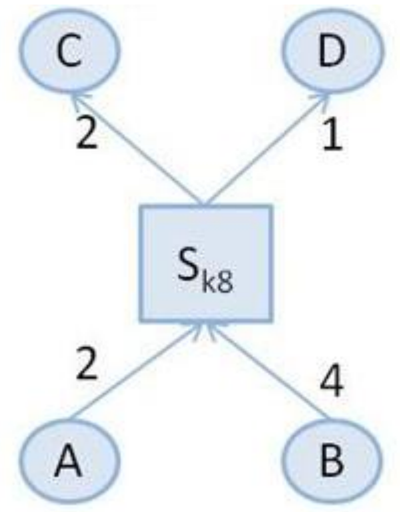
$SO_{i,k}$	S_{k8}
A	0
B	4
C	1
D	3

$SI_{i,k}$	S_{k8}
A	1
B	0
C	0
D	0

(c) Corresponding Stroke matrices

Fig. 2-4 Representation of the stroke graph and stroke matrices from the reverse or divergent BOMs

Besides, the operations that generate two products simultaneously are represented in a similar way (Fig. 2-5).



(a) Stroke graph

$SI_{i,k}$	S_{k9}
A	0
B	0
C	2
D	1

$SO_{i,k}$	S_{k9}
A	2
B	4
C	0
D	0

(b) Corresponding Stroke matrices

Fig. 2-5 Representation of the stroke graph and stroke matrices from complex processes (transfers, transports, etc.)

The fact that there are multiple substitution products (owing to, for instance, product binning) in a given step of the process, could pose a problem which involves excessive growth in the number of strokes required. To avoid this problem, the use of phantom items, "pi", and phantom strokes, "pS_k", is advised. Phantom strokes neither consume resources nor have lead times, and phantom products are not stored. An example of a stroke graph with six products, five substitution products, five phantom items, ten phantom strokes and stroke factors assumed to be 1 is depicted in Fig. 2-6.

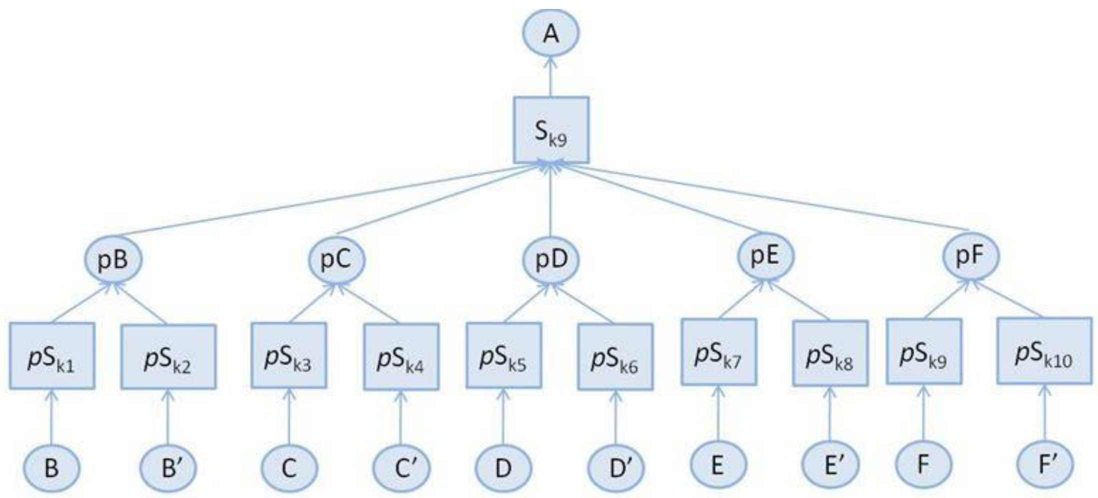
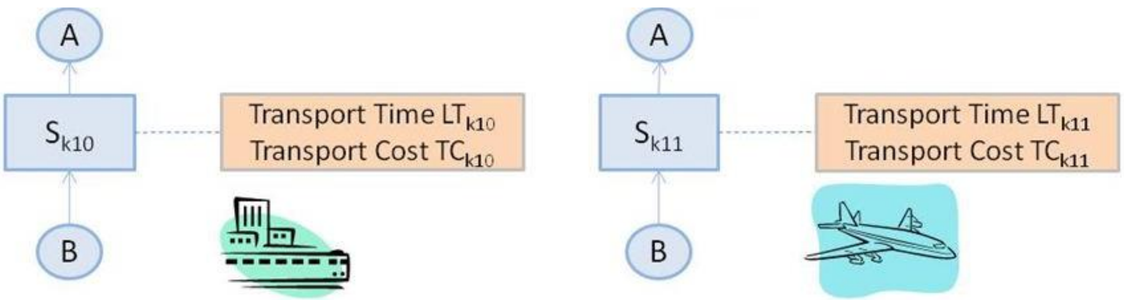


Fig. 2-6 A stroke graph with phantom items and phantom strokes to produce a single product

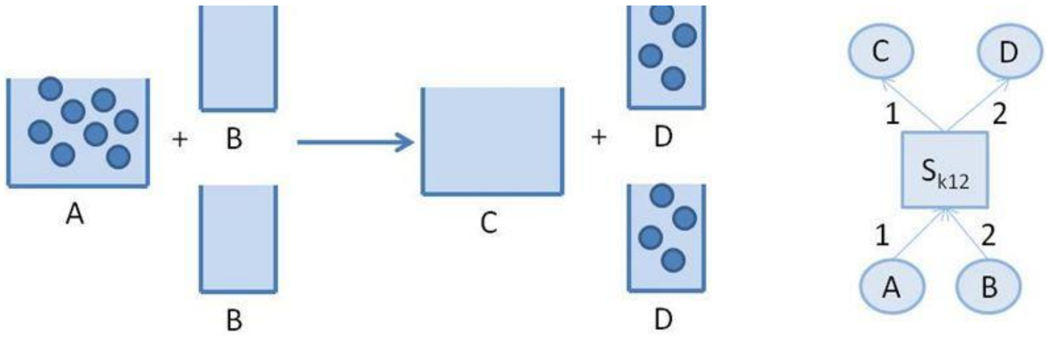
The problem structure needs no amendments if there are alternative forms of transports (with different costs and transit times), as shown in Fig. 2-7.



(a) Stroke of transport by boat (b) Stroke of transport by plane

Fig. 2-7 Representation of stroke graphs showing alternative forms of transport

Considering packagings (represented in Fig. 2-8) as a necessary element to perform an operation, and occasionally as the element resulting from the same operation (empty packaging), does not entail having to amend the problem formulation.



(a) Scheme about Operations of (un)packaging (b) Corresponding Stroke graph

Fig. 2-8 Representation of the strokes of the operations involving change of packaging

In general, and as previously indicated, the proposal would involve products being identified not only by their individual characteristics, but by them bearing the associated packaging and site. In this way, transformation operations would entail product change, but not necessarily packaging or site; transport operations would entail site, but not necessarily product or packaging; finally, packaging change operations would entail neither product change nor site.

V. The GMOP in practice

V. 1. A practical application: the Segura case

The intention here is to generate a production and operations plan for a network of firms which produces and assembles metal elements, basically for the automobile sector. As they are the global supplier of some parts, this entails having to send the same reference on different packaging types depending on whether they are to be returned or not, or if the destination installations have certain, more or less, automated processes.

Furthermore, some products involve more than seven processing stages (including several stamping, welding, chemical treatment, painting stages, etc). Some stages are "convergent" (welding or assembly), while others are "divergent" (cutting); in a given case with four components, two different products are obtained. The structure consists in approximately 500 end products and some 2500 intermediate products in any of its stages. Seven plants located in a radius of roughly 30 kilometers are considered. Products and semi-finished goods are transported inside complete containers. This means having to manage over-deliveries, delays in deliveries and movement of empty containers among plants, among other aspects.

The developed tool not only plans production operations, but also movement of materials and the packaging requirements in all seven plants. Budget limits did not allow the use of professional software to solve the real problem. Therefore, a multi-agent system-based heuristics is implemented which employ the stroke concept in (Garcia-Sabater et al., 2006). Appendix 1 presents a simplified example of the Segura problem for three end products (with variations among them) for two clients (with different quality requirements) at two sites.

V. 2. A practical application: the engines case

The case described in (Garcia-Sabater et al., 2009a) is another application where this form of modeling has been successfully used. Here attempts have been made to plan the assembly and transformation operations of an engine manufacturing plant with 40 engine derivatives, and with a similar number of components and mechanized raw material.

One important peculiar aspect of the system is that there are some components that are classified into two categories given their quality features. Some clients accept engines with components from both categories, while others do not. Seeing as there are 40 engines and that each engine has five different components, if attempts had been made to construct a Gozinto matrix for each combination or way of producing engines, this would have resulted in 1280 different engines in accordance with the components that may be produced. The use of phantom strokes and phantom components leads to a lower number of 80 different engines being produced, and also enables the inclusion of some components that act as substitution products. This problem not only handles complete packagings, but also fills trucks with packagings or considers sequence-dependent setup costs. Presently this tool is able to generate a feasible 42-day horizon plan by considering capacity constraints in just over ten minutes.

V. 3. A preliminary analysis of the advantages and disadvantages of this proposal

The main advantage of this way of formulating the problem is that it represents materials and resources requirements planning in a compact, intelligible fashion as a result of the decision variable, this being the amount of operations (strokes) to be performed in each period. Another advantage is that it proves easier to incorporate alternative processes and products, and it enables the consideration of cyclic materials structures.

With the materials and resources structures of conventional ERP systems, with which attempts have been made to implement them (SAP, BaaN, MfgPro, Movex, etc.), it is reasonably simple to generate an application that converts data structures into the data structures required to implement the application. Furthermore, the presented formulation enables the data that is generally available to be used (as alternative routes), but which the MRP or the MRPII explosion does not generally consider. The fact that the tool in use at the time of implementation does not consider them actually poses an additional problem, that of the data being incorrect: “as they are not used, no-one checks them”. A data control protocol needs to be prepared to avoid this problem.

Another advantage that the proposal offers is that it separates the availability of the materials from the operations employing them. Strokes enable other operations to be modeled; for instance, programmed maintenance procedures, to which a range of periods may be assigned in which they are to take place. It may also absorb the purchase process as a stroke with no raw material.

Perhaps the main problem encountered when introducing these structures is that when former constraints are released, the production department’s “wish list” is triggered, requiring a new and more difficult consideration.

If the complete packagings concept is in use, two fundamental difficulties emerge. The first entails the required incorporation of over-deliveries if orders are not contained in complete packaging units. The second involves the genuine existence of packaging fractions, which the system must somehow deal with. At the mathematical level, using this structure poses certain problems. The first is that the Gozinto matrix has always been used in the MLCLSP problem; thus the considered ways to solve the problem are concentrated in this representation, so there is not a handful of algorithms ready to be used.

On the other hand, it is obvious that the new form of representation could consume more memory for simple problems and use a higher number of variables than its conventional formulation. This larger memory consumption and the higher number of variables could imply longer computing times. Nevertheless, the GMOP model may be easily decomposed by separating sites and through unions by means of transport processes, thus allowing a simple heuristics to be done.

VI. Conclusions and future research lines

A form of modeling the relationship between operations and the materials required to manufacture a product has been considered. This way of defining the relationships between operations and materials suggests a compact mathematical programming model to plan operations in a supply chain. Apart from capacity constraints, this GMOP model also takes into account: direct and reverse BOMs, multisite production, alternative products and resources, co-products, by-products and yields, transport, –including alternative forms of transport– and packagings.

The literature relating to considering problems from both the mathematical and data structure viewpoints has been reviewed. Attempts have been made to define why BOMs and bills of resources were structured from the materials obtained. One suggestion is that this decision subsequently acted as a lock-in. The literature about multi-level lot-sizing problems has also been reviewed by acknowledging how different requirements have been suggested in data structure terms, and by discovering a significant increase in relation to the combination of characteristics in recent years.

The proposed structure has been verified to indeed support the variations analyzed in the MLCLSP, which have been included in a single structure. Two cases to which the tool has been applied have been briefly described.

After accepting this modeling approach, many new lines will be open, and will have to be deployed in the near future. First and more relevant, although considerable work has been done to solve the classical Production Planning Problem and its variants to optimality in a reasonable time (see, for expample, the work done of Prof Gubbström during decades (Grubbström et al., 2010; Grubbström y Thu Thuy Huynh, 2006)), the new formulation presented herein requires changing and adapting the different methodologies.

The incorporation of variants into the demand and/or production parameters such as uncertainty (Mula J. et al., 2007; Mula et al., 2008) is another future research line.

The incorporation of the stroke concept for modeling and solving the distributed problem in a distributed way is a very interesting line. Adapting methods like those described in (Dudek y Stadtler, 2007) is something that should be done in the near future.

Appendix 1: A simplified case study

Let us take a firm that sells three products (A, H, J) to two different clients (α and β). Product A is sold in two different formats: in disposable cardboard boxes (U) with 50 units and in returnable racks (V) with 100 units. Client α purchases product A in the disposable boxes format, whereas client β buys product A in returnable boxes with 100 units. The packaging of this product may change, if required. Disposable boxes cannot be reused, but returnable racks can. Product A is made by welding components B, C and D (the last of which needs two units). Component B is obtained from a stamping process using steel that comes as a spool named E. By stamping the spool of E, 5000 units of B are obtained, which are kept in boxes-pallets (W) holding 250 units each. By using slightly different matrices and the same spool E, 2500 B parts and 2500 C parts may be obtained. Each box-pallet (W) holds 500 C parts. From a certain F spool, 2000 D units are obtained. Unfortunately, the manufacturing process is not capable and produces 25% of the parts of inferior quality, which are called D’. Component D’ cannot be employed to manufacture product A. Each pallet (W) holds 250 D units. The welding of one B unit, one G unit and one D unit produces product H. If we use component D’, we obtain product H’. Component G is purchased directly and only the main plant (π) may purchase it.

Product H is sold in disposable boxes (U) to both clients and each box (U) holds 125 units. However, while H’ or H may be sold to client α, client β only accepts product H. Product J is manufactured by welding component D or D’ with component G, and it makes no difference if this product is made with either of these components. Product J is sold in returnable racks (V) that hold 50 units.

The firm has plant π that works on stamping processes and another plant working on welding processes. The firm also uses subcontractor σ that welds, and this arrangement works out considerably less expensive for some operations. The product may be sent to clients from either the firm’s main warehouse or the subcontractor. However, the subcontractor does not weld product D’.

There is a form of two-way transport between the firm and the subcontractor. Returnable packagings can be returned to the firm’s installations from clients at a given cost, or can be acquired at a different cost. To simplify the analysis of the results, a very important capacity constraint has been incorporated into the transport of product G between the main plant and the subcontractor. Random setup and operation costs have been assigned to each stroke. The cost of storage is equivalent for all the parties, except for the empty packagings with the client, thus allowing them to be immediately returned. To simplify the results analysis, all the operations have a lead time of two time units.

Fig. 2-9 represents the BOM. For simplicity reasons, neither the problems relating to the second qualities associated with the existence of D' nor the different packagings in which A may be served have been represented.

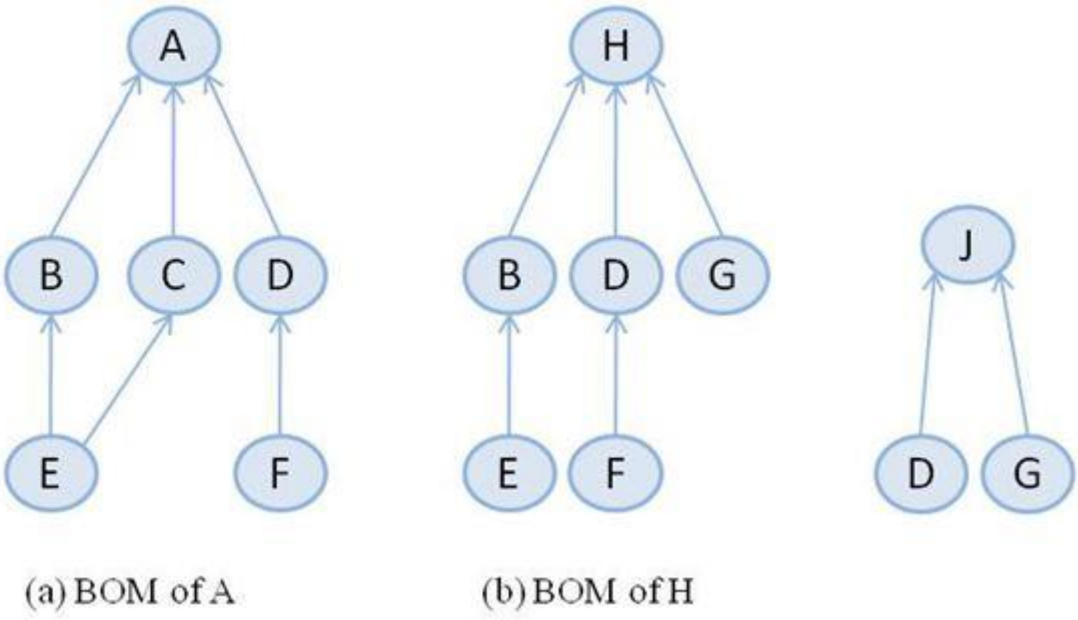


Fig. 2-9 Representation of the BOMs with no second qualities

Fig. 2-10 represents the movement of materials among installations. The route from the facilities of clients α and β and the π facilities refers to empty packagings.

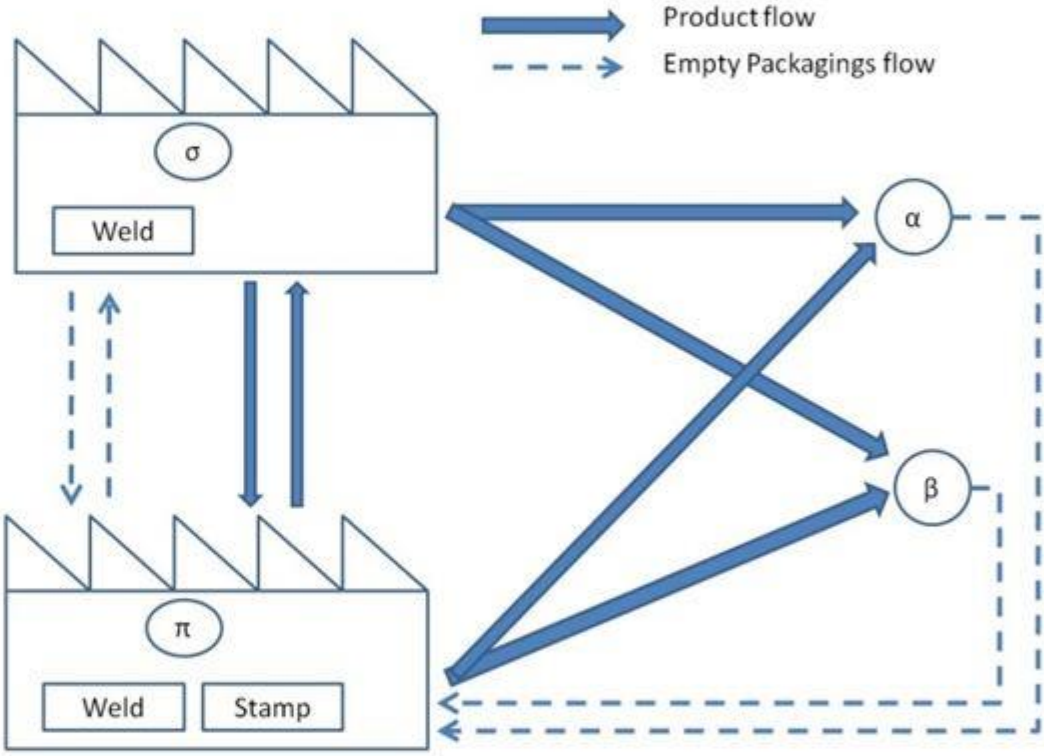


Fig. 2-10 Representation of the distribution network structure

Tabla 2-2 presents a list of the different products considered (reference+site+packaging). They have been coded using three characters: the first refers to the product (an underscore indicates empty packaging), the second indicates site (α,β,π,σ), while the third represents the packaging type used (U,V and W, and an underscore indicates that there is no packaging or that packaging is irrelevant).

As shown in Tabla 2-3, a problem with the demand of a few products in a few periods has been designed to analyze how the model performs (neither the initial level of stocks nor planned receptions have been simultaneously introduced). Since each stage is considered to have two lead time days and some processes have 5 stages, demand has been left empty until period 10.

Although stroke input (SI) and stroke output (SO) are different series, it is useful to represent them as combined manner as a single matrix S, where S=SO-SI, which allows each stroke to be analyzed in a more compact manner. Tabla 2-4 represents the strokes performed in plant π. Similarly, the strokes performed in σ are represented in Tabla 2-5. Tabla 2-6 and Tabla 2-7 respectively represent transport strokes and transformation strokes.

Tabla 2-2 Coding products (reference+site+packaging)

Packagings	*_πU*	*_πV*	*_πW*	*_σU*	*_σV*	*_σW*	*_αV*	*_βV*					
Raw Material	*Eπ_*	*Fπ_*	*Gπ_*	*Gσ_*									
Semi-finished products	*BπW*	*BσW*	*CπW*	*CσW*	*DπW*	*D' πw*	*Dσw*						
End products (origine)	*AπU*	*AπV*	*AσU*	*AσV*	*HπU*	*H' πU*	*HσU*	*JπV*	*JσV*	*Jα_*	*Jαv*	*Jβ_*	*JβV*
End products (destination)	*Aα_*	*AαU*	*Aβ_*	*AβV*	*Hα_*	*HαU*	*H' αU*	*Hβ_*	*HβU*				

Tabla 2-3 Demand for end products

$D_{i,t}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Aα_	0	0	0	0	0	0	0	0	0	1000	0	1000	0	1000	0
Aβ_	0	0	0	0	0	0	0	0	0	0	2000	0	2000	0	0
Hα_	0	0	0	0	0	0	0	0	0	500	0	2000	0	6000	0
Hβ_	0	0	0	0	0	0	0	0	0	0	3000	0	3000	0	0
Jα_	0	0	0	0	0	0	0	0	0	3000	0	3000	0	3000	0
Jβ_	0	0	0	0	0	0	0	0	0	0	500	0	500	500	0

Tabla 2-4 Matrix S for the strokes performed in π

	Unpacks AπU into AπV	Unpacks AπV into AπU	Stamps E into B	Stamps E into B and C	Stamps F into D and D'	Welds AπU	Welds AπV	Welds HπU	Welds H'πU	Welds HsU	Welds JπV with D	Welds JπV with D'
_πU	0	-2	0	0	0	-10	0	-2	-2	0	0	0
_πV	-1	1	0	0	0	0	-5	0	0	0	-5	-5
_πW	0	0	-20	-15	-8	4	4	2	2	0	1	1
AπU	-2	2	0	0	0	10	0	0	0	0	0	0
AπV	1	-1	0	0	0	0	5	0	0	0	0	0
CπW	0	0	0	5	0	-1	-1	0	0	0	0	0
DπW	0	0	0	0	6	-4	-4	-1	0	0	-1	0
D'πW	0	0	0	0	2	0	0	0	-1	0	0	-1
Eπ_	0	0	-1	-1	0	0	0	0	0	0	0	0
Fπ_	0	0	0	0	-1	0	0	0	0	0	0	0
Gπ_	0	0	0	0	0	0	0	-250	-250	0	-250	-250
HπU	0	0	0	0	0	0	0	2	0	0	0	0
H'πU	0	0	0	0	0	0	0	0	2	0	0	0
JπV	0	0	0	0	0	0	0	0	0	0	5	5

Tabla 2-5 Matrix S for the strokes performed in σ

	Welds AσU	Welds AσV	Welds HσU	Welds JσV with D
_sU	-10	0	-2	0
_sV	0	-5	0	-5
_sW	4	4	2	1
AsU	10	0	0	0
AsV	0	5	0	0
BsW	-2	-2	-1	0
CsW	-1	-1	0	0
DsW	-4	-4	-1	-1
Gs_	0	0	-250	-250
HsU	0	0	2	0
JsV	0	0	0	5

Tabla 2-6 Matrix S for the transport strokes

	Transports _σW to _πW	*Transports _πV to _σV*	*Transports _πW to _σW*	*Transports _αV to _πV*	*Transports _βV to _πV*	*Transports BπW to BσW*	*Transports CπW to CσW*	*Transports AπU to AαU*	*Transports AπV to AβV*	*Transports AσU to AαU*	*Transports AσV to AβV*	*Transports DπW to DσW*	*Transports Gπ_ to Gσ_*	*Transports HπU to HαU*	*Transports H'πU to HαU*	*Transports HπU to HβU*	*Transports HσU to HβU*	*Transports JπV to JαV*	*Transports JπV to JβV*	*Transports JσV to JαV*	*Transports JσV to JβV*
_πV	0	-1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
_πW	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
_σV	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
_σW	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
_αV	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
_βV	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AπU	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
AπV	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
AσU	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
AσV	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
AαU	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
AβV	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
BπW	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BσW	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CπW	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CσW	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DπW	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
DσW	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
*Gπ_*	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
*Gσ_*	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
HπU	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	0
H'πU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
HσU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
HαU	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
HβU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
JπV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0
JσV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1
JαV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
JβV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1

Tabla 2-7 Matrix S for the transformation strokes

	Consumes Aα_ from AαU	*Consumes Aβ_ from AβV*	*Consumes Hα_ from HαU*	*Consumes Hα_ from H'αU*	*Consumes Hβ_ from HβU*	*Consumes Jα_ from JαV*	*Consumes Jβ_ from JβV*
_αV	*0*	*0*	*0*	*0*	*0*	*1*	*0*
_βV	*0*	*1*	*0*	*0*	*0*	*0*	*1*
*Aα_*	*50*	*0*	*0*	*0*	*0*	*0*	*0*
AαU	*-1*	*0*	*0*	*0*	*0*	*0*	*0*
*Aβ_*	*0*	*100*	*0*	*0*	*0*	*0*	*0*
AβV	*0*	*-1*	*0*	*0*	*0*	*0*	*0*
*Hα_*	*0*	*0*	*125*	*125*	*0*	*0*	*0*
HαU	*0*	*0*	*-1*	*0*	*0*	*0*	*0*
H'αU	*0*	*0*	*0*	*-1*	*0*	*0*	*0*
*Hβ_*	*0*	*0*	*0*	*0*	*125*	*0*	*0*
HβU	*0*	*0*	*0*	*0*	*-1*	*0*	*0*
*Jα_*	*0*	*0*	*0*	*0*	*0*	*50*	*0*
JαV	*0*	*0*	*0*	*0*	*0*	*-1*	*0*
*Jβ_*	*0*	*0*	*0*	*0*	*0*	*0*	*50*
JβV	*0*	*0*	*0*	*0*	*0*	*0*	*-1*

After executing the model (which, in this case, takes tenths of a second with Gurobi Optimizer 4.5), all the operations that must be done are obtained, including the transport of components, end products and even empty packagings, as represented in the next table.

Tabla 2-8 Planned strokes

$z_{k,t}$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Consumes Aα_ from AαU	0	0	0	0	0	0	0	20	0	20	0	20	0	0	0
Consumes Aβ_ from AβV	0	0	0	0	0	0	0	0	20	0	20	0	0	0	0
Consumes Hα_ from HαU	0	0	0	0	0	0	0	4	0	16	0	48	0	0	0
Consumes Hα_ from H'αU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consumes Hβ_ from HβU	0	0	0	0	0	0	0	0	24	0	24	0	0	0	0
Consumes Jα_ from JαV	0	0	0	0	0	0	0	60	0	60	0	60	0	0	0
Consumes Jβ_ from JβV	0	0	0	0	0	0	0	0	10	0	20	0	0	0	0
Unpacks AπU into AπV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unpacks AπV into AπU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stamps E into B	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0

Stamps E into BβC	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stamps F into DβD'	15	0	0	0	5	0	0	0	0	0	0	0	0	0	0
Welds AπU	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Welds AπV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Welds AσU	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0
Welds AσV	0	0	0	0	4	0	4	0	0	0	0	0	0	0	0
Welds HπU	0	0	14	0	0	0	26	0	0	0	0	0	0	0	0
Welds H'πU	0	0	8	0	0	0	10	0	0	0	0	0	0	0	0
Welds HσU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Welds JπV with D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Welds JπV with D'	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0
Welds JσV with D	0	0	0	0	8	4	4	4	0	0	0	0	0	0	0
Transports _σW to _πW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transports _πV to _σV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transports _πW to _σW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transports _αV to _πV	0	0	0	0	0	0	0	0	0	60	0	60	0	60	0
Transports _βV to _πV	0	0	0	0	0	0	0	0	0	0	30	0	40	0	0
Transports BπW to BσW	0	0	8	4	12	0	0	0	0	0	0	0	0	0	0
Transports CπW to CσW	0	0	4	2	6	0	0	0	0	0	0	0	0	0	0
Transports AπU to AαU	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0
Transports AπV to AβV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transports AσU to AαU	0	0	0	0	0	0	0	20	0	20	0	0	0	0	0
Transports AσV to AβV	0	0	0	0	0	0	20	0	20	0	0	0	0	0	0
Transports DπW to DσW	0	0	24	44	0	0	0	0	0	0	0	0	0	0	0
Transports Gπ_ to Gσ_	0	1000	1000	1000	1000	1000	0	0	0	0	0	0	0	0	0
Transports HπU to HαU	0	0	0	0	0	0	0	4	0	28	0	0	0	0	0
Transports H'πU to HαU	0	0	0	0	0	16	0	0	0	20	0	0	0	0	0
Transports HπU to HβU	0	0	0	0	24	0	0	0	24	0	0	0	0	0	0
Transports HσU to HβU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transports JπV to JαV	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
Transports JπV to JβV	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Transports JσV to JαV	0	0	0	0	0	0	20	0	0	60	0	0	0	0	0
Transports JσV to JβV	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0

Capítulo 3 La Matriz de Operaciones y Materiales y la Matriz de Operaciones y Recursos, un nuevo enfoque para resolver el problema GMOP basado en el concepto del Stroke

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Abstract. La gestión de materiales de productos multi-nivel usa desde los años 1970 la metodología denominada MRP. La incorporación del CRP en los ERP conjuntamente al MRP tradicional dio nacimiento a los llamados MRPII. Sin embargo, desde aquella época en la literatura, se asigna una única lista de materiales y una lista única de recursos a cada producto susceptible de ser ensamblado lo que implica fuertes limitaciones para considerar operaciones alternativas. En el problema GMOP, se propone el uso del concepto del stroke para resolver el problema de planificación de las operaciones y de los materiales considerando operaciones alternativas. En este artículo, se presenta primero una evolución del problema GMOP introduciendo las planificaciones programadas, y segundo, se presenta el despliegue y análisis de las matrices que se proponen para facilitar la implementación de un modelo y una herramienta que se basen en el concepto de stroke.

Keywords: Cadena de Suministro, Planificación de las Operaciones, Operaciones alternativas, Stroke, MRP, GMOP.

I. Introducción

La gestión de materiales de productos multi-nivel usa desde los años 1970 la metodología denominada *Material Requirement Planning* (MRP). Esta metodología impulsada por Orlicky (1975) que se basa únicamente en la planificación de los materiales con lista de materiales directas tuvo que evolucionar para hacer frente a las necesidades cada vez más complejas de las distintas industrias. Una de las evoluciones más relevantes fue la incorporación del *Capacitated Ressource Planning* en los *Enterprise Ressource Planning* conjuntamente al MRP tradicional para incorporar las limitaciones de capacidad y el *routing* (Plenert, 1999) en los llamados MRPII (Wight, 1984). Billington et al. (Billington et al., 1983) propusieron plantear el MRP capacitado mediante programación matemática. Evidentemente las limitaciones tecnológicas les impedían afirmar que el modelo sin más fuera aplicable y en el mismo artículo propone métodos para resolver el problema. El planteamiento de los autores consistía en asignar una única lista de materiales y una lista única de recursos a cada producto susceptible de ser ensamblado. Esa estructura se ha mantenido en la literatura desde entonces sin modificaciones.

La matriz que vincula cada producto padre (*parent ítem*) con los componentes que son necesarios para ensamblarlo (*child items*) aparece en esa formulación. Esta matriz se denominó Gozinto (Vazsonyi, 1954). En (Billington et al., 1983), se incorpora el tiempo de entrega (*Lead-Time*) que se asocia también al producto, así como un *yield* a la producción, y la lista de recursos también en forma de matriz. Pero no se incorpora diferentes rutas para producir un mismo producto o tampoco se considera la posibilidad de usar listas inversas o alternativas de producción así como la posibilidad de trabajar entre dos niveles de una cadena teniendo en cuenta alternativas de transporte.

En este artículo, se pretende proponer el uso de una nueva estructura que reemplaza la tradicional lista de materiales y la lista de recursos. El modo de construcción y la interpretación de dicha estructura, basada en tres o cuatro matrices, permite la planificación de las operaciones en estricto nivel de igualdad a la de requerimientos de materiales. Es de destacar que dichas matrices permiten planificar las operaciones teniendo en cuenta todas las estructuras posibles de productos, las rutas alternativas, las alternativas en cuanto a las Operaciones (que sean de aprovisionamiento, de transformación, de venta o de transporte) pero también permiten una fácil integración para el caso de redes de suministro multi-sitio y permiten considerar operaciones de apoyo como es el caso del mantenimiento.

Este artículo presenta una doble contribución. En primer lugar se presenta una evolución del problema *Generic Materials & Operations Planning* (Garcia-Sabater et al., 2012b) en el que se introduce las planificaciones programadas debido a los strokes que ya se están ejecutando a principio del horizonte de planificación. Se aborda explícitamente el problema de planificación de una red de suministro multi-nivel y se incluye la consideración de las recepciones planificadas. Además se propone una nomenclatura para los productos que incluya de manera consistente no sólo el nombre o número de referencia de cada artículo sino también su embalaje, su ubicación y la cantidad de unidades que van en ellos. La segunda aportación es el despliegue y análisis de las matrices que se proponen para facilitar la implementación de un modelo y una herramienta que se basen en el concepto de stroke.

El resto del artículo se ha estructurado como sigue. En el segundo apartado, se describe brevemente el concepto del stroke que se plantea para la planificación de las operaciones y se aporta una caracterización del stroke que extiende la presentada en (Garcia-Sabater et al., 2012b) . En el tercer apartado, se presenta el modelo propuesto del llamado problema GMOP (*Generic Materials & Operations Planning*) que se basa en el concepto del stroke incorporando los efectos del lead-time. Para resolver el problema GMOP, se necesita como mínimo el uso de dos matrices que se introducen y se caracterizan: la *matriz de Operaciones & Recursos* que se presenta en el cuarto apartado y la *matriz de Operaciones & Materiales* que se presenta en el quinto apartado. En el sexto apartado, se analiza la estructura para un problema multi-sitio y un caso práctico de aplicación. Finalmente, se presentan las conclusiones y algunas líneas futuras de investigación identificadas.

II. El concepto de Stroke

Los productos que se consideran en el problema GMOP son, o pueden ser, SKUs (*Stock Keeping Units* en inglés), es decir productos en su embalaje y su ubicación, y también se consideran los recursos que se tienen que planificar. Se asume que cada stroke puede necesitar un producto o un conjunto de productos localizados (o ningún producto en casos determinados) en un posible embalaje determinado que se consumen durante dicho stroke. A estas entradas, se las denomina *stroke inputs* y la cantidad de cada SKU consumido se denomina *stroke input factor* (concepto similar al factor de Gozinto). Al conjunto de productos (si existe) que se obtiene mediante la ejecución de un stroke determinado, se le denomina *stroke output*. Y la cantidad de cada SKU que se genera depende del *stroke output factor*.

Una definición de un stroke sería la siguiente:

"Un stroke representa cualquier operación básica (en su sentido más genérico), tarea o actividad. Puede transformar, transportar o consumir un conjunto de productos (medido preferentemente como SKU) para obtener o generar otro conjunto de productos (también medido preferentemente en SKU). Cada stroke puede utilizar o inmovilizar recursos en su ejecución."

Los recursos que se consideran pueden ser de diferente naturaleza (maquinaria, recursos humanos, medios de transporte) pero no se pueden mover entre ubicaciones: En el problema GMOP aquí presentado los recursos no se adquieren o se venden durante el horizonte de planificación: están o no disponibles. Estos recursos, a los cuales se pueden asociar una capacidad, se vinculan directamente a cada stroke y no al producto (o conjunto de productos) que se obtiene como se puede apreciar en la Fig. 3-1. En general se pueden obtener de la Lista de Recursos (Tatsiopoulos, 1996).

Dicha operación, y por tanto el stroke que la representa, puede tener costes asociados (como por ejemplo coste de setup y/o coste unitario de ejecución), plazo de entrega asociado, y puede consumir una cierta cantidad de recursos a partir del primero de los periodos de planificación del plazo de entrega.

Para poder estructurar los datos de forma sencilla, se propone a continuación el uso de una nomenclatura para definir los SKUs:

- El producto “01” almacenado en la planta A será denominada P01@A mientras que el mismo producto ubicado en la planta B se denominará P01@B.
- El rack “01” con 12 productos “02” en él y ubicado en la planta B se denominará R01#12P02@A.
- El rack “01” vacío en la planta C se denominará R01#00@C.

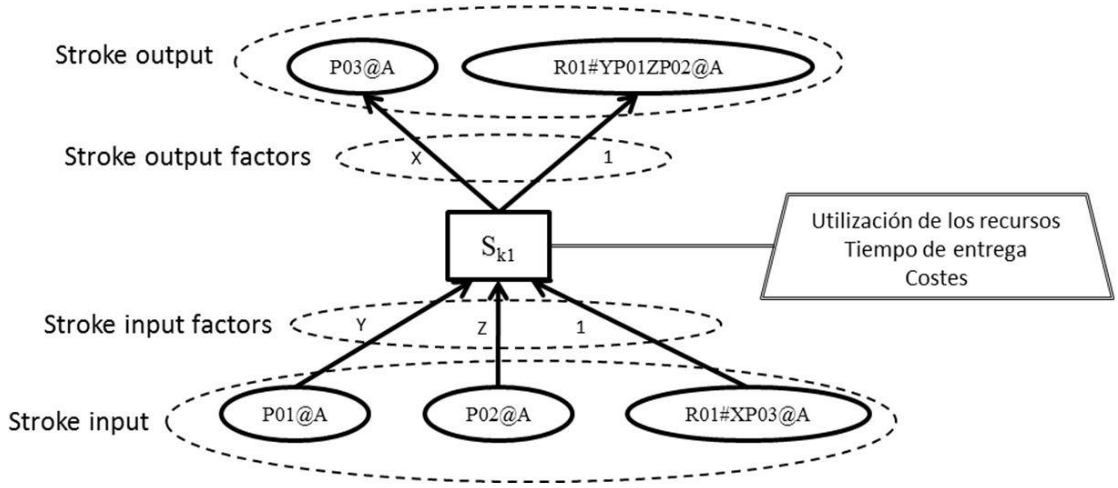

Fig. 3-1 Representación conceptual de un Stroke S_k

En el ejemplo presentado en la Fig. 3-1, el stroke Sk1 tiene 3 *inputs* y 2 *outputs*. Los stroke *inputs* son: *Y* unidades de P01@A, Z unidades de $P02@A$ y 1 unidad de R01#XP03@A. Los *outputs* que se generan cuando se ejecuta una unidad de S_{k1} son X unidades de P03@A y 1 unidad de R01#YP01ZP02@A. Para la realización de una unidad de este stroke, un lead-time, unos costes así como la utilización de recursos se consideran.

Las hipótesis que se asumirán para el problema GMOP son las siguientes:

- El consumo en recursos de un stroke se representa en un periodo completo de planificación.
- El consumo en recursos de un stroke se limitará al primer periodo de la ejecución del mismo stroke.
- Un recurso no puede cambiar de localización. Esto puede implicar, si es necesario, que un recurso de transporte (por ejemplo un camión) se tenga que considerar como un *SKU*.
- La cantidad de strokes que se planifican en un periodo de tiempo es un entero positivo.
- Un stroke tiene que tener siempre algún dato asociado no nulo para ser válido.

III. El problema GMOP

El modelo GMOP que se presenta a continuación no se limita a presentar el modelo presentado en (Garcia-Sabater et al., 2012b) sino que se incorpora el efecto del lead-time sobre las ecuaciones de continuidad del inventario y además considera los niveles iniciales de inventario. Resolviendo así una de las principales limitaciones en su implementación práctica que aquel modelo tenía. La notación del modelo de programación matemática se presenta en la Tabla 3-1.

Tabla 3-1 Notación para el problema GMOP

Índices y conjuntos	
$i \in P = \{1, \dots, p\}$	*SKUs*
$r \in R = \{1, \dots, m\}$	*Recursos*
$k \in S = \{1, \dots, n\}$	*Strokes*
$t = 1, \dots, T$	*Periodos*
$L_X \subseteq S$	*Conjunto de strokes cuyo lead-time es inferior a* $X \in \{0, \dots, l\}$
$S_r \subseteq S$	*Conjunto de strokes que utilizan el recurso r*
Parámetros	
d_{it}	*Demanda en SKU i durante en el periodo t*
h_{it}	*Coste de almacenar una unidad de SKU i durante el periodo t*
ot_{kr}	*Tiempo de operación para la ejecución de una unidad de stroke k en el recurso r*
st_{kr}	*Tiempo de setup del stroke k en el recurso r*
p_{kt}	*Coste de planificar la ejecución de una unidad de stroke k durante el periodo t*
f_{kt}	*Coste de setup del stroke k durante el periodo t*
I_{i0}	*Nivel inicial de inventario del SKU i*
Y_{it}	*Recepciones planificadas en SKUs i durante el periodo t*
K_{rt}	*Capacidad disponible del recurso r durante el periodo t*
SO_{ik}	*Número de unidades de SKUs i resultado de la ejecución de una unidad de stroke k (stroke output factor)*
SI_{ik}	*Número de unidades de SKUs i que se consumen durante la ejecución de una unidad de stroke k (stroke input factor)*
LT_k	*Lead time de un stroke k*
Variables	
z_{kt}	*Cantidad de strokes k que empiezan durante el periodo t*
I_{it}	*Nivel de inventario del SKU i al final del periodo t*
δ_{kt}	*Vale 1 si el stroke k está en set up durante el periodo t (0 en caso contrario)*

El problema GMOP se formula como un modelo de programación entera mixta:

$$Minimizar\ F(z, I, \delta) = \sum_{t=1}^{T} \left(\sum_{i \in P} \left(h_{it} \cdot I_{it} \right) + \sum_{k \in S} \left(p_{kt} \cdot z_{kt} + \delta_{kt} \cdot f_{kt} \right) \right) \quad (0.7)$$

Sujeto a

$$I_{it} = I_{i,t-1} + Y_{it} - d_{it} + \sum_{k \in S} \left(SO_{ik} \cdot z_{k,t-LT_k} \right) - \sum_{k \in S} \left(SI_{ik} \cdot z_{kt} \right) \quad i \in P, t = l+1, \dots, T \quad (0.8)$$

$$I_{i,t} = I_{i,t-1} + Y_{i,t} - d_{i,t} + \sum_{k \in L_{t-1}} \left(SO_{ik} \cdot z_{k,t-LT_k} \right) - \sum_{k \in S} \left(SI_{ik} \cdot z_{k,t} \right) \quad i \in P, t = 1, \dots, l \quad (0.9)$$

$$z_{kt} - M \cdot \delta_{kt} \leq 0 \quad k \in S, t = 1, \dots, T \quad (0.10)$$

$$\sum_{k \in S_r} \left(\delta_{kt} \cdot st_{kr} + z_{kt} \cdot ot_{kr} \right) \leq K_{rt} \quad r \in R, t = 1, \dots, T \quad (0.11)$$

$$I_{it} \geq 0 \quad i \in P, t = 1, \dots, T \quad (0.12)$$

$$z_{kt} \geq 0,\ \delta_{kt} \in \{0,1\} \quad k \in S, t = 1, \dots, T \quad (0.13)$$

El objetivo (0.7) busca la minimización de los costes de setup de los strokes, de los costes unitarios de stroke y de los costes de almacenamiento. La ecuación (0.8) representa la continuidad de los niveles de inventario de los SKUs i. El nivel de inventario al final de un periodo considera el nivel de inventario al final del periodo anterior, las recepciones planificadas (debido a strokes en proceso), la demanda del producto y el consumo y la producción de SKUs debido a la ejecución de strokes. Debido a la existencia de lead-times no nulos, se considera en (0.9) la ecuación de continuidad para los primeros periodos. Con la restricción (0.10), si se produce un stroke en el periodo t, se asigna un valor no nulo a la variable que representa la existencia de setup. La restricción (0.11) representa la limitación de la capacidad productiva en cada periodo para cada recurso. Las ecuaciones (0.12)-(0.13) definen el dominio de definición de las variables.

Como se puede apreciar en el modelo GMOP, planificar usando la variable stroke resulta muy diferente a la planificación tradicional que se basa en la matriz Gozinto y la lista de recursos ya que lo que se planifica es el stroke (la operación, la tarea o la actividad). Expresado en otros términos, el stroke es la variable de decisión mientras que los materiales se generan y/o consumen en función de la ejecución de los strokes, por tanto no se planifica la producción del material sino las operaciones que se llevan a cabo para obtenerlos.

Debido a la necesidad de trabajar con una nueva representación de los datos, se propone en el apartado siguiente una descripción de la matriz de Operaciones & Recursos y en otro apartado, se propone la descripción de la Matriz de Operaciones & Materiales.

IV. La Matriz de Operaciones & Recursos

IV. 1. Construcción de la matriz de Operaciones & Recursos

La matriz de Operaciones & Recursos es la matriz que asigna a cada stroke los diferentes recursos que se inmovilizan o utilizan y el valor de la utilización del conjunto de recursos asociados. Esta matriz se construye en función una matriz de asignación de recursos a strokes que se denotará como R^S. Esta matriz $R^S = [r_{kr}]$ es una matriz de asignación binaria (en el sentido que $r_{kr} \in \{0,1\}$ para todos los *k* y *r*) como se puede observar en la Tabla 3-2.

Tabla 3-2 Ejemplo de una matriz $\mathbf{R^S}$

r_{kr}	*1*	*2*	*3*
1	*1*	*0*	*0*
2	*0*	*1*	*0*
3	*1*	*0*	*1*
4	*0*	*0*	*0*

Gracias a la matriz R^S, se puede construir la matriz que asigna a cada par stroke-recurso el valor del consumo de tiempo asociado.

IV. 2. Ejemplo de una matriz de Operaciones & Recursos

Como en la mayoría de los problemas reales, un stroke usa un número muy limitado de recursos, la matriz de Operaciones & Recursos consta de mucho elementos nulos. Para facilitar la construcción de la matriz, se propone en la Tabla 3-3 el ejemplo de una matriz “sparse” que define el consumo de recursos de diferentes strokes.

Tabla 3-3 Ejemplo de una matriz sparse de Operaciones & Recursos

$Stroke\ k$	$Recurso\ r$	ot_{kr} $(unidades\ de\ tiempo)$	st_{kr} $(unidades\ de\ tiempo)$
1	*1*	*14*	*12*
2	*2*	*13*	*1,14*
3	*1*	*0,7*	*200*
3	*3*	*100*	*44*

Usar la matriz de Operaciones & Recursos permite considerar rutas alternativas pero también permite considerar strokes que no consumen ningún tipo de recurso. Si consideramos la Tabla 3-3, asumiremos que el recurso r1 es el recurso “máquina 1”, r2 el recurso “máquina 2” y el recurso r3 la “máquina 3”. Se puede entonces interpretar esta matriz:

- El stroke *k1* consume capacidad de un único recurso *r1* y el stroke *k2* consume capacidad de un único recurso *r2.* En este caso, los strokes *k1* y *k2* son strokes básicos en cuanto a recursos.
- Se puede considerar el caso en el cual se agregan las operaciones tal como es el caso del stroke *k3*. Este stroke no solamente consume tiempo del recurso *r1* sino también del recurso *r3*. Si el recurso r3 fuera de mano de obra, el stroke consideraría al mismo tiempo un consumo de tiempo de máquina y un tiempo de mano de obra, lo que puede resultar interesante en casos determinados.
- Pueden existir casos en los cuales un stroke no consume ningún recurso planificado (caso del stroke *k4*). No significa por tanto que el stroke no consume ningún recurso, sino que no es necesaria la planificación de los recursos consumidos por cualquier motivo. En la matriz de Operaciones & Recursos, tendríamos en ese caso $\sum_r r_{rk} = 0$.

Es relevante observar que los costes asociados a los strokes no pertenecen a esta matriz. Los costes asignados a los strokes dependen únicamente del stroke y del periodo considerado y contienen directamente el coste por consumir tiempo de los diferentes recursos. Y el tiempo de entrega afecta únicamente al stroke pero no a su recurso asociado. Del mismo modo que el lead-time sólo afectará al stroke.

V. La Matriz de Operaciones & Materiales

V. 1. Construcción de la matriz de Operaciones & Materiales

La matriz de Operaciones & Materiales representa para cada stroke el valor de los stroke *outputs* y de los stroke *inputs* asociado con el uso de una matriz única. Esta matriz que escribiremos $SS = [s_{ki}]$ se forma de elementos naturales enteros. Se compone de elementos positivos asociados a los *outputs* y valores negativos asociados a los *inputs*.

Esta representación no se puede usar para el uso directo en modelos de programación matemática cuando existe un lead time no nulo para un stroke. Sin embargo, se puede transformar esta matriz de forma sencilla para su uso efectivo en el modelo GMOP. Esta matriz se divide en dos matrices positivas tal que $SS = [s_{ki}] = SO - SI = [so_{ki}] - [si_{ki}]$ asumiendo que so_{ki} y si_{ki} sean elementos naturales positivos para cualquier valor del índice *i* o *k*. El valor de so_{ki}

es el stroke *output* factor presentado en el segundo apartado. El valor de si_{ki} es el stroke *input* factor. Con el fin de poder describir la matriz SS, se presentan nuevas notaciones en la Tabla 3-4:

Tabla 3-4 Nuevos índices para caracterizar la Matriz de Operaciones & Materiales

Índices	
$j \in J = \{j_1, \dots, j_n\}$	*Ubicaciones/Localizaciones/Plantas consideradas*
$p \in L = \{p_1, \dots, p_n\}$	*Producto en su embalaje sin considerar la ubicación*
$p(j)$	*Producto p en la localización j*
$k(j)$	*Stroke k que se ejecuta en la localización j*

El índice j hace referencia a una localización definida geográficamente o a un miembro en particular de una red de suministro. El índice p hace referencia a producto (con su embalaje) pero sin tener en cuenta su localización. En teoría, un producto p disponible en una localización j1 y el mismo disponible en una localización j2 son dos productos distintos. Por esta razón, usaremos el índice p(j) para distinguir p(j1) de p(j2). Observar que con el índice i que se plantea en la tabla1, ya se contempla esta distinción entre estos dos productos pero el análisis de las matrices resulta difícil de explicar. En función de esta caracterización se puede determinar la naturaleza de los diferentes strokes que se pueden considerar y realizar una comparación de los strokes entre ellos.

V. 2. La naturaleza de los strokes

Stroke de Compra

Un stroke de compra es un stroke que no considera ningún stroke *input* pero que tiene por lo menos un stroke *output* asociado a la ejecución de este. De esta forma, se puede caracterizar un stroke de compra k1 de la forma siguiente:

$$\sum_i so_{i,k1} > 0$$
$$\sum_i si_{i,k1} = 0$$

Stroke de transformación

Un stroke de transformación puede ser una operación de ensamblaje, de desmontaje, de (des)empaquetado, o una transformación química. Estas operaciones deben ser localizadas en el sentido que el producto no puede cambiar de ubicación. Así, se puede caracterizar un stroke de transformación k1(j1) de la forma siguiente:

$$\sum_{p(j1)} so_{p(j1),k1(j1)} > 0$$
$$\sum_{p(j1)} si_{p(j1),k1(j1)} > 0$$
$$\sum_{p(j2)} so_{p(j2),k1(j1)} = \sum_{p(j2)} si_{p(j2),k1(j1)} = 0, \quad \forall j2 \neq j1$$

Los strokes que incluyen la gestión de los embalajes, se asimilarán a strokes de transformación. Los embalajes se pueden dividir en dos categorías, los embalajes retornables (como las paletas) y los embalajes duraderos que se usan a los largo de los procesos de fabricación/transporte. En cualquier caso, esos productos se consumen (por uso) y se producen (con procesos de desembalaje) a los largos de los procesos productivos sin ninguna regla en particular.

Stroke de destrucción y stroke de venta

Planificar las operaciones usando el concepto del stroke permite considerar también de forma uniforme strokes de destrucción de productos. La destrucción de productos es un hecho básico en la logística inversa y puede ocasionar costes asociados. Este stroke considera productos como *inputs* pero ningún producto en *output*. En la matriz de Operaciones & Materiales, el stroke k de destrucción se representaría de la forma siguiente:

$$\sum_i so_{i,k} = 0$$
$$\sum_i si_{i,k} > 0$$

Los strokes de venta se pueden considerar de forma análoga a los strokes de destrucción ya que tienen *inputs* pero no tienen *outputs*.

Stroke de transporte entre dos plantas

Un stroke de transporte entre dos plantas es un stroke que transporta un SKU p(j1) en un SKU p(j2) con j2 diferente de j1. En este caso, este stroke se representaría de la forma siguiente:

$$\left[si_{p(j1),k}\right] = \left[so_{p(j2),k}\right], \quad j1 \neq j2$$
$$\sum_{p(j2)} so_{p(j2),k)} > 0, \quad j1 \neq j2$$
$$\left[so_{p(j1),k}\right] = \left[si_{p(j2),k}\right] = [0], \quad j1 \neq j2$$

Stroke de transporte entre de una planta hacia varias plantas

El caso de envíos agrupados se puede considerar también. Si los envíos se hacen desde j1 hasta $u = \{j_2, \dots, j_n\}$ pues se tendría el stroke k(j1) siguiente:

$$\left[so_{p(j1),k(j1)}\right] = \left[si_{p(u),k(j1)}\right] = [0]$$
$$si_{p(j1),k(j1)} = \sum_{p(u)} so_{p(u),k(j1)}$$

Stroke de apoyo/decisión

Otro ejemplo de stroke que se puede considerar es la inmovilización de un recurso o el consumo planificado de recursos durante un periodo dado. Un ejemplo práctico es la necesidad de planificar ventanas temporales de mantenimiento para ciertos recursos. En la matriz de Operaciones & Materiales, este stroke no consideraría ni *inputs* ni *outputs* de forma que sii,k = 0 y soi,k = 0 para todo i y k. Ese el caso por ejemplo de tareas de mantenimiento que se deben planificar en secuenciación o en planificación y que dejan inmovilizado a un recurso. También puede ser el caso de tiempos parados sin fabricación cuando por ejemplo se envían en formación a equipos de trabajo.

V. 3. Propiedades interesantes

Gracias al uso de las matrices presentadas anteriormente, la mayor aportación destacable del uso de estas es que se puede considerar operaciones alternativas. A continuación, se presenta algunas de las posibles alternativas que se puede considerar.

Strokes con inputs alternativos

En la práctica, a veces las listas de materiales son "flexibles" en el sentido que una combinación alternativas de productos en *inputs* pueden ser utilizado para producir un conjunto de productos. En la literatura, se denominan *alternative BOMs, flexible BOMs, alternate BOMs*, problemas de recetas, *product sustitution* o incluso *transhipments*. Usando el concepto del stroke, los *alternative BOMs* son strokes con *inputs* alternativos. Un stroke k2 con *input* substituto al stroke k1 tiene las características siguientes:

$$\left[so_{i,k1}\right]=\left[so_{i,k2}\right]\neq[0],\quad k1\neq k2$$
$$\left[si_{i,k1}\right]\neq\left[si_{i,k2}\right],\quad k1\neq k2$$

Strokes con outputs alternativos

Un stroke con *output* alternativo puede representar muchas operaciones o procesos en la realidad industrial. Por ejemplo en la química, se puede poner los mismos productos en condiciones distintas para obtener productos finales distintos. Otro ejemplo interesante es la inyección de piezas de plástico, los problemas de corte e inclusión las operaciones en prensas usando matrices distintas. En todos estos casos, los *inputs* de la operación pueden ser iguales y de la misma cantidad, pero al usar diferentes recursos o condiciones externas controladas, el resultado de la operación (es decir los *outputs*) será distinto. Las características matriciales serían las siguientes:

$$\left[so_{i,k1}\right]\neq\left[so_{i,k2}\right],\quad k1\neq k2$$
$$\left[si_{i,k1}\right]=\left[si_{i,k2}\right]\neq[0],\quad k1\neq k2$$

Strokes alternativos con outputs e inputs no-nulos

Un stroke alternativo k1 a otro stroke k2 es un stroke que tienen los mismos *outputs* y los mismos *inputs*. En este caso, se asume que por lo menos un *input* se consume y un *output* se genera al ejecutar los strokes para no considerar los strokes de compra o de venta.

Estos stroke se deben distinguir por sus matrices de Operaciones & Recursos (si no, es un dato redundante). La característica que representan los strokes alternativos aparece en la literatura con los nombres de *resource substitution* y *alternative routing*. En la matriz de Operaciones & Materiales, los vectores tienen las características siguientes:

$$\left[S_{i,k1}\right] = \left[S_{i,k2}\right] \neq [0] \; con \;\; k1 \neq k2$$

Stroke alternativos de compra

El uso del stroke permite también considerar strokes alternativos de compra. Un stroke k1 es stroke alternativo de compra a k2 si los dos strokes tienen como *output*s el mismo producto p1 pero que sus costes son diferentes, que sus stroke *output* factors (lote de compra) son diferentes, que los lead-times son diferentes o que los proveedores son diferentes.

De forma similar, existen strokes alternativos de ventas. Un stroke k3 es stroke alternativo de venta a k4 si los dos strokes tienen como *inputs* el mismo producto p2 pero que sus costes son diferentes, que sus stroke *input* factors (lote de venta) son diferentes, que los lead-times son diferentes o que los proveedores son diferentes.

VI. Análisis de una Matriz de Operaciones & Materiales genérica multi-sitio

VI. 1. Análisis de la estructura de la matriz de Operaciones & Materiales genérica en un caso de red multi-sitio

Con el fin de poder entender la estructura que tiene todas las matrices de Operaciones & Materiales, se propone en la Tabla 3-5 la introducción de nuevos conjuntos para facilitar el entendimiento de estas.

Tabla 3-5 Conjuntos que permiten caracterizar la Matriz de Operaciones & Materiales

Conjuntos	
A_j	*Conjunto de strokes de compra con outputs exclusivos en j*
T_j	*Conjunto de strokes de transformación que se ejecutan en j*
D_j	*Conjunto de strokes de transporte con outputs en j*
M_j	*Conjunto de strokes de decisión/apoyo que se consideran en j*
S_j	*Conjunto de strokes que se ejecutan en j con* $S_j = A_j \cup T_j \cup D_j \cup M_j$
P_j	*Conjunto de productos que se consideran en la ubicación j*

La matriz de Operaciones & Materiales tiene una estructura básica en cuanto a las Operaciones que se realizan en una matriz multi-sitio. Esa estructura se basa en las operaciones básicas que se realizan y se planifican en la red de suministro. La estructura que se propone en la figura 3 es un ejemplo de matriz para una red de suministro con 3 ubicaciones con envíos directos.

En la Fig. 3-2, se observan dos aspectos interesantes:

- Se ve que los diferentes strokes son responsabilidad de una localización.
- La matriz de transporte asociado a *j1* consiste en el conjunto de strokes cuyos *outputs* se ubican en *j1*. En el caso de la matriz de transporte asociado a *j2* se consideran los strokes que

no tienen *outputs* en *j1* (y en el caso más general, en los niveles superiores de la cadena de suministro).

- La matriz entera consta con muchos bloques de datos nulos y bloques de datos que dependen de las diferentes áreas de planificación.

VI. 2. Aplicación a un caso sencillo

Para entender con datos reales el modo de construcción de una Matriz de Operación y Materiales, se propone un ejemplo sencillo que se presenta a continuación.

En este ejemplo, se consideran tres plantas en ubicaciones distintas (j1, j2 y j3). La planta j1 trabaja en *Just In Sequence* para un OEM del sector del automóvil. La planta j1 recibe de la planta j2 racks llenos p6(j1) de productos. Un rack p6 se compone de 1 rack vacio p8 y de 8 productos p5. La operación básica que consiste en desempaquetar los embalajes llenos es k5(j1). Una vez desempaquetado, los productos p5 se pueden colocan en un soporte de mecanización que debe tener 3 productos en él. Debido a un proceso productivo complejo, se puede colocar los productos p5 en dos soportes a la derecha (stroke k4(j1)) o se pueden colocar 3 productos en un soporte a la izquierda y 3 otros en un soporte a la derecha con el stroke k3(j1). Si se realiza la operación k4, se obtienen 2 productos p2(j1) mientras que se realiza k3(j1) se obtiene 1 p2(j1) y 1 p3(j1). El proceso de mecanización y la operación que consiste en quitar los productos acabo se representa con los strokes k1(j1) y k2(j1). Estos dos últimos strokes se diferencia por la razón siguiente: en el primero, se considera mecaniza un producto p3 y un p4 mientras que en el segundo, se mecaniza 2 productos p3. Esta línea de mecanización necesita un mantenimiento periódico con lo cual se debe tener en cuenta y se debe determinar cuándo se debe ejecutar este mantenimiento. Esta operación de mantenimiento se considera con el stroke k6(j1).

La planta j2 es una planta dónde se ejecutan operaciones de inyección y operaciones de ensamblaje. Las operaciones de inyección se realizan en dos prensas. Para realizar los productos p9(j2) y p10(j2), la empresa puede usar una maquina 1 usando una matriz o usar la maquina 2 usando otra matriz diferente. Usando la maquina1, se consume 0.8 unidades de p12(j2) para fabricar 1 unidad de p9(j1) y dos unidades de p10(j). Por otro lado, si se usa la maquina2, consumiendo 1,2 unidad de p12(j12), se obtiene 1 unidad de p9(j1) y 4 unidades de p10(j2).

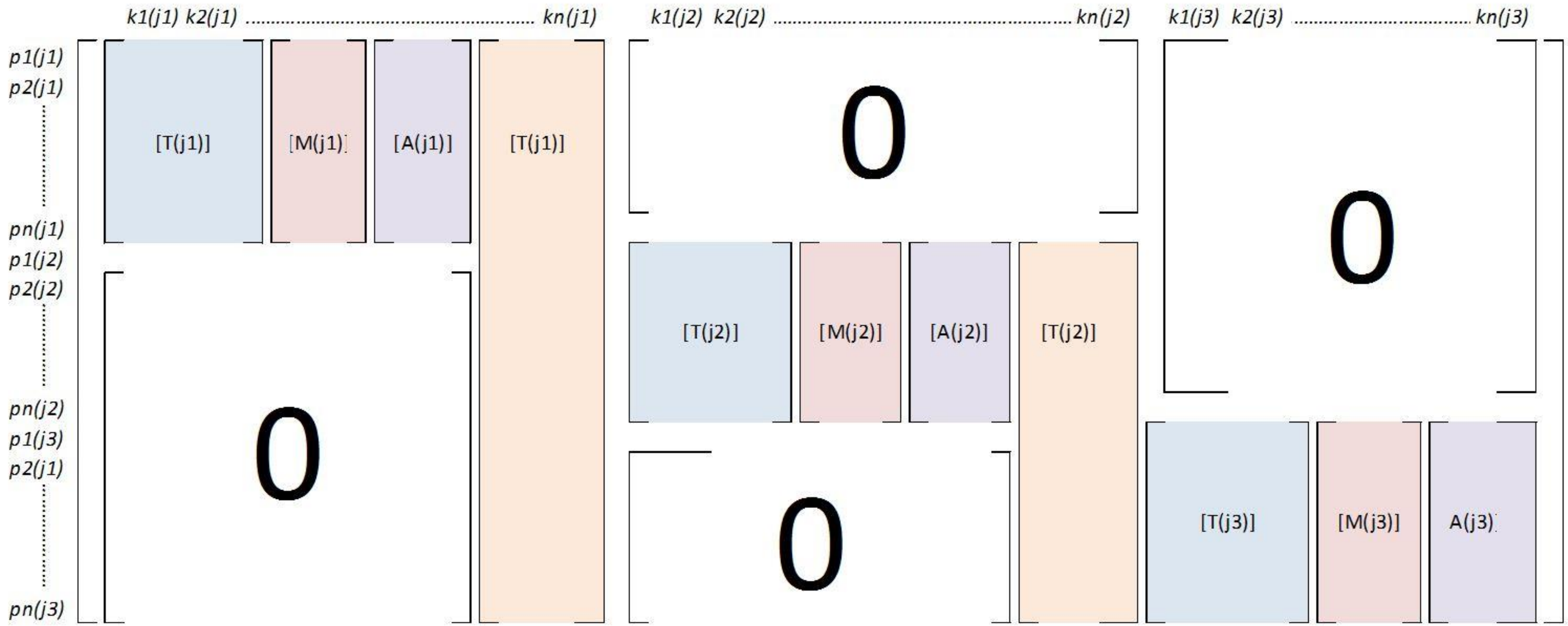

Fig. 3-2 Estructura de la matriz de Operaciones & Materiales en función de las operaciones consideradas

La segunda parte del proceso es el proceso de ensamblaje de productos. Para ensamblar una unidad de p5(j2), se necesita una unidad de p9(j2), una de p11(j2) y 3 unidades de p10(j2).

El producto p11(j2) se puede comprar a un proveedor externo con un tamaño de lote de 50 o se puede transporte desde la planta j3. Esta última planta es capaz de producir el producto p11(j3) con un tamaño de lote de 20 unidades.

Otra operación se deben considerar: los strokes de recirculación de racks vacíos, el transporte de racks llenos entre j2 y j1, el empaquetado de productos en j2 y los strokes de compra de p12(j2) y p12(j3).

La matriz de Operaciones y Materiales asociada al caso de estudiado presentado encima se presenta en la Fig. 3-3 a continuación.

		Desmontar productos pintados derecha e izquierda	Desmontar productos pintados derecha	Montar productos derecha e izquierda	Montar productos derecha	Desembalar racks llenos de productos no-pintados	Mantenimiento linea de pintura	Transporte racks llenos via camion	Transporte racks llenos via avion	Recirculacion de racks vacios	Packaging productos	Ensamblaje producto	Injección con molde 1	Injeccion con molde 2	Comprar Producto C	Compra Polvo en j2	Transportar entre planta j2 y j3 el Producto C	Injección Producto C	Compra polvo en j3
	S_{ki}	k1(j1)	k2(j1)	k3(j1)	k4(j1)	k5(j1)	k6(j1)	k7(j1)	k8(j1)	k9(j1)	k10(j2)	k11(j2)	k12(j2)	k13(j2)	k14(j2)	k15(j2)	k16(j2)	k17(j3)	k18(j3)
Producto derecha pintado	p1(j1)	3	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Producto izquierda pintado	p2(j1)	3	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soporte con 3 puertas derechas	p3(j1)	-1	-2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soporte con 3 puertas izquierdas	p4(j1)	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Puertas no pintadas	p5(j1)	0	0	-6	-6	8	0	0	0	0	0	0	0	0	0	0	0	0	0
Rack llenos de puertas no pintadas	p6(j1)	0	0	0	0	-1	0	1	1	0	0	0	0	0	0	0	0	0	0
Soportes de pintura vacios	p7(j1)	2	2	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Racks vacios	p8(j1)	0	0	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0
Rack llenos de puertas no pintadas	p6(j2)	0	0	0	0	0	0	-1	-1	0	1	0	0	0	0	0	0	0	0
Puertas no pintadas	p5(j2)	0	0	0	0	0	0	0	0	0	-8	1	0	0	0	0	0	0	0
Racks vacios	p8(j2)	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0
Producto A	p9(j2)	0	0	0	0	0	0	0	0	0	0	-1	1	1	0	0	0	0	0
Producto B	p10(j2)	0	0	0	0	0	0	0	0	0	0	-3	2	4	0	0	0	0	0
Producto C	p11(j2)	0	0	0	0	0	0	0	0	0	0	-1	0	0	1	0	1	0	0
Polvo	p12(j2)	0	0	0	0	0	0	0	0	0	0	0	0.8	1.2	0	50	0	0	0
Producto C	p11(j3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	20	0
Polvo	p12(j3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	50

Fig. 3-3 Caso sencillo de una matriz de Operaciones & Materiales

VII. Ventaja y desventajas de la planificación con el uso de la variable stroke

VII. 1. Límites de la representación

La construcción de estas matrices es sencilla pero a medida que vaya aumentado el número de productos, de operaciones, de recursos y de localizaciones el tamaño de las matrices irá creciendo. Y esto probablemente tendrá por consecuencia tiempos de carga de datos y tiempos de resoluciones más importantes.

VII. 2. Uniformidad de la variable de decisión

Como se puede apreciar en las figuras presentadas anteriormente, el uso del stroke permite representar de forma uniforme una gran variedad de problemas que se presentan en la planificación de operaciones. Basándose en una estructura más uniforme y sencilla con el concepto de stroke, el modelado matemático y la resolución del problema de planificación considera una única variable de decisión. Gracias a esta estructura es posible desarrollar algoritmos que se basen en un único vector homogéneo.

Como se observa en la Fig. 3-4, las variables típicas de producción, compras, transporte o de operaciones diversas se pueden representar mediante una variable única que se puede representar en una tabla única con la variable z_{kt}.

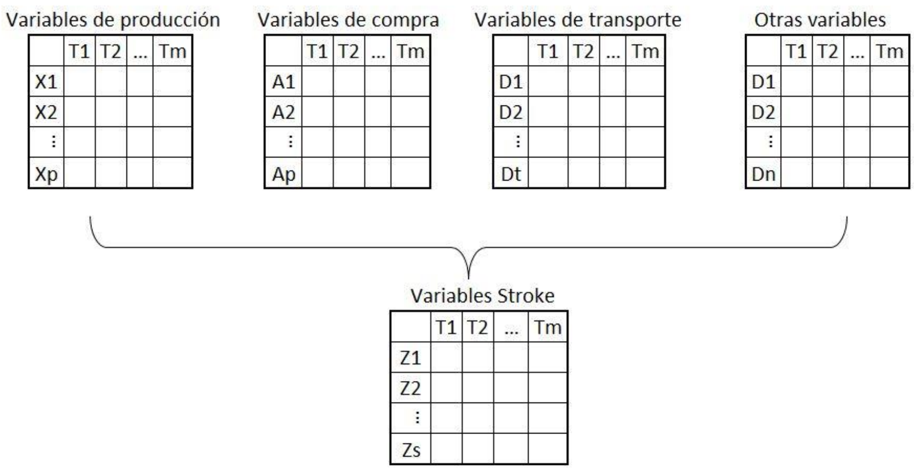

Fig. 3-4 Uniformización de la variable de decisión gracias al Stroke

Esta uniformización de la variable de decisión permite limitar el número de tipos de variables en la función objetivo. Así también, aunque un stroke se caracterice por unos stroke *outputs* y strokes *inputs*, el modelo no necesita presentar mucho índices.

VIII. Discusión, Conclusión y Líneas futuras de investigación

En este trabajo, se ha presentado un modelo de programación matemática para la resolución del problema GMOP. Este problema se basa en el concepto “stroke” para la planificación de las Operaciones y de los Materiales en un nivel estricto de igualdad. En el modelo, se ha incorporado el efecto de los lead-times sobre las ecuaciones de continuidad de los niveles de inventario.

Este nuevo enfoque implica la necesidad de trabajar con nuevas matrices diferentes a la matriz de Gozinto. En este trabajo, se propone la introducción de la matriz de Operaciones & Materiales y el uso de la matriz de Operaciones & Recursos que se basa en una matriz de asignación de strokes a recursos. Este trabajo propone un sencillo análisis de la matriz, presenta un caso sencillo de aplicación de las matrices. También se plantean las limitaciones y ventajas de este nuevo enfoque. Es de destacar que una de las principales ventajas del concepto de stroke y de las matrices introducidas es que permite un análisis estructurado del problema de planificación de las operaciones. También, se puede considerar alternativas de producción con una cierta facilidad ya que se puede introducir de forma estructurada nuevos datos.

Futuras líneas de investigación consisten en proponer procedimientos para la transformación de bases de datos tradicionales en bases de datos que soportan la planificación desde un punto de vista de las operaciones con el concepto del stroke. Otra línea de investigación consistirá en hacer experimentos para determinar el efecto de trabajar con el concepto de stroke sobre los tiempos de computación. También, resultará de gran interés analizar las estructuras de datos que hacen que el problema GMOP resulta más o menos difícil en su resolución. Y otra línea de investigación consistirá en apoyarse sobre estas novedosas estructuras de datos para resolver el problema distribuido de redes de suministro multi-sitio.

Capítulo 4 A Two-Stage Sequential Planning Scheme for Integrated Operations Planning and Scheduling System using MILP: The Case of an Engine Assembler

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Abstract. This paper presents an operations planning scheme based on mathematical programming models (specifically, Mixed-Integer Linear Programming (MILP) models) integrated into a web-enabled Advanced Planning and Scheduling System (APS), developed for and implemented in an engine assembler that supplies the car industry. One objective of this paper is to provide empirical insights into some operations planning characteristics in the automotive industry. The other main objective is to show MILP models and their use to create plans that enable the coordination of different planning levels (mid-term and short-term) and planning domains (procurement, production and distribution). The APS fulfills the requirements of an engine assembler in the automotive sector (namely lean-type constraints and objectives). The system is based on two MILP models, which have been purposely developed together along with their relations. The models presented herein provide a solution that considers supply chain objectives and constraints, and are integrated by means of data and constraints which have proven sufficient to fulfill users' and stakeholders' requirements. This case study presents the models' most relevant aspects and their implementation.

Keywords: Advanced Planning and Scheduling System (APS), Mixed-Integer Linear Programming (MILP), Supply Chain Management (SCM), Automotive Industry, Just In Time (JIT).

I. Introduction

Supply Chain Management (SCM) may be defined as: "the task of integrating organizational units through the supply chain (SC) and of coordinating the flow of material, information and financing for the purpose of fulfilling the client's demands" (Stadtler y Kilger, 2002). Dudek (2004) states three SCM objectives: improve service for clients; lower the amount of resources to serve clients; improve the SC's competitiveness. Improving competitiveness lies on two main pillars: integrating the SC and coordinating it (Stadtler, 2005). Coordinating the SC is, in turn, based on: using information and technology to improve the flow of information and materials; process orientation in order to accelerate the execution of processes and associated activities; and Advanced Planning (Stadtler, 2005). Advanced Planning of the SC addresses decisions regarding SC design, its mid-term coordination and the short-term planning of processes. Advanced Planning systems attempt to fulfill the aforementioned objectives by using specific software (Fleischmann y Meyr, 2003).

Many managers tend to think that Enterprise Requirement Planning (ERP) systems will solve their planning issues. Yet despite its name, ERP systems are usually transaction-based systems rather than planning systems (Chen, 2001). Traditional production planning methods, such as Material Requirements Planning (MRP), consider only the availability of materials, and totally ignore factors such as capacity limits and SC configurations (Caridi y Sianesi, 1999). Furthermore, planning functions in large companies are usually executed by different organizational units at different locations. The lack of coordination between these planning functions often results in excess inventories, poor customer service, and insufficient capacity utilization (Kannegiesser y Günther, 2010).

The broad extension of ERP systems has brought about the emergence of the so-called Advanced Planning and Scheduling Systems (Chern y Hsieh, 2007) which may be viewed as "add-ons" of the ERP system to plan and optimize the SC (Rashid et al., 2002). An Advanced Planning and Scheduling System (APS) extracts data from the ERP systems, and supports decision making to reduce costs and inventory and increase manufacturing throughput and improve productivity (Lee et al., 2002). Once the decision has been made, it is sent back to the ERP system for its final execution (Fleischmann y Meyr, 2003). For this support, APS uses optimization techniques to model and determine the quantities to be produced, stored, transported, and procured by respecting real constraints of the SC (Günther y Meyr, 2009). APS might help with the management of the whole SC, specifically its operations (Parush et al., 2007). There are many commercially available APS software (David et al., 2006). The various software modules cover all the segments of the operations planning throughout the SC, in all the planning horizons (Stadtler, 2005). Although an interesting application may be found in (Sillekens et al., 2010), the use of Advanced Planning tools in the automotive industry is minimal (Meyr, 2004). Perhaps this is because over the years, it has been claimed that the application of lean principles and the use of Information Technology are incompatible (Riezebos et al., 2009). It is not in vain that what is considered the first article in English on the Toyota Production System (Sugimori et al., 1977) suggests that the use of computer systems to organize logistics would introduce uncertainty and unnecessary costs.

Many Lean companies now use ERP/MRP methods to communicate demand through SC, and hybrid situations have become common in the automotive industry (Riezebos y Klingenberg, 2009). Indeed, the need to coordinate capacitated transport and production together with low stock levels, and its relation with lean systems, is probably no small concern. MRP does not offer planning tasks in this sense (Drexl et al., 1994); instead, it supports planning, but only to a limited extent (Chung y Snyder, 2000), and a program that works on the shop floor cannot be obtained through its use (Ho y Chang, 2001). In fact, MRP systems are supplemented with spreadsheets into which data are manually gathered to develop production plans (Hahn et al., 2000). This lack of use of more Advanced Systems might be related with the complexity of the SC in the automotive sector (Choi y Hong, 2002).

The research presented in this paper came about with the request of an IT Consultancy firm which had been asked to automate the operations planning process, which then involved several technical operators. The automotive company, with engine plants worldwide, had a proprietary ERP system that did not consider an Advanced Planning and Optimization module. The request characteristics included the development of a tool which exports results to an Excel spreadsheet so they can be modified. This paper shows the planning scheme based on mathematical programming that was developed in line with this request.

One of the main objectives of the paper is to provide new insights into the Operations Planning process, thus the paper is presented as a case study. The second objective is to propose a mathematical modeling approach to solve the problem by “satisficing” users’ requirements. Of course, the models proposed are not the only possible ones, but have been able to solve the issues which arose during the process.

This paper presents a successful implementation of a web-enabled APS that coordinates the SC of an engine assembler. Our case study includes an overview of mid-term master planning and short-term operations planning using MILP models, and demonstrates how coordination between business functions and temporal scales has been achieved. The framework used in this paper is similar to that presented by Meyr et al. (2005), which covers the main areas of any APS.

The remainder of the paper is organized as follows: first, an overview of the problem is introduced. Then, the different modules that have had to be generated are thoroughly described. Sections 4 and 5 introduce the designed and implemented models. Section 6 offers an overview of the system in which the models have been included, together with an implementation analysis and a summary of the new system’s advantages. The paper ends with a conclusion and a further research section.

II. Problem overview

II. 1. The product and clients

An internal combustion engine is an assembly product composed of a variety of components that are manufactured and assembled on an assembly line (Wang y Sarker, 2005). Although there are many other parts that are also assembled in the final product, the most relevant components, known as the 5Cs, are cylinder blocks, cylinder heads, crankshafts, connecting rods and camshafts (Lloret et al., 2009). Each component type is produced on a different and highly automated specific line.

The main clients of an engine assembly line are car assembly lines. The cost of backlogging those clients is very high since a car cannot be assembled without an engine.

The other clients of an engine plant are mainly spare part distribution systems and customized car builders (among these, R&D departments). These clients have very low demand and their backlogging costs are not that high.

Each client requires different engines, and the volume of each one might vary considerably (both from client to client and among different periods). For instance, a research center might request a few units per week, whereas a car assembly plant might require dozens or hundreds of units per day.

Overall demand in a normal week might be higher than 5000 units. Yet fluctuations caused by clients' calendars (e.g., summer holidays) and the final demand of cars exist. Variety of final products (engines) has increased in the last decades. Some 25 years ago, the plant did not produce more than 4 or 5 types simultaneously, but nowadays, it can produce about 40 variants in the same week.

Moreover, engine components can also be sold elsewhere. The main external clients for components are the spare part operations system and other engine plants all over the world. Fluctuations in external demand for components are even greater than at the engine level.

The demand forecast is the result of a previous MRP explosion done through corporate software. The larger the product sales volume, the better the forecast. Demand has a 6-month horizon. It is very accurate for the first 4-5 weeks in the horizon, even though the demand in the final periods is most unreliable. Fig. 4-1 represents the different elements and flows in the SC of the engine assembler.

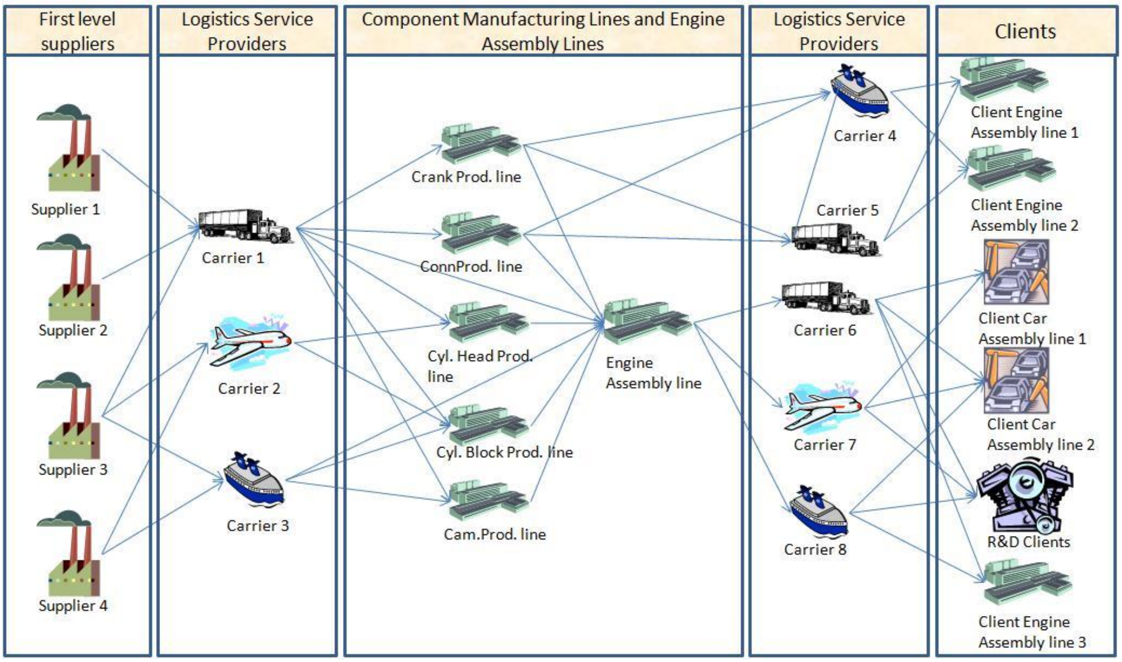

Fig. 4-1 Supply chain of an engine assembler scheme

Transport to clients might be by truck, ship, train, or even plane. In any case, the whole capacity should be used since transportation costs amount to almost 60% of logistics costs. In our case study, long distance and large quantities transport justifies the Full Truck Load (FTL) strategy (Bilgen y Günther, 2009).

II. 2. The supply chain topology

To better understand the SC planning problem in the case presented in this paper, Tabla 4-1 describes the functional and structural attributes of the component production lines and the engine assembly line.

The engine assembly line is a mixed model assembly line (MMAL); however, a multi-model assembly line has emerged in the last 15 years ago. Some characteristics of shorter complexity times have been kept, and they avoid the possibility of sequencing all the possible variants simultaneously. In fact, some of the line's physical characteristics are shown by limiting the constraints in the number of models to be assembled simultaneously. This line has no setup costs and does not require a setup time to change the model.

Component lines did not evolve from the multi-model assembly line concept, and their setup costs are highly relevant and sequence dependent. The setup process has evolved in order to avoid setup times.

The raw material for all five main components (the so-called 5Cs) is bought directly from different foundries with long lead times. As previously mentioned, these engine factories frequently buy and sell components to other engine factories. There is limited capacity storage between both stages, and this storage capacity differs for the various lines since products are stored in different racks, and different tools are used to manipulate them.

The different supply modes presented in (Boysen et al., 2009) also appear (to a lesser extent) on the engine assembly lines. The supply that a simple engine plant requires has to consider not only the foundries that deliver the five components which are the raw materials for the 5Cs lines, but also some plastic components and other subassemblies. Some suppliers are local, but with others, transit times can run to more than 10 weeks given the use of global suppliers for some components. These times can be unreliable owing to customs, shipping, and so on.

The operations planning process presented in this paper involves several departments. The main stream of the work was done together with the material planning and logistics department, but production, human resources, maintenance or quality department constrain the definition of the problem and/or use the results obtained.

Tabla 4-1 Supply chain topology for the engine supply chain

Functional attributes		
	Component Production Lines	*Engine Assembly Line*
Attributes	*Contents*	*Contents*
Number and type of products procured	*Few, 3-7 major raw materials for each line*	*Important, 5 mains components (5Cs) & 350 commodities*
Sourcing type	*Single (Raw Material Family)*	*Single (for European Supplier), Multiple (for local Supplier)*
Supplier lead time and reliability	*8-12 weeks for cylinder block and cylinder head & uncertain, Short (days) & reliable for the others*	*Short (hours) for Products supplied in JIT & reliable, Medium (days) & reliable for the others*
Materials´ life cycle	*Long (1 year)*	*Medium (6 months) before small engineering changes*
Organization of the production process	*Flow line*	*Mixed Model Assembly Line*
Repetition of operations	*Large batches (depends on the considered line)*	*Small batches*
Changeover characteristics	*Sequence dependence setup costs*	
Bottlenecks in production	*Known*	*Known*
Working Time flexibility	*Frequently used, additional shifts*	*Frequently used, additional shifts*
Distribution structure	*One stage*	*One stage*
Pattern of delivery	*Continuous FTL*	*Continuous FTL*
Deployment of transportation means	*Unlimited*	*Unlimited*
Availability of future demands	*Forecasted for external demand and orders for internal demand*	*Forecasted for external demand.*
Demand curve	*Stable, highly dependent on new product development*	*Stable, highly dependent on new product development*
Products' life cycle	*One year*	*Several months*
Number of product types	*20*	*50*
Degree of customization	*Standard products*	*Standard products & some customized products*
Bill of Material (BOM)	*I-Type*	*A-Type and Alternative BOMS*
Portion of service operations	*N.A.*	*N.A.*
Structural attributes		
	Component Production Lines	*Engine Assembly Line*
Attributes	*Contents*	
Network Structure	*Mixture*	*Mixture*
Degree of globalization	*International*	*International*
Location of decoupling point(s)	*Make to Stock*	*Make to Stock*
Major constraints	*Stock capacity, Dependent Setup, Material Availability*	*Manpower, Capacity of Assembly line, Material Availability*
Legal position	*N.A.*	*N.A.*
Balance of power	*Customer*	*Customer*
Direction of coordination	*Mixture*	*Mixture*
Type of information exchanged	*Forecasts & Orders*	*Forecasts & Orders*

III. The supply chain matrix in this case study

In this section, an overview of the planning needs in this case study is presented. The framework presented by Meyr et al. (Meyr et al., 2005), as seen in Fig. 4-2, was used to cover the main system areas. In this case study, mid-term corresponds to the 6-month planning horizon with bucket periods of weeks, while short-term planning corresponds to a 4-week planning horizon with daily buckets. Lastly, the daily scheduling tasks are solved with a 2-day horizon with variable buckets.

The structure of this section goes through the different planning levels, and covers domains such as the Supply Chain Planning matrix modules. The particular characteristics of the different APS modules implemented are highlighted.

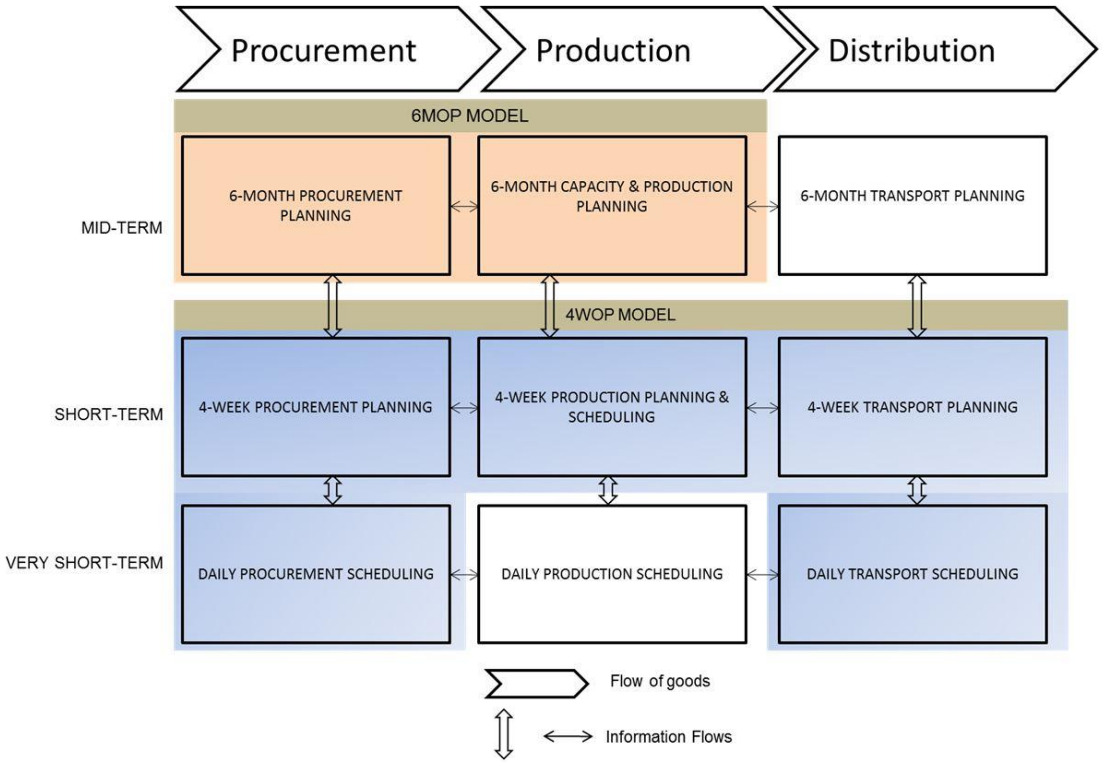

Fig. 4-2 Coverage of the mathematic models implemented in the APS in this case study

The main characteristics of the models herein presented are similar, since both of them are operations planning models. The differences between them are those related with different horizons and periods. Therefore the main differences will show up in terms of objectives and constraints formulation than on their own definition.

III. 1. Six-month master planning (6MMP)

Mid-term planning is usually divided into two main modules: Master Planning (MP) and Demand Planning. Demand Planning is not treated in this case study since it was defined by the other firm’s levels. Our work proposes to solve the 6MMP, along with the 4-week operations planning, to synchronize the whole network flow of materials on a mid-term basis.

According to several authors, the planning horizon comprises at least one seasonal cycle, typically one year (Stadtler, 2005). In our case the planning horizon should at least cover until the end of the next long holiday period (Easter, Summer, Christmas).

The six-month plan presented in this case study not only considers the capacity planning activities at the production level, but also includes material requirements, production and transport planning at a reasonable detailed level. With this horizon, transport planning activities are usually considered to select transport modes. However, these decisions are beyond the scope of the case study presented herein, which also happens with supplier selection activities.

To better understand the planning tasks, objectives, constraints and decisions to be taken at this level, a summary is proposed in Tabla 4-2. This table describes it by separating the functional areas of procurement, production and distribution that are considered in the same model.

The 6MMP process delivers plans for each functional area:

- 6-month capacity production plans for all five production lines and the assembly line, including production rates and the working calendar.
- 6-month production plans for each line for the purpose of setting stock levels at the end of each week with the 6-month horizon.
- 6-month material requirements plans for short-distance suppliers and a 6-month detailed material procurement plan for long-distance suppliers.

As explained later, the mathematical model is used in two separate instances: first, to help define the 6-month capacity production plan; second, the production levels have to be defined together with the rest of the plans.

In the 6-month master planning, 6-month transport planning has not been incorporated since it confers great complexity to the modeling problem and it is usually done at the 4-week level. So, after some meetings with the staff related to the problem, it was decided to not include it in the mathematical planning.

Tabla 4-2 6MMP characteristics

	Procurement	*Production*
Tasks	*Raw material requirement planning for short-distance suppliers* *Ordering raw material for long-distance suppliers*	*6-month master production planning*
Objectives	*Minimize raw material stock levels*	*Minimize total operating costs (minimization of productive days and extra days production)* *Minimize storage costs* *Maximize the stability of the plans*
Constraints	*Working calendars* *Lead time of long-distance suppliers* *Raw material in transit*	*Working calendars* *Production rates* *Safety stocks levels* *Storage capacity limits* *Availability of raw materials and components*
Decisions	*6-month material requirements plan for short-distance suppliers* *6-month detailed material procurement plan for long-distance suppliers*	*6-month capacity production plans (new working calendars; adjustments in production rates capacity)* *6-month production plans for each line*

6-month capacity production plans

Wang and Liang (2004) state that MP aims at determining the best means of meeting demand by adjusting production capacity (workforce levels, overtime, out-sourcing, contracting, etc.) and stock levels.

Piper and Vachon (2001) state that there is an overwhelming trend to follow the chase strategy, i.e., adapting capacity to demand. The chase strategy requires planning the production rate of each line and a working calendar for each line months in advance. For the mid-term planning horizon, the workforce’s flexibility and working time play a particularly important role (Sillekens et al., 2010).The production rate decision will have an impact on the manning required: the higher the production rate, the more people required to work with it.

Therefore, the flexibility to change production rates is limited by the ability to hire people and changes cannot be made too frequently.

Although JIT requires stability on demand (Monden, 1994), demand changes are frequent. They can be due to changes in client requirements, to the global network that is being served, or due to different working schedules held by international clients. Moreover, the production rate cannot be changed too frequently since these changes affect the stability of the SC requirements, which might have a huge impact on the system performance (Bozarth et al., 2009).

Since each line (both assembly and component) has different demand requirements and production rates, a different working calendar has to be defined for all six lines. Therefore, factory working calendars are used to chase demand by adding extra shifts or new down days –a down day is a normal working day when the factory decides to stop production to help balance the production level and the demand level-. Down days are used, for instance, to do extraordinary maintenance or workers training. Calendars should respect the working calendars preestablished by staff and external stakeholders such as trade unions. Therefore, a penalty on the addition or removal of extra working shifts should be considered.

Since plant flexibility is limited, minimum stockpiling is admitted mainly to prevent holiday “clashes”. The way to ensure that the inventory does not rise very much is to establish objective stock levels at the end of any long holiday period. The product demand has to be satisfied by the production capacity. If a decoupling of production over buffers is possible, then buffers have minimum and maximum amounts of stock (Sillekens et al., 2010). The plant will stockpile for weeks, and even months ahead of the holiday period foreseen, but stock levels will have to be reduced at the end of the period with a given objective.

This quantity of stock, due to the stockpiling process, should be balanced among those products with larger demand. Although from a mathematical point of view it is not relevant which product is to be stocked (or should it be the cheapest), from a practical point of view it does not make sense to manufacture too many units of a given product and nothing of the rest (although the product is only produced to be stocked). There is a practical reason for that requirement: an unbalanced production will lead to an unbalanced supply. In terms of stock managers it is also shown up as a dislike to unbalanced shipping banks. Nor do they like to have too many units of those products with low demand, since the demand of those products might disappear unexpectedly.

6-month detailed production plans and 6-month material requirements plans

Once the 6-month capacity production plans have been accepted, detailed production plans and material requirement plans are required. Production plans will have to cope with transport requirements and will generate material requirements.

Due to the relatively high number of components and products being produced, the detailed production and stock levels of the products in each period will help us know if we will be able to cope with the problem.

Requirements have to be communicated to the entire SC so that each area can adjust its productive capacity. In the case study presented herein, the critical raw materials for several of the major engine components are purchased directly from international foundries working with long and variable supply times.

According to the user requirements, only the five major components (5Cs) are planned, and the rest are done using the company’s ERP system that holds the whole BOM.

III. 2. 4-week operations planning (4WOP)

The 4-week operations plan must satisfy the requirements of the logistics department, but must also take into account the constraints that the production department defines. Both these departments have contradictory objectives and different constraints, and the trade-off that usually occurs in real meetings has to be considered with the implemented model.

Using the same approach as for the 6MMP, Tabla 4-3 summarizes the case of the 4WOP and some of the characteristics considered.

In this case study, the 4WOP process generates three main plans.

- 4-week transport plan aimed to optimize products and component shipping costs.
- 4-week engine production plan and 4-week detailed component production plans with different objectives for each production line in an attempt to accomplish stability in one case and to cut setup costs for the others.
- 4-week material requirements plan that aims to both schedule production quantities to short-distance suppliers and order shipping quantities to long-distance suppliers.

Tabla 4-3 4WOP characteristics

	Procurement	*Production*	*Distribution*
Tasks	*Ordering materials for short-distance suppliers* *Material requirements planning*	*Engine production planning* *Detailed Component production plans*	*Engine transport planning* *Component transport planning*
Objectives	*Minimize raw material stock levels*	*Maximize production leveling* *Minimize inventory faults* *Minimize set-ups costs*	*Maximize engine delivery fulfillment* *Minimize backlog costs*
Constraints	*Working calendars* *FTL strategy* *Truck and rack capacity*	*Safety stock level constraints* *Maximum stock level limits* *Max/Min number of derivate products manufactured* *Daily production capacity* *Availability of raw materials and components*	*Working calendars* *FTL Strategy* *Truck and rack capacity* *Demand fulfillment*
Decisions	*4-week material requirements plan*	*4-week engine production plan* *4-week detailed component production plans*	*4-week transport plan*

The overall objective is always said to minimize total costs; yet in general, these costs are unknown. The model was designed to hold them all. A parameter tuning was manually and heuristically performed in the implementation phase.

The 4-week transport plan

Transport planning is a fundamental task since the costs involved are substantial. The demand of each client, expressed in units per day with a 4-week horizon, is obtained from the company's ERP system.

In our case, each client has a different working calendar, and shipping calendars have to be calculated from them. Each client is different and backlogging has different costs for each one (e.g., it is not the same to stop a car assembly line than to delay the shipment of two units to the R&D department).

Trucks and containers have a different rack capacity depending on the client. Racks have a different capacity depending on the product. Although filling trucks might not be seen as a lean practice, the transport efficiency will require this practice. The FTL strategy (Ozdamar y Yazgac, 1999), and its associated unit load constraints, generate the need to consider over-deliveries when serving before being requested in order to fill trucks. In practice, each client will accept different under-delivery or over-delivery levels. In this paper, this situation is named positive and negative backlogging.

The 4-week production and detailed production plan

As mentioned earlier, the system can be defined as a two-stage hybrid flow shop in which the second stage is a mixed model assembly line and the first stage involves multi-model production lines (Quadt y Kuhn, 2008). This specific type of flexible flow shop with assembly operations, quoted for instance at Yokoyama (Masao, 2008), does not sustain simple objetives. The objectives for the first stage are to reduce the number of setups, and to minimize inventory and production costs of various kinds (Garcia-Sabater y Vidal-Carreras, 2008). In the second stage, however, reaching a leveled production is the main objective, i.e., the MMAL problem (Bautista et al., 1996).

In our case, it also has to consider the transport plan. The integration of transport and production decisions into SCs has been the object of several papers and it is shown to be a difficult task (Cardos y Garcia-Sabater, 2006; Günther y Seiler, 2009; Mula et al., 2010; Simpson y Erenguc, 2001).

In the traditional approach, planning and scheduling are implemented sequentially. The production plan is determined before the actual scheduling (Lee, 2002). In this case study, engine production planning should also be synchronized with component production scheduling due to the capacity limits at the inventory level. Each production line is characterized by its production rate and by its relatively long cycle times and high setup costs. Besides, the supply lead-time is measured in days or weeks for some components. Thus, coordination between planning and scheduling for the whole SC is critical.

In order to achieve this coordination, specific constraints for the different characteristics are to be considered. For instance, in the case of the assembly line the number of derivatives that may be simultaneously assembled on the engine line is limited. In the case of the 5C manufacturing line, the setup process on the components lines is not standard and requires different levels of manning depending on the urgency of the setup, and it holds sequence dependency. The inventory capacity between lines and at the shipping bank is limited. Alternate BOMs are possible depending on the availability of components.

The planning process will use the information supplied by the 6MMP process in the form of calendar and stock targets at the end of each planning period (i.e., the week).

The 4-week material requirements planning

Apart from some raw materials that arrive from long distance suppliers, the bulk of the purchased components come from European suppliers or from suppliers on a nearby industrial park. The European suppliers have a lead-time of around 4-7 days. Local suppliers might serve on the same day.

A 4-week purchase plan with daily periods is created to take into account the entire supply base. Depending on the supplier, a frozen period is established and some changes are not allowed.

III. 3. The daily planning process

For years, the explicit and implicit constraints, objectives and goals of each team involved in the reception, production and delivery of materials were fitted in daily meetings by changing almost any part of the plan. Since plans were generated manually, this form of managing constraints and objectives was not a bad option, and anything could be changed if everyone agreed.

Yet if we intended to use an automatic planning system that considers such meetings, it could not be managed in the same way.

Now, constraints have to be explicit and should be given before the plan is to be made. To help the planning department staff deal with the other departments, the above-mentioned plans are transformed into a very short-term schedule for each section. Detailed engine production plan for the assembly line and a detailed transport plan for some suppliers and clients were generated to show the plans to help during the negotiation process. Tabla 4-4 offers the basic characteristics of the daily planning process.

Tabla 4-4 The daily planning process characteristics

	Procurement	*Production*	*Distribution*
Tasks	*Ordering materials* *Reception planning* *Detailed load truck planning for procurement*	*Engine quantity definition*	*Detailed load truck planning for transport*
Objectives	*Minimize raw material stock levels* *Maximize truck fulfillment*	*Minimize set-ups costs*	*Maximize truck fulfillment*
Constraints	*FTL strategy* *Truck and rack capacity*	*Max/Min number of product derivates manufactured* *Sequence dependence*	*FTL strategy* *Truck and rack capacity* *Demand fulfillment*
Decisions	*Daily detailed procurement plan*	*Daily detailed engine plan*	*Daily detailed transport plan*

It has to be pointed out that initially the purpose of the project was to create the detailed production plan for each and every line. Since that schedule required a huge quantity of non-yet available data (for instance, maintenance plans), this objective was eliminated.

Therefore, there is no model available to solve the daily planning process. However, considering the objectives and constraints in the daily planning process is necessary since the 4WOP model has to propose a schedule to be used to create detailed and definitive schedules for each line.

In general, objectives and constraints are considered at previous planning levels to ensure that solutions are executable at the next planning level. For instance, the sequence on the assembly line is done with a specific software that sequences the Mixed Model Assembly Line. This software has to be fed with information about the quantity of engines to be assembled. The 4WOP process creates a plan that can be easily transferred by considering the limitations of the number of derivatives (both minimum and maximum).

IV. MILP model formulation for the 6-month master planning process

This section introduces the mathematical formulation for the 6MMP process as it has been modeled in this specific case.

IV. 1. Basic assumptions

In our 6-month master plan, the horizon is divided into 25 time buckets of one week each. This was the original way of working and has been maintained. For each week, demand forecasts are known, although the latest periods are not complete neither fully reliable. The planners' main objective is to firstly generate a feasible calendar that includes production rates, number of working days and down days, and the number of extra shifts per week.

Capacity might lessen by adding new down days. Similarly, capacity might increase by adding new extra shifts to those already planned. The calendar and the production rate for each line are decided at a plant level. Therefore, our tool generates plans to assess the best combination, but it does not decide it.

Inventories and the BOM of each product are also known (using the company´s ERP system), but only the data related with the main 5Cs components are considered. Stock levels are considered in two different ways. First, the stock level of each product has to be over a predefined safety stock level, although the available stock at the end of each period should be balanced between product types. This stock balance implies to keep a shipping bank (end product ready to be sent) as balanced as possible by keeping a similar run out for each product type.

IV. 2. Notation

To mathematically formulate the problem, it is necessary to define the nomenclature presented in Tabla 4-5, Tabla 4-6 and Tabla 4-7.

Tabla 4-5 Sets and indexes

i, i_1, i_2	*Indexes for products (engines and components)*

$E \in \{E_1\}$	*Index for engine assembly line*
$C \in \{C_1, \dots, C_5\}$	*Index for components production lines*
$\xi \in \{C, E\}$	*Index for production lines*
t	*Index for time ($t = 1 \dots T$)*
L_ξ	*Set of products produced on line ξ*

Tabla 4-6 Parameters notation

T^{EST}	*Number of consecutive weeks of production while maintaining a leveling*
C_{it}^{Y}	*Cost of holding a unit of i during week t*
C_{it}^{Γ}	*Cost of a non leveled plan for product i in week t*
C_t^P	*Cost of a non stable plan in week t*
C_t^L	*Cost of a non balanced shipping bank in week t*
$C_{\xi t}^{ND}$	*Cost of a normal day in week t on line ξ*
$C_{\xi t}^{ES}$	*Cost of an extra shift in week t on line ξ*
SM_{it}	*Maximum stock level of product i in week t*
SS_{it}	*Safety stock level of product i in week t*
SD_{it}	*Desired stock level of product i in week t*
D_{it}	*External demand of product i in week t*
$Q_{i1,i2}$	*Number of units of i2 required to produce one unit of i1*
LT_i	*Lead-time of product i*
$K_{\xi t}$	*Daily production capacity of line ξ in week t*
$J_{\xi t}^{ND}$	*Number of normal days that line ξ is planned to work in week t in a previous plan*
$J_{\xi t}^{ES}$	*Number of extra shifts that line ξ is planned to work in week t in a previous plan*
$J_{\xi t}^{MAXND}$	*Maximum number of normal days that line ξ can work in week t*
$J_{\xi t}^{MAXES}$	*Maximum number of extra shifts that line ξ can work in week t*
$NS_{\xi t}$	*Number of shifts per working day on line ξ in week t*
RPL_{it}	*Scheduled quantity for receipt of product i in week t because of previous plans*
$PX_{it}^{\tau-1}$	*Planned production for product i in week t in a previous plan*
Δ	*Percentage that limits the production mix changes penalization*
ψ	*Limiting percentage that defines if a product has low demand*
$\bar{\Lambda}$	*Latest period in which the whole planned capacity has to be used*

It has to be pointed out that the so-called costs are only penalty parameters. Most will never have a stated value in an accountancy system, and those that do will not be completely reliable.

Tabla 4-7 Variables notation

$y_{it} \in \mathbb{Z}^+$	*Stock level of product i in week t*
$x_{it} \in \mathbb{Z}^+$	*Production of product i in week t*
$r_{it} \in \mathbb{Z}^+$	*Requirement of material i in week t*
$\gamma_{it} \in \mathbb{R}^+$	*Unleveled production of product i in week t*
$p_t^+ \in \mathbb{R}^+$	*Positive production instability rate in week t in relation to previously planned production*
$p_t^- \in \mathbb{R}^+$	*Negative production instability rate in week t in relation to previously planned production*
$\lambda_t \in [0,1]$	*Percentage of the balanced stock level that indicates how far the worst product stock is from its desired level in week t*
$w_{\xi t} \in \mathbb{R}^+$	*Working days in week t*
$n_{\xi t}^{ND} \in \mathbb{Z}^+$	*Proposed new normal days in week t*
$d_{\xi t}^{ND} \in \mathbb{Z}^+$	*Proposed new down days in week t*
$d_{\xi t}^{ES} \in \mathbb{Z}^+$	*Proposed extra shifts in week t*

IV. 3. Objective function

The objective of the proposed model is to minimize total costs (0.14).

$$
\min \left\{ \begin{array}{ll}
\sum_t \sum_i C_{i,t}^Y \cdot \left(y_{i,t} - SS_{i,t} \right) & (1.1.1) \\
+\sum_t C_t^L \cdot \lambda_t & (1.1.2) \\
+\sum_t \sum_\xi \left(C_{\xi,t}^{ND} \cdot \left(n_{\xi,t}^{ND} - d_{\xi,t}^{ND} \right) + C_{\xi,t}^{ES} \cdot n_{\xi,t}^{ES} \right) & (1.1.3) \\
+\sum_t \sum_{i \in L_E} C_{i,t}^{\Gamma} \cdot \left(\gamma_{i,t} - \Delta \right) & (1.1.4) \\
+\sum_t^{\bar{\Lambda}} C_t^P \cdot \left(p_t^+ + p_t^- \right) & (1.1.5)
\end{array} \right\} \quad (0.14)
$$

The holding costs of inventory are only considered if the stock is over the safety stock level (1.1.1). Costs are different per product and per period, since the relevance of the over-stocks depends on both the product and the horizon.

However, inventory has to be controlled to keep a balanced shipping bank of each product, as mentioned previously. In order to do so, the value of the unbalanced shipping bank for each period, together with Constraint (0.17), has to be minimized. This is the purpose of objective (1.1.2): to track and keep a leveled shipping bank among the different products.

Summation (1.1.3) holds to minimize the use of days and extra shifts. The parameters are tuned to prefer a normal day to an extra shift. Yet should staff wish to consider an extra shift, it can be added as a parameter.

Summation (1.1.4) attempts to create a leveled plan by minimizing the differences between the consecutive periods of the same plan. This is a basic objective in order to create and sustain a lean supply chain.

Summation (1.1.5) attempts to create plans that are as stable as possible in terms of the previous plans results. With p_t^+ and p_t^- we intend to measure the maximum positive and negative deviation of the planned production on a given day compared against the previous plan.

Like most real problems, the problem presented herein is a multi-criteria one. We used a weighted criteria approach to reduce it to a single objective. The fine tuning of the so-called cost parameters will enable the creation of a plan that satisfices users.

IV. 4. Constraints

$$y_{i1,t} = x_{i1,t} + y_{i1,t-1} - D_{i1,t} + RPL_{i1,t} - \sum_{i2}\left(Q_{i1,i2} \cdot x_{i2,t}\right) \quad \forall i1,t \qquad (0.15)$$

$$SS_{it} \le y_{it} \le SM_{it} \quad \forall i,t \qquad (0.16)$$

$$y_{it} \ge \left(1-\lambda_t\right) \cdot SD_{it} \quad \forall i,t \qquad (0.17)$$

$$K_{\xi,t} \cdot w_{\xi,t} = \sum_{i \in L_\xi} x_{i,t} \quad \forall \xi, t < \overline{\Lambda} \qquad (0.18)$$

$$\sum_{i \in L_\xi} x_{i,t} \le K_{\xi,t} \cdot w_{\xi,t} \quad \forall \xi, t \ge \overline{\Lambda} \qquad (0.19)$$

$$w_{\xi,t} = J_{\xi,t}^{ND} + \frac{J_{\xi,t}^{ES}}{NS_{\xi,t}} + n_{\xi,t}^{ND} - d_{\xi,t}^{ND} + \frac{n_{\xi,t}^{ES}}{NS_{\xi,t}} \quad \forall \xi, t \qquad (0.20)$$

$$n_{\xi,t}^{ND} - d_{\xi,t}^{ND} \le J_{\xi,t}^{MAXND} - J_{\xi,t}^{ND} \quad \forall \xi, t \qquad (0.21)$$

$$n_{\xi,t}^{ES} \le J_{\xi,t}^{MAXES} - J_{\xi,t}^{ES} \quad \forall \xi, t \qquad (0.22)$$

$$\gamma_{i,t} \ge \max\left(\Delta; \left|\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}}\left(J_{E,\tau}^{ND} \cdot K_{E,\tau}\right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}}\right|\right) \quad \forall i \in L_E, t < T - T^{EST} \qquad (0.23)$$

$$x_{i,t} \le PX_{i,t}^{\tau-1} \cdot \left(1 + p_t^+\right) \quad \forall t < \overline{\Lambda} \quad \forall i / D_{i,t} > \Psi \cdot K_{\xi,t} \qquad (0.24)$$

$$x_{i,t} \ge PX_{i,t}^{\tau-1} \cdot \left(1 - p_t^-\right) \quad \forall t < \overline{\Lambda} \quad \forall i / D_{i,t} > \Psi \cdot K_{\xi,t} \qquad (0.25)$$

$$r_{i2,t} = \sum_{i1}\left(Q_{i1,i2} \cdot x_{i1,t+LT_{i2}}\right) \quad \forall i2 \text{ with long lead-times } \forall t < T - LT(i2) \qquad (0.26)$$

$$\sum_{\tau=1}^{t} r_{i,\tau} \le \sum_{\tau=1}^{t} RPL_{i,\tau} \quad \forall i, t \le LT(i) \qquad (0.27)$$

The classical continuity constraints apply to the model (0.15). There are two origins for product consumption: external demand and internal demand (requirements from the engine assembly process). The second part of demand applies only to those components to be used for the engines on the assembly line. Therefore, it is not necessary to consider lead-times, which might be longer than one day, but no longer than one week.

For any engine and component, its inventory level should not be lower than the safety stock level (0.16). These safety stock levels differ per product and per period since they have to consider the forecasted demand of the product.

However, there are also other stock limits to be considered as a user might impose a limit in terms of:

- quantity for a given time (since it might expect change),
- run-out time (a user that does not wish to hold more than a given amount of days of demand).

These limits are defined before the model is to be launched. Then stock level limits take the form of a (lower and upper) bound constraint.

Another constraint to create acceptable plans is required: the need for balanced shipping banks (i.e., the amount of each end product in stock should be related with users' wishes). Then Constraint (0.17) is created. The system creates (according to product demand) a desired stock level, and we evaluate λ_t with Constraint (0.17) which informs how far the worst engine stock level actually is from its desired level.

Another typical constraint is the capacity constraint, which is usually an inequality. Planned production in the case we present herein has to equal planned capacity. The sum of engine production at any time has to equal the daily production rate multiplied by the number of working days for each line (0.18). Since the data for the latest demand periods are incomplete, Constraint (0.19) relaxes the constraint of producing at full capacity for these bucket periods.

Constraint (0.20) allows the evaluation of the capacity measured on production days. It considers that a new normal day $n_{\xi,t}^{ND}$ might be added or subtracted $d_{\xi,t}^{ND}$ and that new extra shifts might be added $n_{\xi,t}^{ES}$.

Constraint (0.21) limits the number of new normal days which might be added or subtracted, while Constraint (0.22) limits the number of extra shifts that might be added. Previously accepted extra shifts are not to be reduced with the model since it this is a plant decision taken elsewhere.

It is well-known that JIT systems require stability and leverage. The goal of having leveled plans is approached within this model by using Constraint (0.23) together with Objective (1.1.4). This constraint only applies to the engine line.

Production capacity is estimated with $J_{E,t}^{ND} \cdot K_{E,t}$. As Equation (0.23) is nonlinear, Constraints (0.28) to (0.30) linearized it.

$$\gamma_{i,t} \geq \Delta \quad \forall i \in L_E, t < T - T^{EST} \tag{0.28}$$

$$\gamma_{i,t} \geq \left(\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}} \left(J_{E,\tau}^{ND} \cdot K_{E,\tau} \right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}} \right) \quad \forall i \in L_E, t < T - T^{EST} \tag{0.29}$$

$$\gamma_{i,t} \geq -\left(\frac{\sum_{\tau=t+1}^{t+T^{EST}} x_{i,\tau}}{\sum_{\tau=t+1}^{t+T^{EST}} \left(J_{E,\tau}^{ND} \cdot K_{E,\tau} \right)} - \frac{x_{i,t}}{J_{E,t}^{ND} \cdot K_{E,t}} \right) \quad \forall i \in L_E, t < T - T^{EST} \quad (0.30)$$

Constraint (0.23) allows a comparison of production rates to be made between one week and its T^{EST} consecutives. Constraint (0.28) neglects the evaluation changes of less than Δ. This constraint reduces enormously the calculation time without incorporating any significant variation on the result.

Constraints (0.24) and (0.25) help evaluate the stability of the plans deployed on previous days. These constraints only apply to those products with a demand over Ψ of the overall capacity considered. Products with low demand are not considered since product flow it is not largely affected.

As stated above, the implemented model has to create the material requirements for raw materials with long supply lead-times (0.26). These requirements are limited by the scheduled quantity for receipt within their lead-time (0.27).

IV. 5. 6MMP parameter tuning and other implementation issues

Parameter tuning has been done using an iterative approach. Each time the problem has been solved, the management team has been asked to evaluate the solution by pointing out the characteristics of those results they did not like. Their comments have helped us create new constraints in some cases, but they were able to mainly change the parameters value.

Unexpectedly, inventory costs are not relevant for most products. The inventory level cost is translated to the plan through products and production lines limits. Inventory levels are bound or limited, and 6-month inventory costs are only relevant for those products with low demands.

In order to cover demand, planners define a desired stock level in some specific periods (e.g., for a post-holiday period). The plan has to adjust to such levels as much as possible. The objective related with this desired stock level is the most relevant of those related with inventory. Our model only considers the product with the lower run-out time for each period.

Another basic objective in the automotive industry is to reduce the nervousness between consecutive plans. Planners wish to see that previous plans are similar to the current plan. But, in fact, this only applied to products with high demand. Users agreed to consider penalties, but only for products whose demand is higher than 10% of the production capacity.

Stability between consecutive periods of a given plan is basic to implement JIT tools and techniques. Therefore, penalizing unleveled production was relevant, but only for engines with high enough demand and for neglecting variations of less than Δ of capacity (in our case, Δ =5% proved to be a good value for final users). Moreover, the incorporation of this parameter drastically reduced the computational effort without affecting the quality of the solution. Stability refers not only to consecutive periods. Constraint (0.23) allows a comparison to be made of production rates between one week and its T^{EST} consecutives (in our case, considering $T^{EST} = 3$ has proven adequate).

Moreover, Tabla 4-8 presents the values of the tuned costs and the hierarchy of all the objectives for planners. The latest column gives the range of the different summations in different resolutions. In order to understand the table, it has to be pointed out that in some cases the coefficients are null (i.e. the holding cost for high demand products).

Tabla 4-8 Values of the cost and penalty parameters in the 6MMP model

Variable Name	*Control (C) or Decision (D) Variable*	*Number of variables*	*Minimum value of the variable*	*Maximum value of the variable*	*Hierarchy of the objectives*	*Associated cost values*	*Range of objective values after resolution*
$n_{\xi t}^{ES}$	*D*	*750*	*0*	$J_{\xi t}^{MAXES} \approx 3$	*1*	$C_{\xi t}^{ES} \approx 10^3$	$[0 - 10^3]$
$n_{\xi t}^{ND}$	*D*	*750*	*0*	$J_{\xi t}^{MAXND} \approx 2$	*2*	$C_{\xi t}^{ND} \approx 10^2$	$[0 - 5 \cdot 10^3]$
$p_t^+ \& p_t^-$	*C*	*50*	*0*	*1*	*3*	$C_t^P \approx 10^1$	$[0 - 10^2]$
λ_t	*C*	*25*	*0*	*1*	*4*	$C_{it}^{\Gamma} \approx 10^1$	$[0 - 3 \cdot 10^1]$
γ_{it}	*C*	*1092*	*0*	$K_{\xi t} \approx 2000$	*5*	$C_{it}^{\Gamma} \approx 10^{-4}$	$[0 - 5 \cdot 10^0]$
y_{it}	*C*	*1525*	$SS_{it} \approx 400$	$SM_{it} \approx 4000$	*6*	$C_{it}^{Y} \approx 10^{-5}$	$[0 - 1 \cdot 10^0]$

The specific characteristics of the problem herein presented allow us to consider that the different problem objectives have different scales of magnitude. Each time that a new extra-day or a new down-day is added (or subtracted), hundreds of engines (very similar to each other) are (or not) to be produced. This decision greatly affects not only working calendars costs, but also the production and holding costs of the engines and components to be produced and stored. However, it has to be pointed out that the capacity consumed to produce one unit of each engine is the same as the others. When the decision on the working calendars is made, the rest of the problem has a different scale of magnitude, but, as mentioned, this is mainly due to the fact that each engine (although differing among types) is quite similar to other different type engines. Therefore, parameter tuning may be done on different scales of magnitude without affecting the overall result. This behavior cannot be expected when the products to be produced differ from each other by either using different capacities or having very different production or holding costs. In such cases, the parameter tuning process will probably become much more relevant and, therefore, standard multi-objective methods will have to be used to guarantee the structural validity of the problem.

IV. 6. 6MMP Results

6MMP was in fact used to coordinate with two domains, one of which is 4WOP. The other is the plant management staff dealing with the “calendar” problem: extra shifts, down days, production capacity. The plan has to take into account “soft” issues and information sources, such as expected transport strikes, union agreements and potential new clients. They need quick answers and many different alternative plans.

Since the 6MMP model is quite large (see Tabla 4-9), it is expected computational time is too long.

Tabla 4-9 Size of a given instance of the 6MMP

	Variables	*Integers*	*Constraints*	*Non-Zero*	*Density*
6MMP	*5361*	*1503*	*8546*	*20696*	*0.05%*

To cut this time, two paths have been followed. One has been used to avoid minimizing the objective function to the optimum one if not compulsory (e.g., relax Objective (1.1.4) using Constraint (0.28)).

The other has already been outlined and relates to the different users' needs. The 6MMP process was converted into a two-step one. In the first step, we were mostly interested in calendars (the capacity plan), while our aim with the second step (once calendars had been defined) was to reach the optimal production and operations plan.

This two-step strategy has been approached with the model that has been previously described with minor changes. In the first stage we consider only Objective (1.1.3) by multiplying the other objectives by 0, thus neglecting the values of their coefficients.

In the second stage we consider only Objectives (1.1.1), (1.1.2) and (1.1.4), while some objectives and constraints were added by assigning the value of zero to variables $n_{\xi,t}^{ND}$, $n_{\xi,t}^{ES}$, $d_{\xi,t}^{ND}$; by doing so, the calendar parameters (normal days and extra shifts) are made constant.

The purpose of the first stage is to help create a feasible calendar. The primary requirement is to solve the problem in real time to make the decision-making process easier. To go about this, Objectives (1.1.2), (1.1.4) and (1.1.5) are neglected by multiplying their summations by 0 for the objective function. This problem can be solved in 50 seconds using ILOG CPLEX 12.1 in a computer with an Intel Core2Duo 2.40Ghz processor, 4 GB RAM and Windows 7 as OS.

The same problem can be solved iteratively by adjusting the parameters (daily production capacity, limitations about calendars or desired stock level) that rely on top management issues. If required, a handful of calendars may become available at the end of the process. The plant's staff will decide the best feasible calendar and usually accepts the first result.

Once a feasible calendar has been accepted by the plant's staff, the second stage starts. Some parameters and variables are neglected or forced to be null to fix the accepted calendar. Then the model is again solved and the variables values $\{y_{i,t}, x_{i,t}, r_{i,t}\}$ are the plan we were looking for.

Each 6MMP model has a certain number of parameters, these being variables that are expressed for a given instance (the plan starting the second week of November 2009).

A result of a problem solved in November 2009 is shown in Fig. 4-3, where the Christmas stockpiling effect is easily seen.

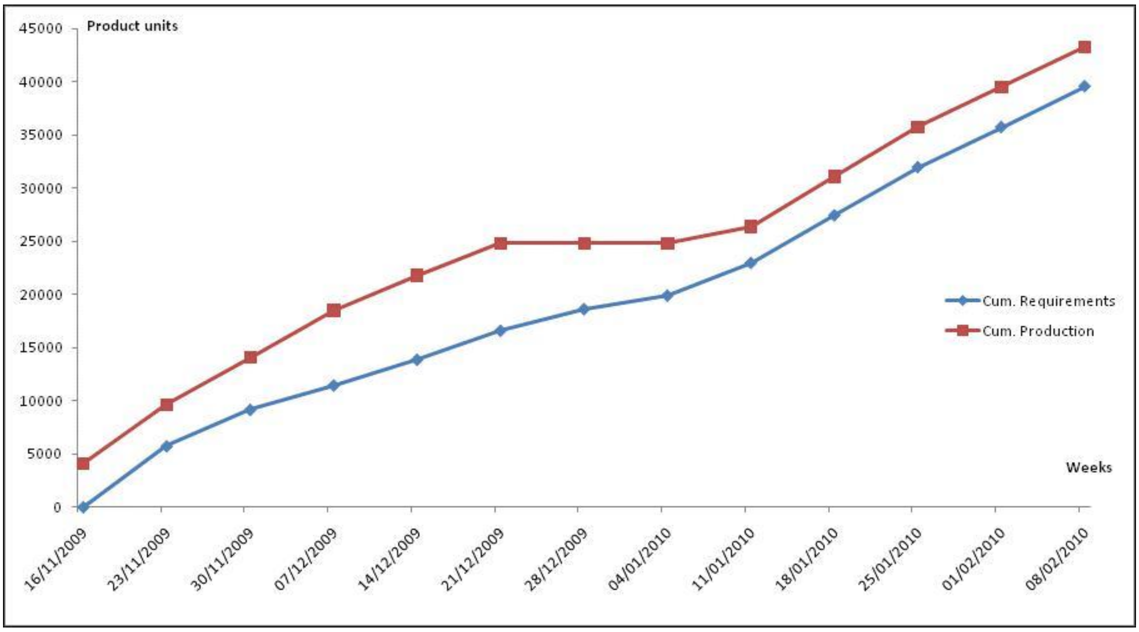

Fig. 4-3 Stockpiling and consumption using the 6MMP

As a result of this solution, stock levels for each particular product at the end of each week ($y_{i,t}$), together with the calendar, will be used to feed the 4WOP. The production plan is also introduced into the corporative ERP system to create the material requirements for the rest of the components, and variable $r_{i,t}$ helps the planner adjust the procurement plan.

V. Model formulation (4WOP)

V. 1. Basic assumptions

To create short-term production plans, a 4-week horizon is divided into days. This was the original way of working, which has been maintained. The demand forecast for each day is known, and is almost certain. The 6MMP results give information about how many shifts are to be worked each day, the production rate that each line is going to reach and the inventory levels that have to be reached per product at the end of each week. The initial stock levels and the backlogs for each client and product (either positive or negative) are known.

The whole BOM is not considered as only the main 5Cs are relevant. Most products have alternative BOMs. The alternative BOM problem has been approached using the stroke concept presented in (Maheut y Garcia-Sabater, 2011) and in (Maheut et al., 2012), which is similar to the task concept presented in (Lang y Domschke, 2010) and (Begnaud et al., 2009).

Our model generates a 6-week horizon plan, but shows only the first four weeks. The last two weeks are used only to guarantee model feasibility by anticipating major variations. The model generates not only production schedules at the two consecutive stages, but also defines inventory levels and determines the delivery of products and raw material requirements.

V. 2. Notation

To help simplify the understanding of this paper, the notation of this model is that it is the same as that in the previous one, even though they do not refer to the same time buckets. However, some new parameters and variables have been introduced, as shown in Tabla 4-10, Tabla 4-11and Tabla 4-12.

Tabla 4-10 Sets and indexes

j	*Index for clients*
k	*Index for strokes*
f, f_1, f_2	*Indexes for product families*
PF_f	*Set of products in product family f*
AL_ξ	*Set of product families produced on line ξ*
Z_ξ	*Set of strokes performed on line ξ*

It should be pointed out that different technologies lead to the various production lines producing completely different products. Therefore, several constraints have been required and created. Nevertheless, the main difference to be found lies between the engine assembly line and the other 5C's production lines.

Tabla 4-11 Parameter notation

D^*_{ijt}	External demand of product i for client j in week t
C^{BN}_{ijt}	Cost of negative backlogging for a unit of i for client j on day t
C^{BP}_{ijt}	Cost of positive backlogging for a unit of i for client j on day t
$C^1_{f_1,f_2,t}$	Cost of the setup when f1 and f2 are produced on the same day t
$C^2_{f_1,f_2,t}$	Cost of having f1 and f2 produced on consecutive days t and t+1
CO_{kt}	Cost of realizing one unit of stroke k on day t
$SL_{\xi t}$	Limiting the accumulated stock level for all the products manufactured on production line ξ on day t
$\underline{DER_t}, \overline{DER_t}$	Minimum/Maximum simultaneous number of derivatives that can be produced on day t on the engine assembly line
U_k	Use of resources when producing stroke k
W_i	Number of products i that must be held in their respective racks
V_j	Number of racks that must be held in a container or truck to client j
SO_{ik}	Number of units of i that generates one unit of stroke k
SI_{ik}	Number of units of i that requires one unit of stroke k
LT^*_k	Lead-time for stroke k
LS_{ij}	Safety lead-time considered of product i for client j
B_{ij}	Initial backlog of product i for client j
RPL_{it}	Scheduled quantity for the receipt of product i on day t
FS_{it}	Intended stock level of product i to be reached at the end of period t

Costs are only penalty parameters that allow to finely tune model performance. They should not be seen as real costs to be considered on any accountancy system. The variables used are presented in Table 12, except the otherwise noted variables, which are always positive integers.

Tabla 4-12 Variable notation

$\nu_{ijt} \in \mathbb{Z}^+$	*Delivery of product i to client j on day t*
$\mu_{ijt} \in \mathbb{Z}^+$	*Numbers of racks of product i to client j on day t*
$\varpi_{jt} \in \mathbb{Z}^+$	*Numbers of trucks or containers to client j on day t*
$z_{kt} \in \mathbb{Z}^+$	*Number of strokes k on day t*
$\beta^+_{ijt} \in \mathbb{Z}^+$	*Positive backlog of product i for client j on day t*
$\beta^-_{ijt} \in \mathbb{Z}^+$	*Negative backlog of product i for client j on day t*
$\chi_{it} \in \{0,1\}$	*=1, if product i is produced on day t (0, otherwise)*
$\pi_{ft} \in \{0,1\}$	*=1, if product family f is produced on day t (0, otherwise)*
$\theta^1_{f_1,f_2,t} \in \{0,1\}$	*=1, if product families f1 and f2 are to be produced on day t (0, otherwise)*
$\theta^2_{f_1,f_2,t} \in \{0,1\}$	*=1, if product families f1 and f2 are to be produced on day t and t+1 (0, otherwise)*

V. 3. Objectives

Creating a plan that satisfies the requirements of both the logistics and the production departments is a complicated task since each department has different goals. In some cases these are expressed as constraints and in others as objectives.

1. Maximize delivery performance
2. Maximize production stability
3. Minimize setup costs
4. Minimize inventory and production costs

The overall objective is to minimize the total costs, although those costs are generally unknown. The model was designed to hold them all, and parameter tuning was heuristically performed in the implementation phase. The whole objective function is presented in equation (0.31).

$$\min \left\{ \begin{array}{ll} \sum_t \sum_i \sum_j \left(C^{BN}_{i,j,t} \cdot \beta^-_{i,j,t} + C^{BP}_{i,j,t} \cdot \beta^+_{i,j,t} \right) & (1.18.1) \\ + \sum_t C^L_t \cdot \lambda_t & (1.18.2) \\ + \sum_t \sum_i C^\Gamma_{i,t} \cdot \left(\gamma_{i,t} - \Delta \right) & (1.18.3) \\ + \sum_t \sum_k CO_{k,t} \cdot z_{k,t} & (1.18.4) \\ + \sum_{t<T} \sum_{f1} \sum_{f2} \left(C^1_{f1,f2,t} \cdot \theta^1_{f1,f2,t} + C^2_{f1,f2,t} \cdot \theta^2_{f1,f2,t} \right) & (1.18.5) \\ + \sum_t \sum_i C^Y_{i,t} \cdot \left(y_{i,t} - SS_{i,t} \right) & (1.18.6) \end{array} \right\} \quad (0.31)$$

The objective is a multi-criteria one. Moreover, we decided to consider a simple weighted schema with penalty weights defined to generate solutions to fulfill the client's requirements.

The objective of optimizing delivery fulfillment was modeled by Summation (1.18.1) in an attempt to minimize both the positive (the classical) and negative (serving in advance) backlogging costs. Backlogging costs differ depending on the product, the client and the time when backlogging exists.

With Summation (1.18.2), the objective to maintain the plan established at the 6-month level (6MMP) is expressed as an attempt to reach the intended stock level.

Summation (1.18.3) is used to maximize the equilibrium at the production levels of the consecutive periods for each product in order to leverage production, even if demand is not stable.

Summation (1.18.4) enables the selection of the cheapest possible alternative BOM. The costs of strokes have been defined so the model tends to select the preferential option, if available.

To consider the minimization of setup penalties, a specifically designed method has been implemented and is expressed in Summation (1.18.5). Components have been grouped into families. Plans are penalized if two different families are produced on the same component production line on the same day or on consecutive days. This way models the setup issue with enough quality and simplifies the whole sequencing process. This approach generates a feasible schedule and avoids the complexity involved in setting a sequence and having to evaluate it.

Finally, Summation (1.18.6) represents the objective of minimizing the inventory costs. From a realistic viewpoint, total stock levels will never be reduced since the production rate is fixed, as is demand. Inventory costs are used to keep the inventory as balanced as possible by penalizing those products with low demand or those that are going to disappear. Moreover, the model applies a penalty only for stocks over the safety stock levels.

V. 4. Constraints

The constraints of the model are presented in this section.

$$SS_{i,t} \le y_{i,t} \le SM_{i,t} \quad \forall i,t \tag{0.32}$$

$$\sum_{i \in L_\xi} y_{i,t} \le SL_{\xi,t} \quad \forall \xi,t \tag{0.33}$$

$$y_{i,t} \ge (1-\lambda_t) \cdot FS_{i,t} \quad \forall i,t \tag{0.34}$$

$$x_{i,t} = \sum_k \left(SO_{i,k} \cdot z_{k,t-LT_k^*} \right) \quad \forall i,t > LT_k \tag{0.35}$$

$$r_{i,t} = \sum_k \left(SI_{i,k} \cdot z_{k,t} \right) \quad \forall i,t \tag{0.36}$$

$$y_{i,t} = y_{i,t-1} + x_{i,t} + RPL_{i,t} - r_{i,t} - \sum_j v_{i,j,t} \quad \forall i,t \tag{0.37}$$

$$\sum_{k \in Z_\xi} \left(U_k \cdot z_{k,t} \right) = K_{\xi,t} \quad \forall \xi,t \tag{0.38}$$

$$\beta^+_{i,j,0} - \beta^-_{i,j,0} - \sum_{t=1}^{LS_{i,j}} D^*_{i,j,t} = B_{i,j} \quad \forall i,j \tag{0.39}$$

$$\beta^{+}_{i,j,t} - \beta^{-}_{i,j,t} = \beta^{+}_{i,j,t-1} - \beta^{-}_{i,j,t-1} - D^{*}_{i,j,t+LS_{i,j}} + v_{i,j,t} \quad \forall i,j,t \qquad (0.40)$$

$$W_i \cdot \mu_{i,j,t} - v_{i,j,t} = 0 \quad \forall j,t \qquad (0.41)$$

$$V_j \cdot \varpi_{j,t} - \sum_i \mu_{i,j,t} = 0 \quad \forall j,t \qquad (0.42)$$

$$\gamma_{i,t} \geq \max\left(\Delta; \left|\frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}}\right|\right) \quad \forall i,t / i \in L_E \qquad (0.43)$$

$$x_{i,t} \leq \left(K_{\xi,t} + 1\right) \cdot \chi_{i,t} \quad \forall i \in L_E, t \qquad (0.44)$$

$$\underline{DER_t} \leq \sum_{i \in L_E} \chi_{i,t} \leq \overline{DER_t} \quad \forall t \qquad (0.45)$$

$$\sum_{i \in PF_f} x_{i,t} \leq \left(K_{\xi,t} + 1\right) \cdot \pi_{f,t} \quad \forall f \in AL_C, t \qquad (0.46)$$

$$\pi_{f1,t} + \pi_{f2,t} - \theta^{1}_{f1,f2,t} \leq 1 \quad \forall (f1,f2) \in AL_C, \forall t \qquad (0.47)$$

$$\pi_{f1,t} + \pi_{f2,t+1} - \theta^{2}_{f1,f2,t} \leq 1 \quad \forall (f1,f2) \in AL_C, \forall t < T \qquad (0.48)$$

$$\pi_{f1,t+1} + \pi_{f2,t} - \theta^{2}_{f1,f2,t} \leq 1 \quad \forall (f1,f2) \in AL_C, \forall t < T \qquad (0.49)$$

The stock constraints are (0.32) and (0.33). For any product and component, inventories should not exceed the storage capacity at any time, and ought not to be less than the defined safety stock level. However, these constraints might be relaxed if the problem has no available solution.

Each production line has a specific limited storage capacity. Constraint (0.33) limits the overall stock capacity of each production line separately.

Constraint (0.34), together with Objective (1.18.2), allows the coordination of the 6-month master plan and this 4-week operation plan through inventory levels. The FS_{it} value is the stock that the 6MMP predicts for the end of each week period. The desired FS_{it} stock level is to be reached at the end of the week.

The main peculiarity of the model presented in this paper is the use of the stroke concept to plan the operation. The stroke concept (Garcia-Sabater et al., 2013) allows the introduction of an alternative BOM. Each stroke represents any operation that transforms a series of products (SI_{ik}) into another series of products (SO_{ik}). Each product i might be produced using one stroke *k* or more. Therefore, the quantity of product i to be produced is a multiple of the stroke that produces it by considering the process lead time, which is reflected as Constraint (0.35).

Furthermore, the requirements and purchases that have to be communicated with the appropriate lead-time are evaluated with r_{ik} using Constraint (0.36) and the stroke concept.

The classical continuity Constraint (0.37) holds for manufactured units.

The production capacity constraints are expressed as Constraint (0.38). The total production on each line should equal capacity, since they are typical assembly lines. So, they should work at the predicted takt time during the production period.

The FTL strategy means that the backlog constraints in this model are also special. Backlog is usually considered as a delay. When racks and containers are to be filled completely, a negative backlog is required. The continuity constraint applies in Constraints (0.39) and (0.40).

The units to be sent should be a multiple of the capacity of the rack that is going to hold them, as expressed in Constraint (0.41). Then the number of racks to be sent to a single client should fill the truck capacity, as in Constraint (0.42).

The purpose of Constraint (0.43) is to leverage the relative production quantity of the different types of engines between consecutive days. As Constraint (0.43) is nonlinear, we propose Constraints (0.50), (0.51) and (0.52) to linearize the constraint.

$$\gamma_{i,t} \geq \Delta \quad \forall i,t / i \in L_E \tag{0.50}$$

$$\gamma_{i,t} \geq \left(\frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}} \right) \quad \forall i,t / i \in L_E \tag{0.51}$$

$$\gamma_{i,t} \geq -\left(\frac{x_{i,t}}{K_{E,t}} - \frac{x_{i,t-1}}{K_{E,t-1}} \right) \quad \forall i,t / i \in L_E \tag{0.52}$$

Constraint (0.43) applies only to those products produced on assembly line (ξ=E). Since we are not interested in reaching an absolute balancing level to reduce the computational time, differences of less than Δ are not penalized.

With Constraint (0.44), we know if product i is produced on day t. We only consider the engines assembled on the assembly line.

The number of simultaneous engine derivatives scheduled on the engine assembly line for a given day influences assembly line management complexity. Production managers asked to limit that number; the way to do this is shown in Constraint (0.45). Availability of a minimum number of derivatives was requested by the plant's staff. In fact, the case of a minimum and maximum number of derivatives is one of the ways the system has to coordinate with the daily production plan since it blindly incorporates some other physical constraints.

With Constraint (0.46), we know if product family f is produced on day t. Constraint (0.47) indicates if two families are scheduled on a given day. Constraints (0.48) and (0.49) do the same for consecutive days. Figure 7 in the implementation section provides a better understanding of our approach's sequencing capability.

V. 5. 4WOP Parameter tuning and other implementation issues

As in 6MMP, parameter tuning was reached after an iterative process, where users' needs, constraints and objectives were considered and implemented.

To set backlogging costs, they were classified into two different levels: high and low. Backlogging costs (both positive and negative) differ per product, client and period. Basically, users consider that low demand products are less relevant than high demand products; assembly line clients are more relevant than spare parts clients; finally, it is not the same planning to not serve tomorrow than planning to not serve next week. The nearest backlog is almost sure and difficult to explain, while the farthest remains unsure (demand and production circumstances might prevent it); in any case, a warning can be launched to the client.

FS_{it} is the stock at the end of the period that has been calculated by the 6MMP model. Due to the delivery process, it is quite feasible that stock is over the forecasted level at the end of the week; therefore, the purpose of the objective is to regularly maximize the approach to that level for all products. More specifically, each day does not have a positive FS_{it} value, but only those at the end of the week (the bucket time period in the 6MMP model).

As with the 6MMP model, stability between the consecutive periods of a given plan is basic to implement JIT tools and techniques. Once again, we penalized unlevelled production, but only for engines with high enough demand by neglecting variations with less than Δ of capacity (in our case, Δ =5% proved a good value for final users).

In 4WOP, we consider alternative ways to produce the same product (mainly engines) and the cost system designed to make this decision simple. The stroke whose priority is to produce the engine has a null cost, and the other alternatives have a cost which, although positive, is much lower than the backlogging costs for the same product.

Setup costs are considered only on some component lines. In order to create feasible plans a reasonable computational time, components were grouped into families and the objective was to reduce the number of setups to a minimum. Cutting setup costs is the most relevant objective for each manufacturing line.

Tabla 4-13 presents approximate values for indices, variables and parameters to help readers understand the hierarchy of objectives, and weights are given to each variable.

Tabla 4-13 Values of the cost and penalty parameters in the 4WOP model

Decision variable	*Control Variable (C) or Decision Variable (D)*	*Number of variables*	*Minimum value of the variable*	*Maximum value of the variable*	*Hierarchy of the objectives*	*Associated cost values*	*Range of objective values after resolution*
β^{-}_{ijt}	*C*	*22876*	*0*	*144*	*1*	$C^{BN}_{ijt} \approx 10^{1}$	$[0 - 10^{5}]$
β^{+}_{ijt}	*C*	*22876*	*0*	*144*	*2*	$C^{BP}_{ijt} \approx 10^{0}$	$[0 - 2 \cdot 10^{5}]$
$\theta^{1}_{f_1,f_2,t}$	*C*	*13552*	*0*	*2*	*3*	$C^{1}_{\xi t} \approx 10^{2}$	$[0 - 7.5 \cdot 10^{3}]$
$\theta^{2}_{f_1,f_2,t}$	*C*	*13552*	*0*	*2*	*4*	$C^{2}_{\xi t} \approx 10^{0}$	$[0 - 1.5 \cdot 10^{2}]$
λ_t	*C*	*42*	*0*	*1*	*4*	$C^{\Gamma}_{it} \approx 10^{2}$	$[0 - 4 \cdot 10^{2}]$
γ_{it}	*C*	*1708*	*0*	$K_{\xi t} \approx 2000$	*5*	$C^{\Gamma}_{it} \approx 10^{-2}$	$[0 - 2 \cdot 10^{1}]$
z_{kt}	*D*	*1900*	*0*	$K_{\xi t} \approx 2000$	*6*	$C^{S}_{kt} \approx 10^{-5}$	$[3 \cdot 10^{1} - 4 \cdot 10^{1}]$
y_{it}	*C*	*1708*	$SS_{it} \approx 400$	$SM_{it} \approx 4000$	*6*	$C^{Y}_{it} \approx 10^{-4}$	$[0 - 1 \cdot 10^{1}]$

The previously commented specific problem structure can be seen in the leveling objective. The cost of an unleveled plan (or an unbalanced shipping bank) cannot be acquired from any database, and it is not relevant to compare it with the cost of having a new extra-shift. The plan has to be leveled to ensure its feasibility when produced on the assembly line. In fact, many physical constraints are hidden when the plan is leveled, but they can arise otherwise. However, it is not necessary to have an exact value of these costs. What is more, the optimal plan, no matter how easy it is to reach, is not necessary to acquire a good plan. Furthermore, low demand products should not be leveled at all. Therefore, costs are evaluated for each product and for each day depending on their forecasted demand. Products with demand lower than 5% of the available planned capacity have no costs relating to their unleveled production. This feature allows the system to work without being retuned when demand changes.

V. 6. 4WOP Results

The 4WOP model is executed with a 6-week horizon, despite it showing only four weeks with a daily review period. Tabla 4-14 presents the data for an execution done in November 2010.

Tabla 4-14 Size of a given instance of 4WOP

	Variables	*Integers*	*Constraints*	*Non-Zero*	*Density*
4WOP	*136657*	*53404*	*120095*	*1540270*	*0.017%*

4WOP's resolution time (using ILOG CPLEX 12.1 on the same computer described above) is long. For the example used, the gap obtained was 2.76% after a 1-minute run. To obtain a gap of 0.15%, a 10-minute run was needed, which cannot be improved since the computer it was executed in went out of memory. It has to be said that bounds and gaps were calculated by the optimization tool.

After analyzing the results of these solutions, it can be stated that the obtained solution, with a gap of 2.76%, was inadequate. The delivery transport part of the solution with this gap could not be used. Fig. 4-4 and Fig. 4-5 illustrate the large differences between the solution with a gap of 2.76%, which was clearly better in terms of backlogging given the solution with a gap of 0.15%.

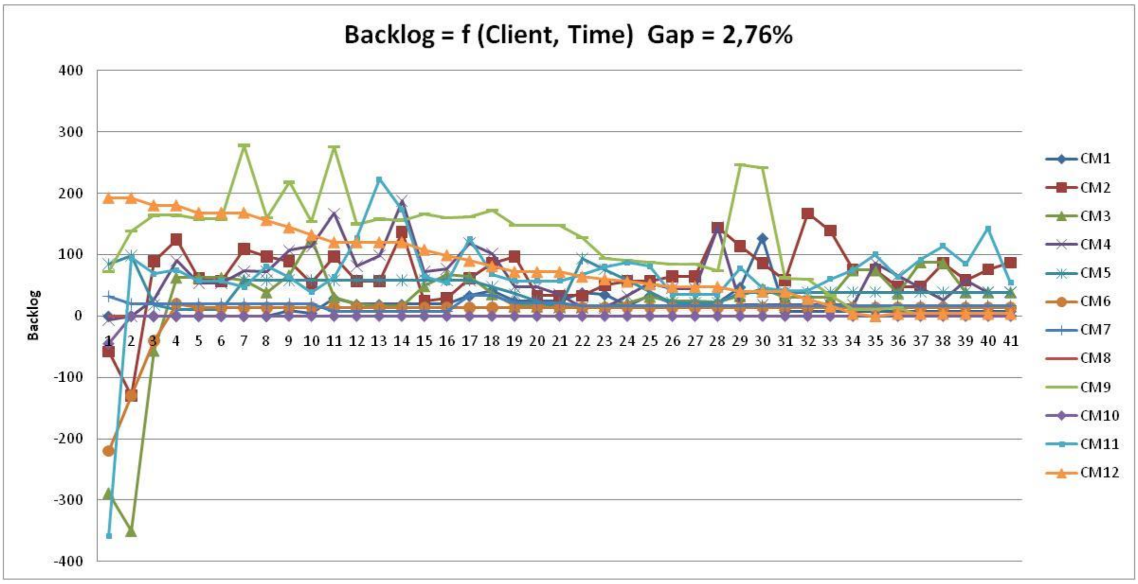

Fig. 4-4 Positive and negative backlogs with a gap of 2.76%

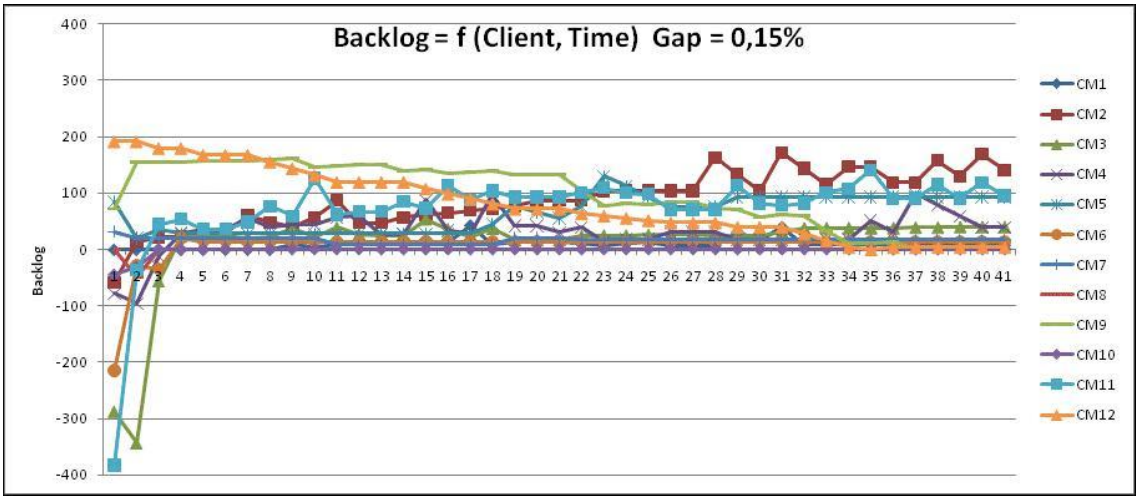

Fig. 4-5 Positive and negative backlogs with a gap of 0.15%

When comparing Fig. 4-4 and Fig. 4-5, and the reality needs, the short term is seen to really matter. This feature has been transmitted to the model by cutting the cost of stocks and backlogging from the final period.

The transport optimization sub-problem (following the FTL strategy) has proved a very hard one. In fact, the problem is a difficult combinatorial problem; the period considered 12 clients (which means 12 trucks to be filled), and each client was buying between 5 and 12 engine derivatives.

At this point of the paper, we have to state that one of the main difficulties arising during the implementation process was the use of non-state-of-the-art solvers to solve the problem since the company did not buy the full license. Therefore, the computational time became too long. The user had to balance solution quality and time performance by looking at the delivery plan and the gap obtained. He had to choose between two different strategies: to lengthen the resolution time or to use a heuristic deployed in (Puig-Bernabeu et al., 2010) to create a feasible delivery plan to accept the created production plan.

The 4WOP model not only solves the delivery problem, but also production scheduling both for the assembly line and the 5C lines. On the assembly line, we need to ensure that the number of produced simultaneous derivatives (product types) is limited. Fig. 4-6 presents these results and also shows how high demand products are produced daily, while the rest are evenly spread throughout the horizon.

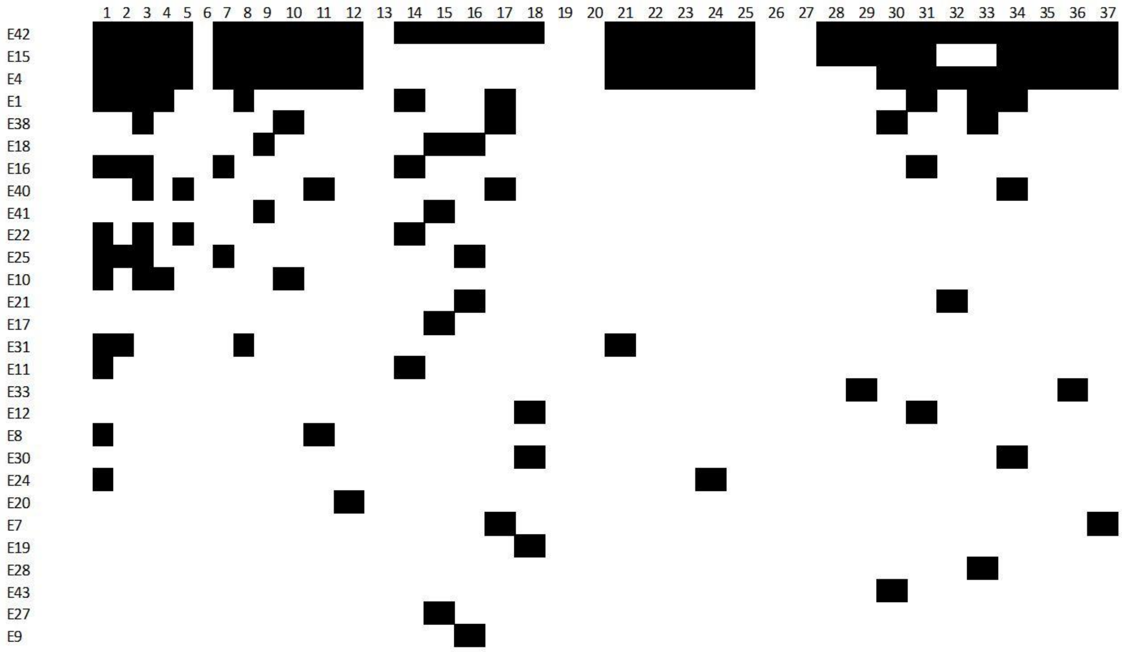

Fig. 4-6 Derivative presence for each within the horizon for each day

The scheduling on the component lines is also defined in the 4WOP model. Fig. 4-7 presents the schedule (using a gantt chart) for the cylinder head manufacturing line. The generated schedule allows the buyer to check if the raw material will become available.

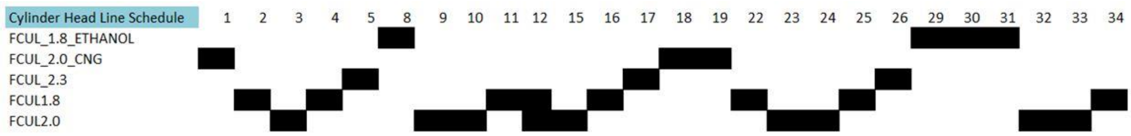

Fig. 4-7 Gantt chart for the cylinder head line

Fig. 4-5, Fig. 4-6 and Fig. 4-7 show how the same mathematical programming model has been able to plan delivery, assembly line production, and production on the components line. Moreover, since material requirements are derived from these calculations, it can be said that a supply chain planning problem is solved.

VI. The Advanced Planning & Scheduling implementation process

VI. 1. The modeling and implementation process

The analysis of the problem (and its modeling) started in May 2008. The first step was to understand how they were processing the information to create plans. The original process was quite iterative and based on the intensive use of separate spreadsheets. These spreadsheets included many colored conditional formatted cells, which allow users to both transmit and check the information gathered and created.

Evidently, the company has its own ERP system. However, working with it as a production planner has been proved somewhat difficult. Moreover, and as usual, the company's ERP system did not offer the possibility of including all the parameters required to generate "easy to use" plans. In some cases, it was simply proved too complicated to upload the information which is easily processed with spreadsheets.

Our approach to the modeling process was based on interviews held with the different users of the planning tools and with stakeholders to create a reliable solution. From their definition of the problem, the initial models were created. These models served as a basis to develop a three-party contract (a consultancy company, our research group and the client). Once we started to work with real data, the models started to change in an iterative process.

It is worth stating that during the fall of 2008 (4 months after starting the project), a global crisis arose. It allowed us to do a genuine sensitivity analysis since the models had been thoroughly tested for 9 months (October 2008 - May 2009). One positive aspect also appeared: the users realized that they needed a tool to help them overcome the new and unstable environment that had emerged as a result of this crisis.

On the other hand, the need for models that take stability into account became relevant. It is well-known that lean environments require stability (Monden, 1981). Before today's crisis, this stability came directly from the demand data. Yet during the above-mentioned critical period, demand was anything but stable. This led to the need to synchronize models and to create stability variables, constraints and objectives.

Once the models were properly running, data such as costs or bounds were lacking. The implementation process included learning the best way to introduce costs, planned activities, critical limits and other apparently minor features.

One of the main aspects learnt was the need to always generate a plan, even if the original data are not feasible with the models above presented. To do so, an algorithm that relaxes constraints one by one was created, and once a solution was found, it was attached together with a message reporting the exact constraints that had been relaxed to allow the user to modify the data.

VI. 2. APS web-based description

This system has been deployed together with everis SLU, a Spanish consultancy company. This firm carried out the development process of the information system. The system not only includes the models presented herein, but also other features related with SC activities.

The task of creating the models and of implementing them using Java has been performed by the authors. We should point out that we have used freemaker and JExcel libraries.

The web-enabled APS runs outside the official ERP system. To obtain data from it and to generate a parallel database that stores the official data from the company and the rest of parameters that need to be used, specific connections were created. Users interact with the software by using standard browsers (to activate and to input data) and spreadsheets (to analyze and to use the results).

The so-called APS consists in four basic modules: DAL module, XML module, Solver module and Excel Module. The XML module retrieves information from the database and the company's ERP system, and then transforms them into XML files. The solver module reads the XML files and solves the. The solution is sent to the XML Module that generates the solution files. Both the data and results are stored in the DAL module. The Excel Module is used to generate XML files that are to be opened with standard MS Excel©.

VI. 3. The information flow between models and with other functions of the company

The given model has been developed to be implemented in an engine manufacturing plant. At this point, it should be clear that our proposal considers two models: 6MMP and 4WOP. The 6MMP model is solved with two different pieces of data with a view to obtaining different results: with the first execution, it calculates a feasible calendar, while it calculates a 6-month production plan in just weeks with the next one.

In order to maintain consistent results, the different plans should be related with the other results/plans in three dimensions (hierarchy, domain and temporal). Fig. 4-8 represents the relations among plans. Variables from other plans (from both previous executions and previous stages) are converted into parameters in subsequent models.

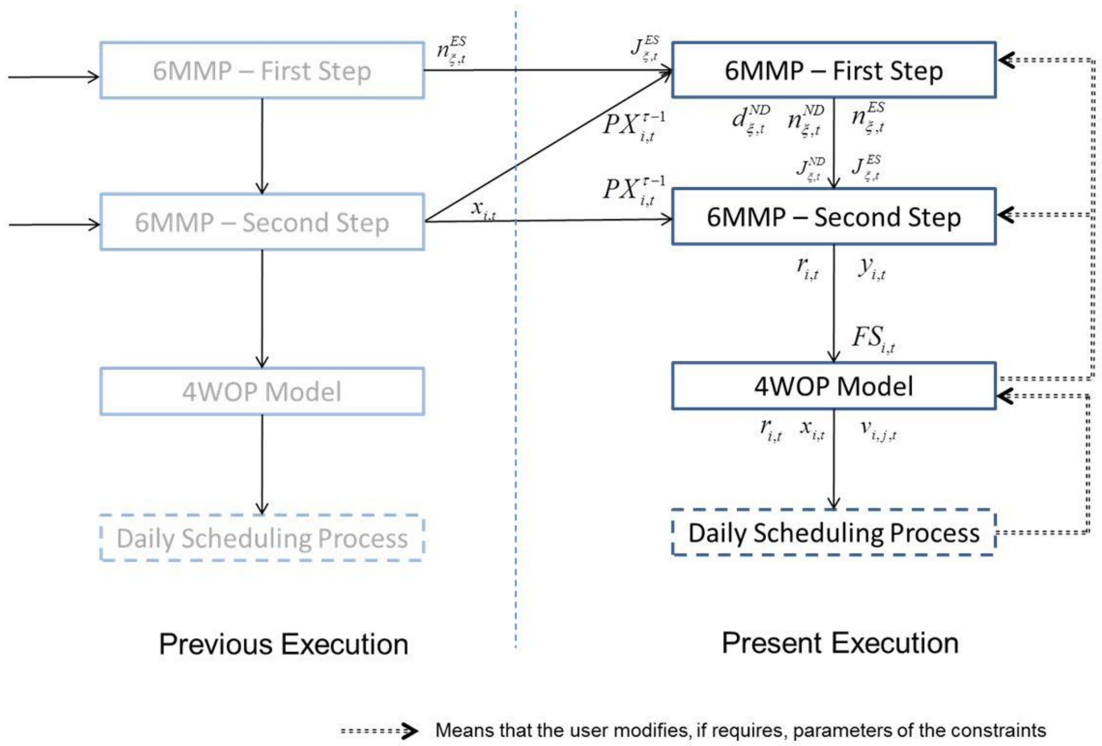

Fig. 4-8 Planning hierarchy

In our case study, integration of the different models has been done using constraints that limit the "autonomy" of each decision level. This is done downwardly (for instance, limiting the changes in the schedule with calendars parameters and production rate $K_{\xi,t}$ to the 6-month plans), and upwardly (i.e., manually including new constraints in the 6MMP model, such as limiting the number of derivatives with Constraint (0.45) or limiting raw material availability in specific periods, if necessary).

The second integration level is business functions integration, which allows business functions to relate to each other. In our case study, this limitation is easily seen since our approach integrates the mathematical objectives and constraints into a single model. This integration is slightly more difficult to perform since objectives have to be counterbalanced and constraints are, in some cases, not compatible. Besides, it is far more difficult to solve because the number of integers and binary variables is quite high.

Finally, the models need to relate to the previous decisions (temporal dimension). This integration is considered with the parameter $PX_{i,t}^{\tau-1}$. This data has been specifically considered into the APS. Stability is not only a matter of planning stable plans; indeed, today's plan has to be similar to the plans of previous days. This concept is basic in the automotive sector and, in fact, there are specific performance measurements that are used only to evaluate stability. This is mainly justified by the fact that the SC cannot, or finds it difficult to, respond to major changes in production levels (Hüttmeir et al., 2009).

The so-called Intended Stock FS_{it} helped coordinate 6MMP with 4WOP since it was (together with limited capacity) the relation that states what is to be produced by looking at the future beyond the first 4 weeks.

VI. 4. Some other considerations

A specific and highly relevant problem that had to be faced (to receive software users' approval when their job was to be substituted) was well managed by the team leader who prepared and waited until the person in charge of the job was about to retire. Turbulence due to the current crisis, with quick and unnoticed changes in demand, also revealed that the standard way of managing plans was no longer useful.

To avoid resistance from the white collar workers who were going to be replaced in the new working system, the APS was implemented by using standard interfaces, such as an Internet browser and an Excel spreadsheet. These interfaces allowed users to continue doing the same kind of activities they did before the Advanced Planning & Scheduling tool was developed. The use of the different Java TM APIs that integrate MS Excel with XML, plus other tools that easily modify the model syntax without having to generate new program files, has proved very interesting.

In order to implement an efficient system that is approved by planners, the system was validated by using a step-by-step approach. Mathematical models, which are at the core of the system, have been created in various spin-offs to cautiously respond to the approach of the different departments involved.

VII. Conclusions

The models presented in this work are part of a more extended APS which was created to help the Supply Chain and Operations Activity in a real engine factory that mechanizes main engine components and assembles them into engines to then deliver them to more than 10 clients, each with its specific requirements.

Although the work presented herein is very practical, as a case study should be, the model development is useful at a theoretical level thanks to the constraints, linkages and coordination methods that appeared. Moreover, we present models that integrate production with transport planning by taking into account the requirements of an industry which is highly involved with JIT production practices.

The problem has been modeled as mixed integer linear programming models. At a practical level, the most relevant improvements in the plant after implementation are:

- The complexity of the operations planning process can be handled at the client level of detail.
- The complexity of the operations planning process can be handled at a deeper level of detail by considering the sequence-dependent setups on production lines, material supply, alternative BOMs and other scheduling issues.
- Freight issues, such as FTL, are explicitly considered in the production planning process.
- Although stock levels have not been reduced as limits (upper and lower), but are fixed by the management staff, the inventory is better balanced; therefore, the number of stock outs is lower.
- The speed of the planning process has improved considerably. The number of people involved in repetitive calculations has been cut from 4 to 2, who now focus on improving data accuracy activities.
- The data capturing process has been automated, the number of rescheduling process has been reduced, while plans' stability has improved.
- A better (and more stable) use of production and maintenance workers has also been achieved since the nervousness of plans (together with the nervousness of planners) has also diminished.

It is worthwhile pointing out some difficulties which arose during the project and can be extended to other projects:

- Difficulties in capturing requirements to design a tool when the information source is people who know that once they have “delivered” their knowledge, they will have to be “at best” moved to a new place in the company.
- Inaccuracy of data when these data (despite being in the corporative ERP) have not been used for a long time (for instance, the alternative BOM).
- Difficulties in obtaining a specific and “a priori” definition of constraints and objectives.
- Relevance of non-standard criteria (such as plan stability, production leverage or balanced shipping banks), together with the lack of relevance of classical objectives such as inventory holding costs.
- Difficulties to ensure the structural validity of the models because of the discrepancy between what planners said they wanted, what the real interest was and what the models were able to represent.

Finally, we wish to stress the idea that the recent advances in MILP resolution time (better hardware and much better software) have helped develop models that consider almost every characteristic of a real problem. As a pitfall, we can state that most users do not understand why they should buy this software as they do not understand what is does.

A future research line would be to develop algorithms that solve the problem without the need for state-of-the-art solvers. This algorithm would allow the use of these comprehensive models in companies which will not pay solvers.

Together, as a future research activity, a more data-resilient model and a resolution procedure are to be built. The model presented in this paper assumes that the data are accurate and that the plan will be executed. Yet in real systems, from time to time data are either not accurate or the reality does not render the model feasible. Providing users the ability to know which data (demand, stocks, production rates, etc.) is inaccurate would be the next good step to take.

Capítulo 5 An Integrated Simulation and Optimization Decision Support System for Supply Network Configuration and Operations Scheduling

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Abstract. This paper presents a decision support system to simultaneously solve the supply network configuration problem and the operations scheduling problem for the machine tool industry. A novel database structure, which is able to consider alternative operations and alternative bills of material, has been used. An algorithm for complete enumeration to not only determines all the feasible solutions, but to also assess each feasible solution in cost and delivery time to select only satisfying solutions, is introduced using stroke graphs. A multiagent-based simulator evaluates the different key performance indicators dealt with by the supply network for each alternative solution (e.g., workload, benefits, delivery times, etc.) to determine the optimum solution by collaborative decision making among its members. A case study based on a Spanish company that assembles highly customized machine tools in several European plants is considered in order to demonstrate that the tool is potentially useful for stakeholders and the central decision maker to make multicriteria decisions collaboratively in a multisite context case.

Keywords: Supply Network Configuration; Decision Support System; Mass Customization; Simulation; Alternative Operations Scheduling; Case study; Collaborative tool

I. Introduction

Supply networks compete and have to differentiate among competitors and other supply networks in an increasingly globalized world, and are always seeking to reduce costs and obtain minimum delivery times by meeting or exceeding customer expectations and by offering high levels of quality and/or services (Christopher, 1998; Mula et al., 2012b; Nagurney, 2010).

For capital goods companies, such as manufacturers of civil engineering and construction machinery, plastic injection machinery or machine tools, the highly competitive environment means that companies are obliged to offer increasingly personalized products to end customers (Saiz *et al.*, 2012). This customization entails offering customers a product catalogue with extensive options, renewing it regularly and assuming the complexity of managing a product inventory with increasingly shorter life cycles (Da Silveira *et al.*, 2001). Such product diversity, increased complexity in operations processes and higher costs of materials are critical management keys to consider in order to remain competitive.

The key question that planners often ask is: how can my supply network (SN) serve the desired products to my customers and meet and/or exceed their expectations in an attempt to minimize total logistics costs, assume short delivery times and ensure levelled workloads in the various production centres to be able to respond to future orders? This question is fundamental for companies that assemble machine tools because orders are not regular, but specific. Given the frequency of orders, the cost of electronic components and raw materials, customer locations or the variety of options offered, a solution based only on either costs or delivery times can be proved and which is suboptimal when a new order arrives.

Due to market pressure, companies working in a mass customization environment have to adapt their inventory management policies to cut their delivery times and to improve customers' service levels. A suitable balance between the products assembled in build-to-forecast (BTF) and those in build-to-order (BTO) has to be struck (Raturi *et al.*, 1990). Generally, given the need to quickly respond to unexpected demand, a switch-to-order (STO) strategy is preferred (Saiz y Castellano , 2008). Product skeletons are released to manufacturing based on the forecasts of the most demanded options. By means of allocation rules, product skeletons are assigned to orders placed by customers. In other cases, product skeletons can be partially reconfigured or adapted to meet customers' requirements. However, when there are no suitable skeletons in stock, reconfiguration may prove expensive (Westkämper, 2003), so the BTO strategy has to be used; however, delivery times can become important. Managers used to think that the appropriate strategy was BTF. Nevertheless when a new order arrives, it is often appropriate to consider, and not just in the case of the non-availability of this product in stock, the possibility of either using alternative bills of material (BOMs) like upgrading (Hung-Yi, 2010; Lang, 2009) or proposing a change to customers to fill new orders and to also reconfigure the products assembled in BTF by assuming the reconfiguration cost. Sometimes, the traditional BTO strategy with the traditional supply base is not suitable because the product due date is short. In this case, another alternative decision is to buy components to different suppliers or competitors to satisfy certain important customers and to maintain them.

Moreover, resources consideration (workforce, machinery, space, etc.) is a concern that must not be treated in an isolated manner because the availability, efficiency and cost of resources can have a great effect on operation scheduling activities (Maheut et al., 2012). For instance, it is common that two plants in two different countries are capable of manufacturing the same product with different costs and constraints (Garcia-Sabater et al., 2013). When operations' planning has to be done in a multisite context and there is a different way to respond to demand, the SN problem can contemplate various possible configurations (Graves y Willems, 2005; Li y Womer, 2008; Li y Womer, 2012). For instance, raw materials can be purchased from different suppliers (Aissaoui et al., 2007), products can be produced or assembled on different machines or in different plants, or products can be delivered/transported by different forms of transport (Maheut y Garcia-Sabater, 2011). Selecting a configuration implies reaching a compromise among the benefits/costs involved, the service levels offered to customers and plant workload levelling by collaborative decision making.

Integrating the supply network configuration (SNC) problem and the operations scheduling problem to be performed in a multisite context in the machine tool industry is required to not only optimize the SN at any given time, but to also anticipate new orders.

To answer these questions, a decision support system (DSS) often proves useful because it is based on a set of procedures supported by models for the data processing of unstructured problems (Power y Sharda, 2009).

In general, and unlike the Advanced Planning & Scheduling Systems (Meyr et al., 2005; Stadtler, 2005), DSSs are specifically designed for a particular industry (see for instance (Elimam, 1995; Respicio et al., 2002; Shang et al., 2008)). The literature contains many references where DSSs have been designed and implemented in specific industry cases. In order to focus on our contribution, some DSSs which propose interesting similar aspects developed in our tool are now presented. For example, Respicio et al. (2002) present a case study where a DSS for production planning and scheduling in a paper industry company is described. In this tool, submodels are coordinated with a hierarchical mechanism. Cowling (2003) presents a DSS for steel hot rolling mill scheduling. In this system, a Tabu Search metaheuristic is used to solve a multi-objective problem where objectives may be conflictive with the manner of satisfying some restrictions. Maness and Farrell (2005) propose a DSS for secondary wood product planning based on linear programming models. The authors' main contribution is based on the use of a relational database that enables the generation of feasible models depending on user inputs. Gomes da Silva et al. (2006) put forward a DSS which uses a multi-criterion MILP model to solve the aggregate production planning problems of a Portuguese company in the construction sector. The authors propose the use of a DSS and an interesting methodology where stakeholders can modify the models so that the results are aligned with reality and where scenarios that enable a “what if?" analysis can be generated.

However to the best of our knowledge, an integrated simulation and optimization DSS capable of simultaneously solving the SNC problem and the alternative operations scheduling problem in a machine tool supply network has not yet been proposed. As this is the aim of this paper, its main contributions are summarized below:

- A DSS to solve the SNC problem and the operations scheduling problem for the machine tool industry that assembles highly customized products in several plants.
- A novel database structure capable of considering alternative operations (purchasing, production, transportation) and alternative BOMs (upgrading, reconfiguring custom products).
- An algorithm based on a direct hypergraph for complete enumeration to determine all the feasible solutions.
- A multiagent-based simulator to evaluate the different key performance indicators (KPIs) dealth with by an SN for each alternative solution.

The following section describes a typical SN for milling machines manufacturing (Section 2). Then, Section 3 describes the proposed DSS, its database architecture, the algorithm for complete enumeration and the simulation module. Section 4 presents a numerical case study and the results in the case of one customized milling machine order. Finally, Section 5 provides conclusions and future research.

II. Supply network description of the milling machine manufacturing industry

II. 1. The product and customers

Milling machines are small machines with a complex structure made up of thousands of different components (see Fig. 5-1). These components are grouped together in functional units that respond to a set of customer attributes. An attribute can be fixed or can belong to a range of values called options.

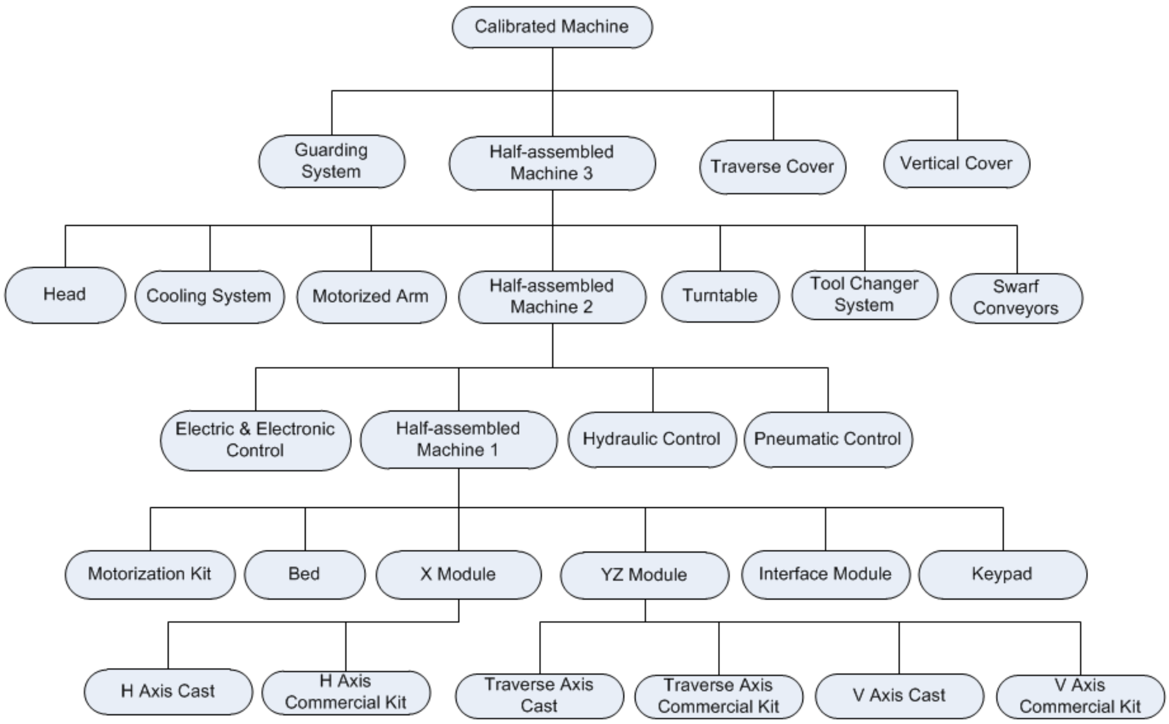

Fig. 5-1 Structure of the milling machine considering operations

The main customers of these products come from very diverse sectors a follows: aerospace, capital goods, railways, subcontractors or mould and die manufacturers. An extensive catalogue including several families depending on machine size, bed type and column type is offered to customers. Customers configure their order by selecting the best option for some attribute suited to the machine that they need; thus, a combinatorial problem is generated.

The variety of end products in the milling machine sector has increased in recent decades. Nowadays, the number of product variants theoretically includes around 2.5 billion possible combinations (Saiz *et al.*, 2009). Generally, each customer orders one machine with specific features and does not fix all the component characteristics.

In the last few years, increasing market pressure on the SN has been continuously detected with a demand for greater product customization capability, shorter delivery times and increasingly competitive costs. One example is what has happened with small milling machines: the market demands delivery times of about 14 weeks for some urgent orders, which is clearly shorter than the 30 weeks indicated to buy all the components, assemble and transport the end product to the customer in the worst case.

II. 2. Inventory policy and order allocation process

When a company receives a new milling machine order, a search is carried out for that which best meets the customer's requirements. This search it is done among all the previously launched BTF machines and which still have not been allocated or available in one plant of the SN. Given the very large number of machine variants that can result from the customer order configuration and the fact that the number of BTF machines in the SN is limited, the probability of finding an exact match between orders and BTF machines is practically zero. So, a set of criteria is established to tackle this problem. These criteria, used in the allocation process, are technical compatibility, economic margin, delivery time and customer profile.

To carry out efficient allocations of orders to BTF machines, a process aims to strike an effective balance between the best conditions which the customer can be offered in terms of delivery time and costs and the widest possible margin that can be generated for the company to cut financial and reconfiguration costs. Use of the STO strategy, by postponing the final configuration of BTF machines, offers several advantages (it reduces the number of variants, average delivery times, etc.). When it is not possible to find a viable allocation in terms of the functional nature required, delivery time or costs, the machine will be a BTO.

II. 3. 2.3. Manufacturing processes

The delivery time for any milling machine takes more than 30 weeks and includes planning tasks, launch and manufacturing activities for the machines, as well as transport activities and installation in the customer's plant.

The first step consists of the order planning stage. This activity starts when a new order comes. Basically, it consists of determining the characteristics of the machine that is to be manufactured and where it is to be manufactured. The planning task not only includes the supply network configuration, but determines the scheduling of the different operations to be performed by considering all the feasible alternative solutions in terms of alternative BOMs (Garcia-Sabater et al., 2012a; Lin et al., 2009; Ram et al., 2006).

As the inventory policy depends on components, some components are available, while others have to be ordered to suppliers. This activity is called a launch activity. Ordered components are received during practically the whole machine assembly process. However, a preliminary procurement stage has been established that covers all the materials that must arrive at the plants before the first machine assembly stage starts. For other components, the procurement time depends on the suppliers' location and on the component.

After to the procurement phase, or during it, the initial machine assembly can start and can take more than 7 weeks. During this stage, the half-assembled machine 1 assembly takes place, together with the preliminary mechanical assembly operations, the common modules assembly in the milling machine and the first fine tuning of the electrics.

Having completed the initial assembly, two situations can arise:

- Case 1: The product has not been allocated and is placed in stock.
- Case 2: The product moves to the final assembly stage in order to carry out the machine (re)configuration operations by adapting it to customer order requirements, the fine tuning of the electronics and mechanical parts, shrouding installation, in-plant testing, machine painting and customer reception. This stage takes approximately 7 weeks.

Finally, the machine is dispatched and taken to the specified place where it is installed and handed over to the customer, and this stage required between 1 and 2 weeks.

III. The REMPLANET DSS simulation-optimization tool

The REMPLANET DSS is a simulation and optimization tool for collaborative decision making that can respond to a set of issues for the milling manufacturing industry: the supply network design with new site location, establishing the position of inventories and replenishment policies, the identification and position of the customer order type decoupling point and the SN configuration problem and operations scheduling for a given SN.

For many scenarios and conditions, this tool allows to not only conduct the systematic testing of the structure and operation of this type of complex SNs, along with their behavioural patterns and properties, but to identify alternative flexible SN structures, as well as those strategies, policies and rules, which better suit their management at both the local and global network levels, at a low cost and with very little risk.

However given the scope of this paper, only the most interesting features about the last cited issue to understand our problem are dealt with. The tool contains four basic components:

- A relational database capable of considering alternative operations
- An optimization model
- An agent-based simulation model
- A graphical user interface

The four components are explained below.

III. 1. The database enables alternative operations

Each product is represented as a stroke keeping unit (SKU), a localized product. All the operations are represented using the stroke concept (Garcia-Sabater et al., 2013): A stroke represents any localized operation that transforms (or transports) a set of SKUs into another set of SKUs. This localized operation and, therefore the stroke representing it, has associated characteristics (stroke cost, lead time, setup stroke cost, etc.) and consumes a certain amount of resources (see Fig. 5-2). As SKUs must consider the site where they are stored, a specific nomenclature has been designed. For example, product "P01" stored in plant PA will be called P01@PA. One unit of SKU P01@A is obtained when one unit of Stroke Stk01 is performed. When this stroke is performed, one unit of P02@A and P04@A and two units of P03@A are consumed.

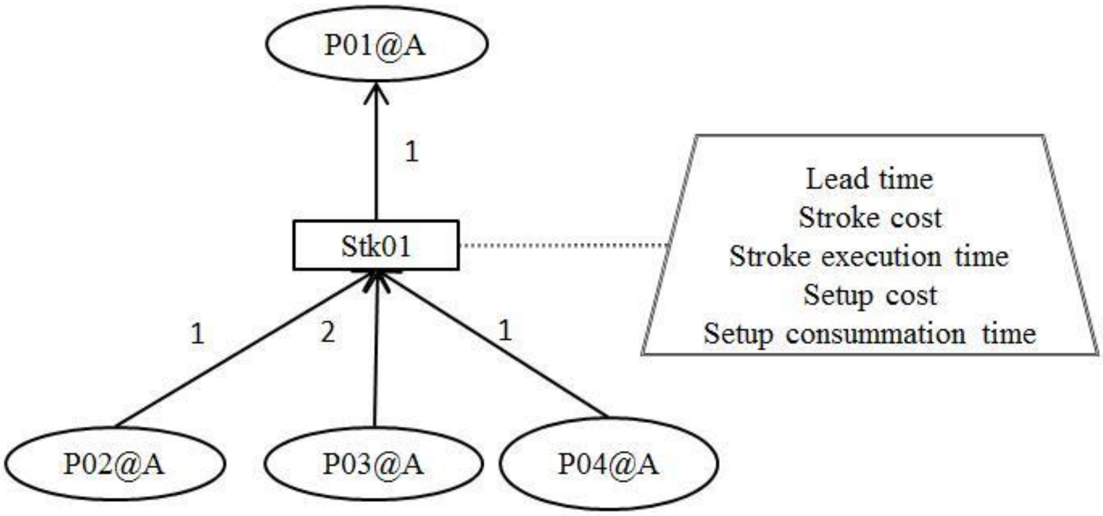

Fig. 5-2 Example of a conceptual representation of one stroke (Maheut y Garcia-Sabater, 2011)

The global relational data comprise tens of tables that structure the data and store them in order to solve nine different problems such as the evaluation of replenishment and restocking strategies, the assessment of alternatives for a new site location, or the identification and position of the type of customer order decoupling point in the supply network. However, in order to emphasize our contribution, this section presents only those tables required to consider alternative operations and alternative BOMs (see Fig. 5-3).

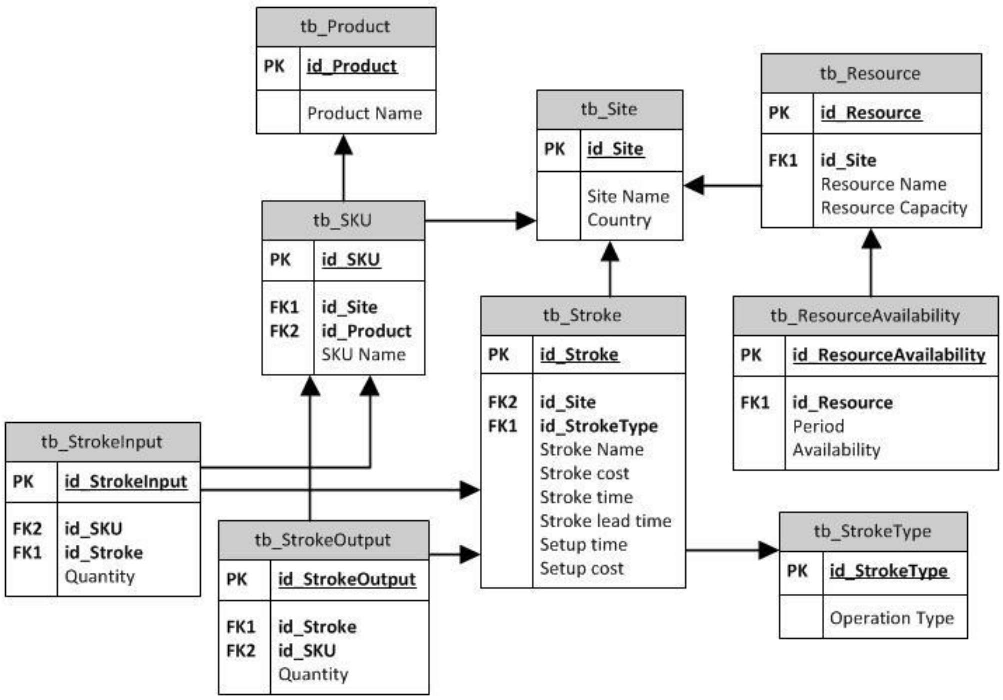

Fig. 5-3 The architecture of the relational database enables alternative operations

Nine tables are needed to consider alternative operations (see Fig. 5-3). Each relational database table is explained in Tabla 5-1.

Tabla 5-1 The relational database tables

Table name	*Description*
tb_Site	*> Lists data about each plant, supplier, and customer of the SN. Each site is unique.*
tb_Product	*> Lists all products considered in the SN.* *> Describes all the data relating to a product, item or packaging.*
tb_SKU	*> Lists all stock keeping units (SKUs) which are localized products in its corresponding packaging. A product presents in two different sites or packaging is represented with two distinct and unique SKUs.* *> Generates with tb_Sites and tb_Product.*
tb_Resource	*> Lists all localized resources.* *> Localized resources are machineries, workforce resources or any resource that have to be planned and with an available capacity.*
tb_StrokeType	*> Lists the different operations types that must be considered.* *> Operations types considered are assembly, procurement, selection, transport.*
tb_Stroke	*> Lists all localized operations.* *> Each stroke has a unique identifier, location, and type.* *> Stores data about the immobilized resources when one unit of stroke is performed (in terms of cost and time).*
tb_StrokeOutput	*> Lists the associated SKUs which are generated when one unit of stroke is performed.* *> The quantity of SKUs generated is a crucial data in case of lotsizing.*
tb_StrokeInput	*> Lists the associated SKUs which are consumed when one unit of stroke is performed.* *> The quantity of SKUs generated is a crucial data in case of lotsizing.*

Unlike traditional BOMs based on a parent item table, a child item table and called in-going parts of the parent item in (Aydin y Güngör, 2005), our database structure proposes a list of the operations (strokes) that must be incorporated between two tables that list SKUs' consummation and SKUs' generation.

Traditionally, in order to consider alternative BOMs, a table with substitutes is associated with each parent item table or child item table. Similarly, the consideration of alternative resources is made with another table, and co-products or by-products can be considered with other tables.

In order to avoid the deficiency of using multiple tables and to consider alternatives at the same time, Garcia-Sabater et al. (2013) demonstrate that use of the stroke concept is a compact way of representing alternative operations. Moreover, this relational database (see Figure 3) proposes the architecture to structure data to be able to consider alternatives, which may occur in industry, as Maheut and Garcia-Sabater evidence (2011).

Each SN member can import its BOMs onto a website. To collaborate in the planning process, each member must manually enter new strokes to consider alternatives. When a new order arrives, the web-based tool collects all the tables of each member and builds a centralized database instance.

However, various data problems usually occur: members do not consider transport between plants, some purchase transactions are not contemplated, the difficulty to assess or consider alternatives that have not been considered before, or reconfiguration and upgrading operations do not exist by definition in the traditional information systems.

To overcome these data problems, different mechanisms to check data are implemented to ensure database integrity. Two are described below:

- A data mechanism checks that each SKU consumed in the set of strokes has the output of at least one stroke of the same location. If no stroke consuming the SKU exists in the same location, and if a stroke in another location generates the SKU, the generation of a new transportation stroke is offered to members. If no stroke generates the SKU, it is proposed to the planner of the location to introduce a new purchase stroke or to modify its data.
- If some non-allocated SKUs are in stock and belong to the same family or have similar attributes to some components in the order, another mechanism proposes the introduction of a reconfiguration stroke with its associated costs and times.

In this way, the different mechanisms ensure database integrity and the consideration of assembly operations and disassembly operations (as in the case of reconfiguration) in a multisite context. The introduced mechanism allows certain collaboration between the different SN members in sharing information.

III. 2. Optimization model: an algorithm for complete enumeration

As previously mentioned, once the database has been completed and integrated into the central decision-making tool, the end product ordered by the customer can be achieved in at least one way and a stroke graph can be represented (see Fig. 5-4). However, the existence of alternatives in the SN and the need to evaluate and assess each feasible and practical solution justify the need to offer stakeholders and the central decision maker the complete enumeration of all the possibilities to configure the SN and to schedule operations.

In Fig. 5-4, the Calibrated Machine can be assembled completely in plant1, completely in plant2 or the assembly of half-assembled machine 3 can be performed in plant2. Then the assembly is sent to plant1 where the final activities are carried out before transportation to the customer plant.

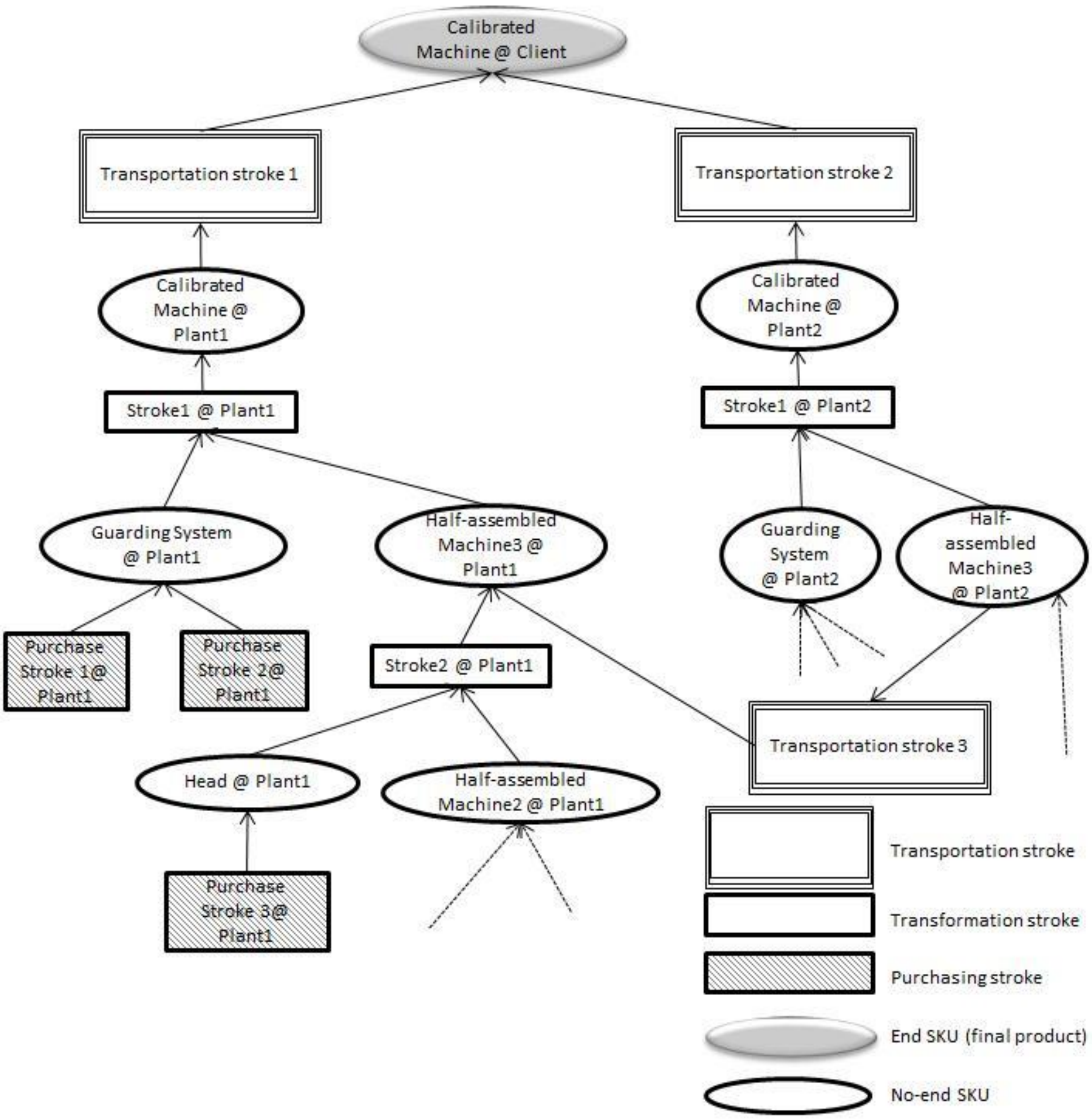

Fig. 5-4 The relational database tables

To go about this, a procedure based on complete enumeration has been implemented. As the same SKU can be generated by different operations and the theoretical combination number can prove important, some steps to transform the database and to generate only a unique and feasible solution has been developed. So, in order to avoid generating repetitive/similar solutions, the procedure consists of the following steps:

- The relational database enables alternative operations to be generated for the order to be transformed into a hybrid database. It consists in the incorporation of selection strokes to determine where there are alternatives (see Fig. 5-5).
- An AND-XOR hypergraph is created from the hybrid database. Strokes and SKU are transformed into nodes and arcs (see Fig. 5-6).
- All the feasible solutions are generated by binary arc and node vectors. An algorithm based on the complete enumeration of vectors is used. Then the costs and times associated with each solution are calculated.
- For each feasible hypergraph solution, a procedure finds the associated strokes that must be performed.
- If the quantity of feasible solutions is large, a selection mechanism has been developed to help the central decision maker to select those solutions that have an interesting ratio between benefits and delivery times.

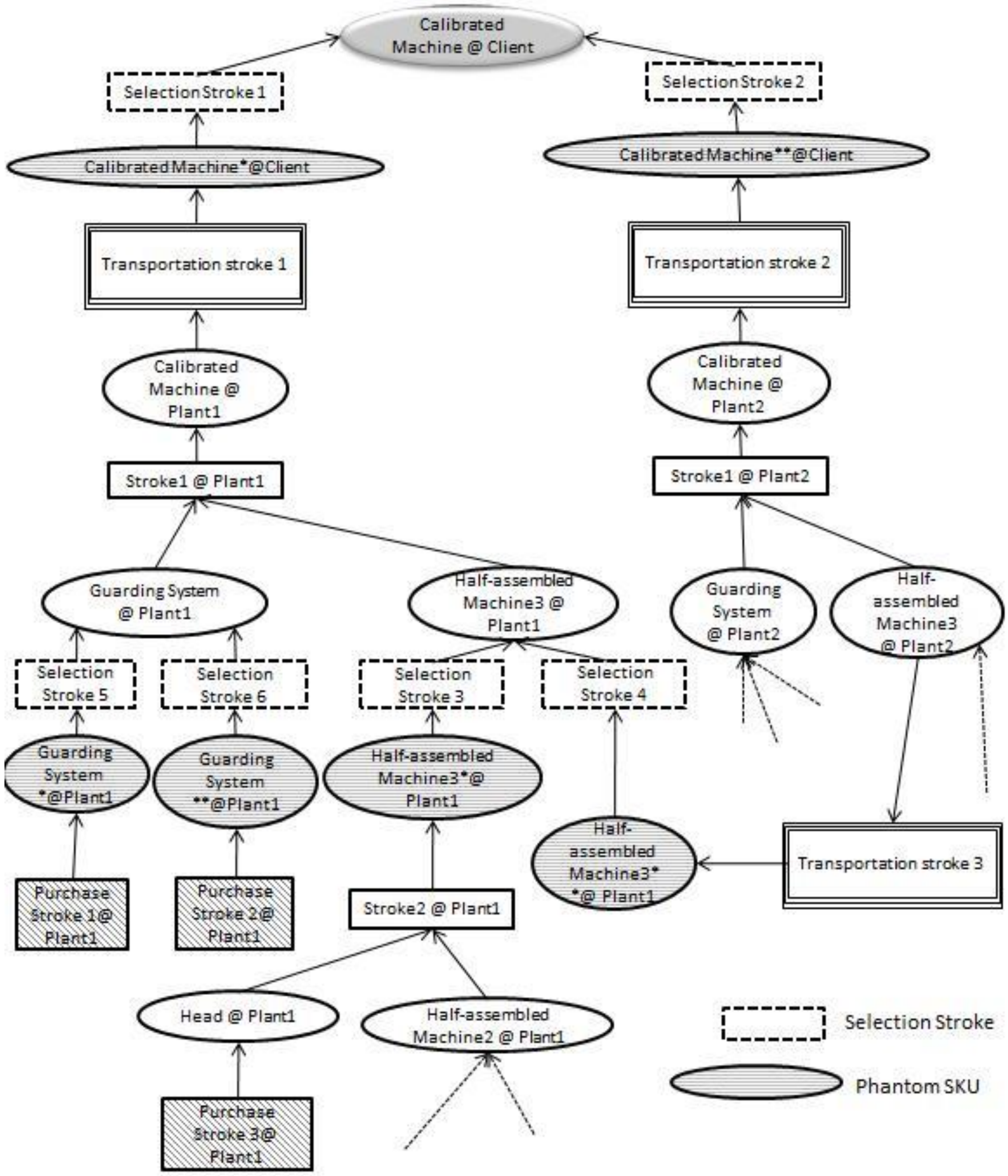

Fig. 5-5 Hybrid hypergraph

In Fig. 5-5, the selection strokes and phantom SKUs have been introduced for the following SKUs: Calibrated Machine@Client, Guarding System @Plant1 and Half-assembled Machine3@Plant1.

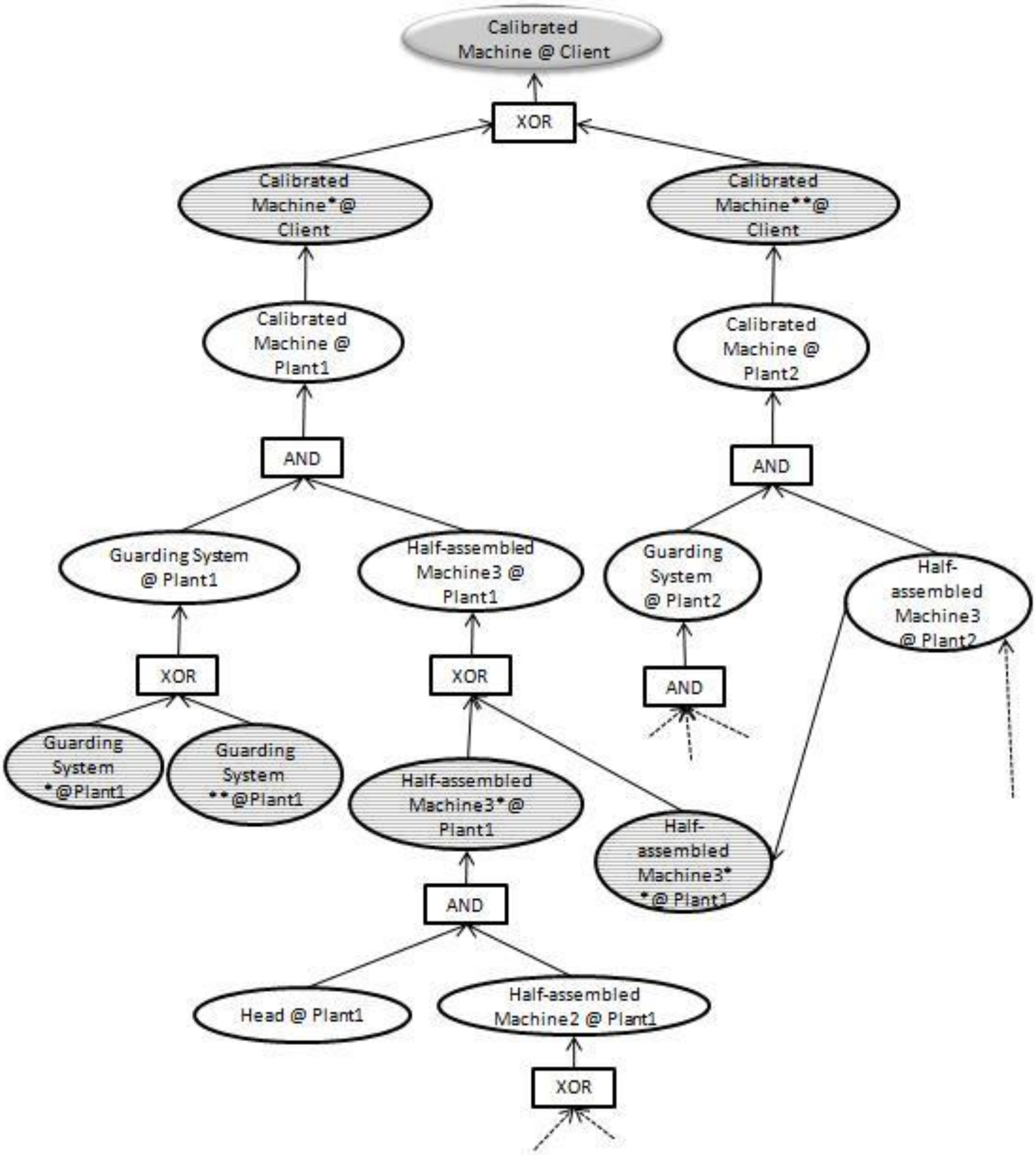

Fig. 5-6 AND-XOR hypergraph

Each selected solution is evaluated in the simulation tool and the optimum solution is selected by the central decision maker in order to fix the SN instance for the order. To do this, the strokes to be performed to complete the order are obtained from the arcs activated in the chosen solution.

III. 3. The DSS simulator

This simulator has been developed with the Anylogic simulation software®. AnyLogic is a forward-looking simulation software which uses an object-oriented approach, Unified Modelling Language visual notation, supports agent-based modelling, as well as other modelling approaches, it provides a rich animation of model execution and handles randomness (Karpov *et al.*, 2005). The software combines three main simulation methodologies: system dynamics, discrete-event and agent-based modelling (Merkuryeva y Bolshakovs, 2010). The simulation methodology used in the DSS is mainly agent-based modelling, but discrete-event modelling has also been used. The different types of agents implemented are presented as follows:

- Supply chain agent: designs the agents' network and records indicators of response in a KPIs structure.
- Market agent: characterizes the order type.
- Point sales agent: creates product orders following the rules defined in the market.
- Coordinator agent: decides when and how a response has to be made for a determined customer order, supervises execution of orders from the reception to the delivery of the product to the customer, and updates the strategy indicators defined in the KPIs structure.
- Customer order agent: is an internal agent of the coordinator agent which executes the order and supervises how the customer order develops.
- Plant agent node: is a network node (suppliers, assemblers, manufacturers, warehouses) that produces the customized product for each customer order. It receives orders from the coordinator agent.
- Items agent: simulates the operation of the materials composing the product in terms of replenishment strategies.

The following UML sequence diagram shows the interaction of the SN agents over time (Fig. 5-7). Each solution is evaluated in the simulation tool and the optimum solution is selected by the central decision maker in order to fix the SN instance for the order.

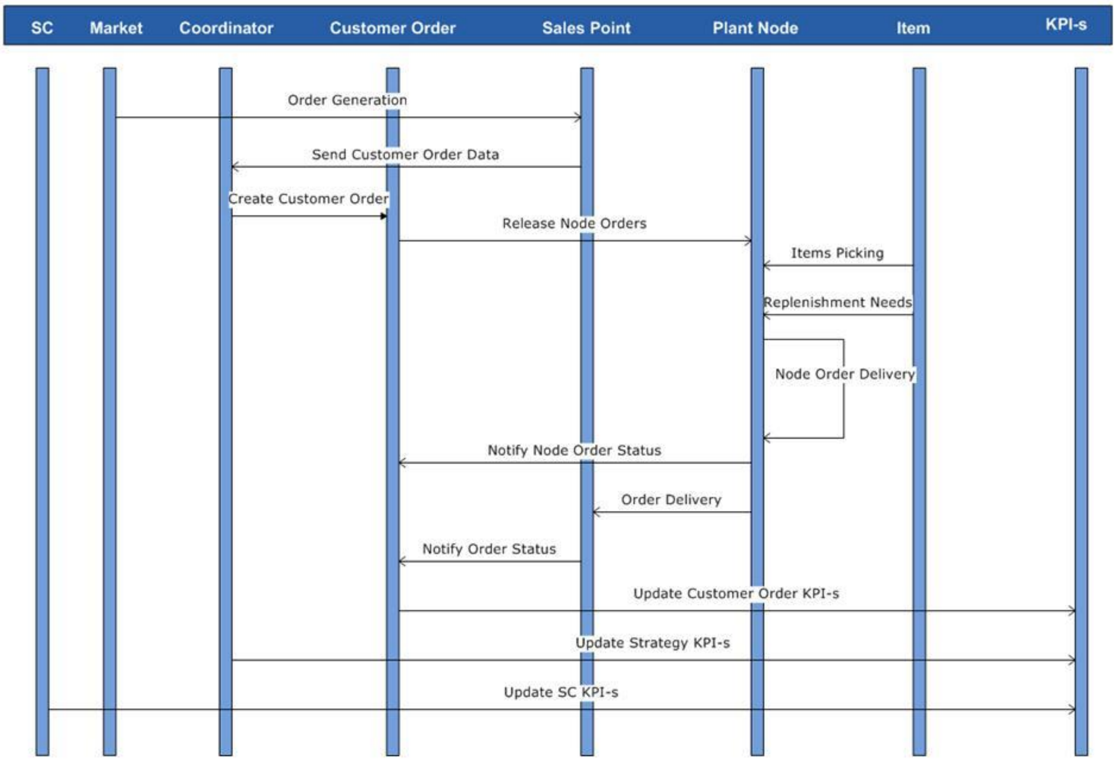

Fig. 5-7 The DSS Sequence Diagram

The KPIs proposed for this case study are:

- Order delivery time: Time periods (in day units) needed to serve the customer the order from the time the customer order arrives.
- Order cost: Total cost of manufacturing the order. Its cost includes: purchasing costs, production costs, transportation costs, inventory costs and management costs.
- Order benefit: the benefit generated with the order fulfilment. It represents the difference between the sales price minus the order cost.
- Average SN delivery time: Average time periods in days needed by the SN to serve the set of orders.
- Average SN workload: Ratio between the SN capacity used and the SN available capacity.
- Average plant inventory cost: Average holding cost in euros at the plant level.
- Average plant workload: Ratio between the plant capacity used and the plant available capacity.

III. 4. Simulation interface

The DSS has several interfaces and screens: for the data entry/queries in the database, for the parameterization of optimization models, and also for the parameterization of simulations. To limit the paper scope, only the interface corresponding to the simulation runs is described. To visualize the simulations results, a user-friendly interface has been designed (see Fig. 5-8).

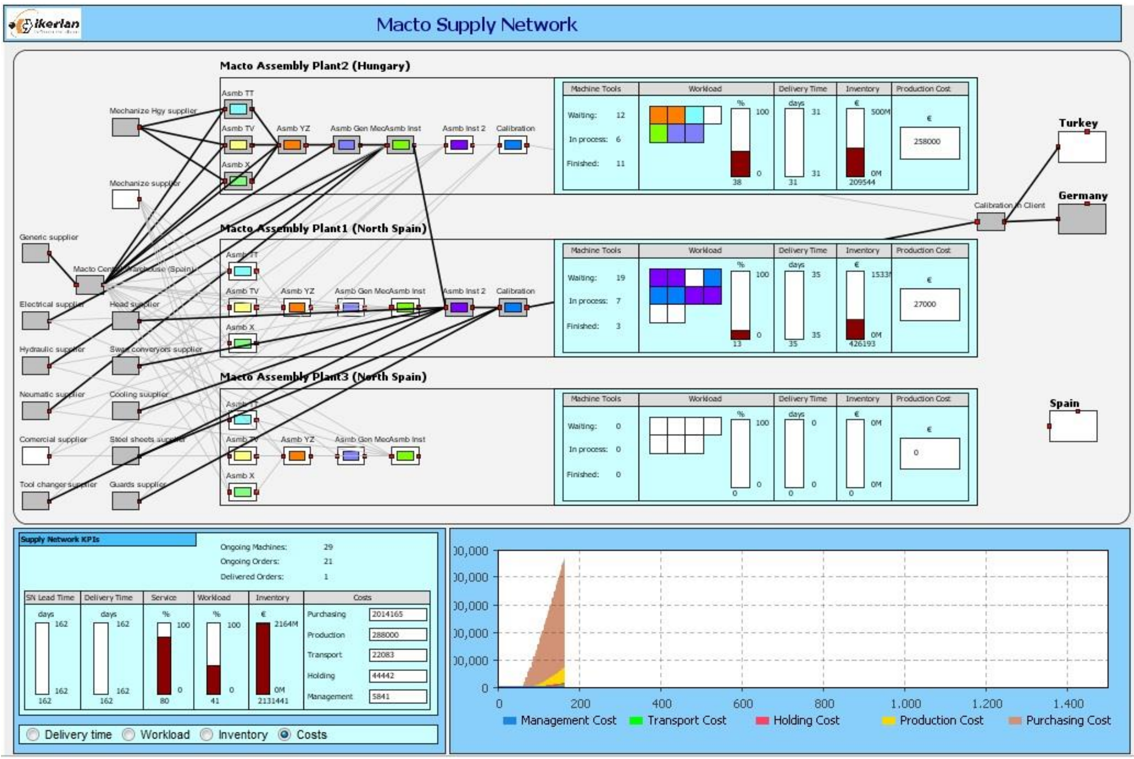

Fig. 5-8 Screenshot of the Simulator Interface

In the simulation interface of the DSS, two main parts can be observed:

- The SN configuration at the top.
- The different SN KPIs below.

At the top, the three plants considered in the set of orders are represented in the centre of the window. In each one, the different process activities are depicted with different coloured squares and their names. For each plant, production indicators about the number of machines waiting, either in process and finished, are depicted. As a physical resource (available capacity) is no small concern, a graphical representation is used. The other indicators, like workload, delivery time, holding and production costs, are also represented.

To the left of the plants that share all the information, a generic supplier of each type of component is depicted. In this way, a generic supply base is represented (at least those involved in one of the set of orders) with squares, which do not provide all the details about the supplier involved. In addition, the three markets are represented to the right. To represent the flow of material and information, the lines between the different SN members and processes are depicted. Lines appear in boldface when flows are activated in the SN instance, which is simulated.

In Figure 8, the order is fulfilled using the components from the central warehouse in Spain and some local suppliers. The first assembly phase is performed in a Hungarian plant until the completion of the “Mec Asmb Inst” process. The product is then transported to the Spanish plant where the ultimate assembly and calibration processes have been performed. Then the machine is sent to the German customer and is setup in the customer plant.

Next the simulation is run, and the central decision maker obtains results to make a multicriteria decision based on the different KPIs values obtained after each run and to provide stakeholders with information about the activities to be performed.

IV. Case study

IV. 1. Case study description

The case study is about a Spanish company that designs and manufactures milling machines and milling centres in three assembly plants distributed in Europe. After the assembly phases, the machine is then transported to and installed in the customer plant. This company is composed of several European plants managed in a distributed manner and its supply base comprises about forty suppliers with whom attempts are made to collaborate in planning tasks, by sharing demand data for example.

Two of the plants are located in Spain and the third one is found in Hungary. The overall demand for milling machines in one year might exceed 80. Machines are sold principally in Europe (the major sales markets are Spain, Germany and Turkey), but Asia is a growing market.

Traditionally, the decision-making process is decentralized and leads to suboptimal decisions. With the DSS is in use, the company strategy aims is to create a synergy among plants via a collaborative planning tool for SN configuration and operations scheduling for all the SN members.

Assembly operations for milling machines can be performed in any assembly plant, but costs differ among each one because of workforce costs, productivity and available capacity. Generally, the first assembly stages are performed in Hungary because workforce costs are lower and the plant has its own local supplier network for cast-iron and machined parts. After finalizing the initial assembly, the machines assembled in the first stages in Hungary are transported to Spain, where customization operations, electrical and mechanical assemblies, careenage, tests and painting are performed. In the same plant, machine inspection and customer approval tasks take place before shipping to the destination where the final in-house installation is done. Nevertheless recently, the Hungary plant layout has been modified and final assembly can be performed there, which helps cut total costs and increase flexibility.

In this case study, the SN receives a new order from a German customer for a milling machine with very low demand because of some specific specifications. The milling machine can be assembled using different SNC or BOMs. Different SNCs in this case can be considered: location of assembly execution and supplier selection.

Each plant has its physical constraints and the milling machine ordered has geometric characteristics that prevent it from being assembled in one of the Spanish plant of the SN. So, the milling machine can be assembled completely or partially in Plant1 in Spain or in Plant2 in Hungary.

One assembly component is the Horizontal Axis Cast (H Axis Cast), which can be supplied by different suppliers. Each plant has its supplier base to stock up with different associated lead times and costs. For example, the procurement time for cast-iron and machined parts (e.g., an H Axis Cast) is about 12 weeks and costs €11,000 for the Spanish plant and takes 12 weeks and costs €7,500 for the Hungarian plant. Nevertheless, suppliers cooperate with the assembly plants to provide the possibility of urgently supplying plants over-costs.

Another alternative to solve the problem is to consider alternative BOMs. For example, the motorization set presents four possible variants and some can be substitutes for others. In this case, the customer requests specific specifications that imply the assembly of one variant, which has to be purchased. The delivery time for this component is quite long since this variant is a low-demand product. However according to the inventory data, another variant of the motorization set, a top component (in both technology and cost terms) could prove to be a compatible substitute component. This component variant is available in both plants and the customer is not opposed to upgrading provided the short delivery time of the machine is respected and at the price agreed with the sales department.

In order to optimize its material flow, the assembly company offers certain flexibility to perform its transshipments. This flexibility, a common alternative in this industry, is to consider different ways of transporting a half-finished assembly between plants. To do this, it is quite common to hire a single driver for normal transport. If necessary, the company can assume the consequent over-cost to hire two or more drivers to cut the delivery time.

The next subsection presents the complete solution data for the optimization and simulation calculation of this order. The results and the KPIs values of each different solution for the given problem are discussed.

IV. 2. Numerical results

Once each member has introduced its data, the procedure based on complete enumeration finds thirty-two feasible solutions. Each solution is characterized by its supply network configuration. Currently these two plants have ten fixed orders either in process or planned to be assembled. The new order to be simulated is the eleventh. Tabla 5-2 lists each solution's characteristics. In this case, the first and second assembly phases can be performed in the two assembly plants (see the first and second columns). In the third and fourth columns, the use of alternative suppliers and BOMs is presented, while the fifth column characterizes the type of transshipment used. Normal transshipment is an operation costing €2,500 and lasting 6 days, Type 1 costs €4,500 and 3 days, while Type 2 costs €6,250 and 2 days.

Some data from one solution are provided in the following tables. Tabla 5-3 lists the purchase strokes. The first column lists the name of the different purchase strokes, the second provides the associated SKUs, and the third column associates the supplier of the transaction. Finally, the last three columns present the quantity of SKUs generated, the cost to perform one purchase transaction and its associated delivery time (or lead time). As observed, the named stroke is formed by the combination of stroke type, SKU and supplier. Note that in this case, the SKU is unique and unitary for each purchase stroke.

Tabla 5-4 lists the transportation strokes for one solution. In this case, only two transportation strokes are considered. For instance, the first consists in transporting product "TA Inst Asmb" from Plant1 to Plant2. This operation takes 6 days and costs €2,500. The second stroke is the transportation of the product called TA-A from Plant2 to the German customer plant location.

Tabla 5-2 Characteristics of the feasible solution

Solutions	*Assembly phase 1*	*Assembly phase 2*	*Use of alternative supplier*	*Use of alternative BOM*	*Type of transhipment*
sol-1	*Plant2*	*Plant2*	*yes*	*no*	*No transhipment*
sol-2	*Plant2*	*Plant2*	*no*	*no*	*No transhipment*
sol-3	*Plant2*	*Plant2*	*yes*	*yes*	*No transhipment*
sol-4	*Plant2*	*Plant2*	*no*	*yes*	*No transhipment*
sol-5	*Plant1*	*Plant1*	*yes*	*no*	*No transhipment*
sol-6	*Plant1*	*Plant1*	*no*	*no*	*No transhipment*
sol-7	*Plant1*	*Plant1*	*yes*	*yes*	*No transhipment*
sol-8	*Plant1*	*Plant1*	*no*	*yes*	*No transhipment*
sol-9	*Plant2*	*Plant1*	*yes*	*no*	*Normal*
sol-10	*Plant2*	*Plant1*	*yes*	*no*	*Type1*
sol-11	*Plant2*	*Plant1*	*yes*	*no*	*Type2*
sol-12	*Plant2*	*Plant1*	*no*	*no*	*Normal*
sol-13	*Plant2*	*Plant1*	*no*	*no*	*Type1*
sol-14	*Plant2*	*Plant1*	*no*	*no*	*Type2*
sol-15	*Plant2*	*Plant1*	*yes*	*yes*	*Normal*
sol-16	*Plant2*	*Plant1*	*yes*	*yes*	*Type1*
sol-17	*Plant2*	*Plant1*	*yes*	*yes*	*Type2*
sol-18	*Plant2*	*Plant1*	*no*	*yes*	*Normal*
sol-19	*Plant2*	*Plant1*	*no*	*yes*	*Type1*
sol-20	*Plant2*	*Plant1*	*no*	*yes*	*Type2*
sol-21	*Plant1*	*Plant2*	*yes*	*no*	*Normal*
sol-22	*Plant1*	*Plant2*	*yes*	*no*	*Type1*
sol-23	*Plant1*	*Plant2*	*yes*	*no*	*Type2*
sol-24	*Plant1*	*Plant2*	*no*	*no*	*Normal*
sol-25	*Plant1*	*Plant2*	*no*	*no*	*Type1*
sol-26	*Plant1*	*Plant2*	*no*	*no*	*Type2*
sol-27	*Plant1*	*Plant2*	*yes*	*yes*	*Normal*
sol-28	*Plant1*	*Plant2*	*yes*	*yes*	*Type1*
sol-29	*Plant1*	*Plant2*	*yes*	*yes*	*Type2*
sol-30	*Plant1*	*Plant2*	*no*	*yes*	*Normal*
sol-31	*Plant1*	*Plant2*	*no*	*yes*	*Type1*
sol-32	*Plant1*	*Plant2*	*no*	*yes*	*Type2*

Tabla 5-3 The purchase stroke table

Stroke	SKUOutput	Supplier	SKUOutput Quantity	Delivery Time (days)	Cost (euros)
Purchase_Bed 01@Mechanized Supplier@Plant1	Bed 01@Plant1	Mechanized Supplier	1	50	6625
Purchase_Guarding System@Guard Supplier Rum.@Plant2	Guarding System@Plant2	Guard Supplier Rum.	1	40	8951
Purchase_H Axis Cast 01@Mechanized Supplier Alt.@Plant1	H Axis Cast 01@Plant1	Mechanized Supplier Alt.	1	50	14000
Purchase_H Axis Commercial Kit 01@Central Warehouse@Plant1	H Axis Commercial Kit 01@Plant1	Central Warehouse	1	50	6734
Purchase_H Axis Kit 01@Mechanized Supplier@Plant1	H Axis Kit 01@Plant1	Mechanized Supplier	1	40	1250
Purchase_Head 01@Head Supplier@Plant2	Head 01@Plant2	Head Supplier	1	40	26000
Purchase_Interface Module 01@Mechanized Supplier@Plant1	Interface Module 01@Plant1	Mechanized Supplier	1	40	600
Purchase_Keypad 01@Guard Supplier@Plant1	Keypad 01@Plant1	Guard Supplier	1	20	1200
Purchase_PED11_Cooling System@Tank Supplier@Plant2	PED11_Cooling System@Plant2	Tank Supplier	1	20	7441
Purchase_PED11_Hydraulic Group@Hydr. Pneum. Supplier@Plant1	PED11_Hydraulic Group@Plant1	Hydr. Pneum. Supplier	1	20	4651
Purchase_PED11_Pneumatic Group@Hydr. Pneum. Supplier@Plant1	PED11_Pneumatic Group@Plant1	Hydr. Pneum. Supplier	1	20	1860
Purchase_PED11_Swarf Conveyor@Swarf Conveyors Supplier@Plant2	PED11_Swarf Conveyor@Plant2	Swarf Conveyors Supplier	1	20	9301
Purchase_PED11_Turntable@Table Supplier@Plant2	PED11_Turntable@Plant2	Table Supplier	1	50	44000
Purchase_PED11_Warehouse Adaptation@Tool Changer Supplier@Plant2	PED11_Warehouse Adaptation@Plant2	Tool Changer Supplier	1	40	1000
Purchase_Pulse X@Central Warehouse@Plant1	Pulse X@Plant1	Central Warehouse	1	15	0
Purchase_Pulse YZ@Central Warehouse@Plant1	Pulse YZ@Plant1	Central Warehouse	1	15	0
Purchase_Tool Changer System 04@Tool Changer Supplier@Plant2	Tool Changer System 04@Plant2	Tool Changer Supplier	1	40	4000
Purchase_Traverse Axis Cast 01@Mechanized Supplier@Plant1	Traverse Axis Cast 01@Plant1	Mechanized Supplier	1	50	4000
Purchase_Traverse Axis Commercial Kit 01@Central Warehouse@Plant1	Traverse Axis Commercial Kit 01@Plant1	Central Warehouse	1	50	3805
Purchase_Traverse Axis Kit 01@Mechanized Supplier@Plant1	Traverse Axis Kit 01@Plant1	Mechanized Supplier	1	40	1500
Purchase_Traverse Cover@Guard Supplier Rum.@Plant2	Traverse Cover@Plant2	Guard Supplier Rum.	1	20	400
Purchase_V Axis Cast A 01@Mechanized Supplier@Plant1	V Axis Cast A 01@Plant1	Mechanized Supplier	1	50	8045
Purchase_V Axis Cast B 01@Mechanized Supplier@Plant1	V Axis Cast B 01@Plant1	Mechanized Supplier	1	50	4000
Purchase_V Axis Commercial Kit 01@Central Warehouse@Plant1	V Axis Commercial Kit 01@Plant1	Central Warehouse	1	50	6169
Purchase_V Axis Kit 01@Mechanized Supplier@Plant1	V Axis Kit 01@Plant1	Mechanized Supplier	1	40	1700
Purchase_Vertical Cover@Guard Supplier Rum.@Plant2	Vertical Cover@Plant2	Guard Supplier Rum.	1	20	500

Tabla 5-4 The transportation stroke table

Stroke	*SKUInput*	*SKUOutput Quantity*	*SKUOutput*	*SKUOutput Quantity*	*Transportation Time (days)*	*Cost (euros)*
Transport_PED11_TA Inst Asmb@Plant1_PED11_TA Inst Asmb@Plant2	*PED11_TA Inst Asmb@Plant1*	*1*	*PED11_TA Inst Asmb@Plant2*	*1*	*6*	*2500*
Transport_PED11_TA-A@Calibration R._PED11_TA-A@G.Customer	*PED11_TA-A@Plant2*	*1*	*PED11_TA-A@G.Customer*	*1*	*3*	*4000*

Tabla 5-5 (respectively Tabla 5-6) presents the SKU input table (the SKU input table) for transformation strokes. As observed, as all the transformation operations considered in this case study are of an assembly type, each transformation stroke has a unique and unitary SKU as the output. However in Tabla 5-6, different SKUs are inputs for different strokes. For instance, stroke “Transformation_PED11_TA Inst 2 Asmb@Plant2” consumes one unit of the following SKUs when one stroke unit is performed: “Head 01@Plant2”, “PED11_Cooling System@Plant2”, “PED11_Swarf Conveyor@Plant2”, “PED11_TA Inst Asmb@Plant2”, “PED11_Turntable@Plant2”, “PED11_Warehouse Adaptation@Plant2” and “Tool Changer System 04@Plant2”.

Tabla 5-5 SKU output of the transformation stroke table

Stroke	*SKUOutput*	*SKUOutput Quantity*	*Operation time (days)*	*Cost (euros)*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_TA Inst 2 Asmb@Plant2*	*1*	*3*	*1400*
Transformation_PED11_TA Inst Asmb@Plant1	*PED11_TA Inst Asmb@Plant1*	*1*	*13*	*1900*
Transformation_PED11_TA Mechanical Asmb@Plant1	*PED11_TA Mechanical Asmb@Plant1*	*1*	*3*	*600*
Transformation_PED11_TA-A@Plant2	*PED11_TA-A@Plant2*	*1*	*3*	*5211*
Transformation_PED11_TAA@Plant2	*PED11_TAA@Plant2*	*1*	*13*	*3500*
Transformation_PED11_X Module@Plant1	*PED11_X Module@Plant1*	*1*	*3*	*600*
Transformation_PED11_YZ Module@Plant1	*PED11_YZ Module@Plant1*	*1*	*8*	*1272*

Tabla 5-6 SKU input of the transformation stroke table

Stroke	*SKUInput*	*SKUInput Quantity*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*Head 01@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_Cooling System@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_Swarf Conveyor@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_TA Inst Asmb@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_Turntable@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*PED11_Warehouse Adaptation@Plant2*	*1*
Transformation_PED11_TA Inst 2 Asmb@Plant2	*Tool Changer System 04@Plant2*	*1*
Transformation_PED11_TA Inst Asmb@Plant1	*PED11_Hydraulic Group@Plant1*	*1*
Transformation_PED11_TA Inst Asmb@Plant1	*PED11_Pneumatic Group@Plant1*	*1*
Transformation_PED11_TA Inst Asmb@Plant1	*PED11_TA Mechanical Asmb@Plant1*	*1*
Transformation_PED11_TA Mechanical Asmb@Plant1	*Bed 01@Plant1*	*1*
Transformation_PED11_TA Mechanical Asmb@Plant1	*Interface Module 01@Plant1*	*1*
Transformation_PED11_TA Mechanical Asmb@Plant1	*Keypad 01@Plant1*	*1*

Transformation_PED11_TA Mechanical Asmb@Plant1	Motorization Kit 04@Plant1	1
Transformation_PED11_TA Mechanical Asmb@Plant1	PED11_X Module@Plant1	1
Transformation_PED11_TA Mechanical Asmb@Plant1	PED11_YZ Module@Plant1	1
Transformation_PED11_TA-A@Plant2	PED11_TAA@Plant2	1
Transformation_PED11_TAA@Plant2	Guarding System@Plant2	1
Transformation_PED11_TAA@Plant2	PED11_TA Inst 2 Asmb@Plant2	1
Transformation_PED11_TAA@Plant2	Traverse Cover@Plant2	1
Transformation_PED11_TAA@Plant2	Vertical Cover@Plant2	1
Transformation_PED11_X Module@Plant1	H Axis Cast 01@Plant1	1
Transformation_PED11_X Module@Plant1	H Axis Commercial Kit 01@Plant1	1
Transformation_PED11_X Module@Plant1	H Axis Kit 01@Plant1	1
Transformation_PED11_X Module@Plant1	Pulse X@Plant1	1
Transformation_PED11_YZ Module@Plant1	Pulse YZ@Plant1	1
Transformation_PED11_YZ Module@Plant1	Traverse Axis Cast 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	Traverse Axis Commercial Kit 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	Traverse Axis Kit 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	V Axis Cast A 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	V Axis Cast B 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	V Axis Commercial Kit 01@Plant1	1
Transformation_PED11_YZ Module@Plant1	V Axis Kit 01@Plant1	1

The different KPIs values of the simulation runs are presented in Tabla 5-7. In this case, the order cost and benefit for order 11 are necessary because, in some cases, the sales price can change depending on the BOMs. For example, in solution 16, the price is not as high because one component is not suitable for the customer and a discount has to be offered.

Tabla 5-7 Experimental results

	KPIs for Order 11			KPIs for Supply Network		KPIs for Plant1		KPIs for Plant2	
Solutions	Delivery Time (days)	Order Cost (euros)	Benefit (euros)	Average Delivery Time (días)	Workload (%)	Workload (%)	Total Inventory cost (euros)	Workload (%)	Total Inventory cost (euros)
sol-1	136	179254	22746	141	79,2	72,6	405135	85,8	252939
sol-2	136	181754	20246	141	79,2	72,6	405135	85,8	254386
sol-3	130	179986	22014	141	79,2	72,6	405135	82,5	247436
sol-4	121	182486	19514	140	75,9	72,6	405135	82,5	242148
sol-5	133	199120,75	2879,25	141	82,5	92,4	459209	72,6	200217
sol-6	133	202120,75	-120,75	141	82,5	92,4	461073	72,6	200217
sol-7	133	200652,75	1347,25	141	82,5	92,4	458083	72,6	200217
sol-8	118	203652,75	-1652,75	140	79,2	85,8	447592	72,6	200217
sol-9	145	191191,75	10808,25	142	79,2	79,2	450633	82,5	212012
sol-10	142	193191,75	8808,25	142	79,2	79,2	449194	82,5	212012
sol-11	141	194941,75	7058,25	142	79,2	79,2	448714	82,5	212012
sol-12	145	193691,75	8308,25	142	79,2	79,2	450837	82,5	213256
sol-13	142	195691,75	6308,25	142	79,2	79,2	449397	82,5	213256
sol-14	141	197441,75	4558,25	142	79,2	79,2	448917	82,5	213256

sol-15	139	191923,75	10076,25	142	79,2	79,2	447227	79,2	209795
sol-16	136	193923,75	807,25	141	79,2	79,2	445788	79,2	209795
sol-17	135	195673,75	6326,25	141	79,2	79,2	445308	79,2	209795
sol-18	130	194423,75	7576,25	141	79,2	79,2	443113	79,2	208441
sol-19	127	196423,75	5576,25	140	79,2	79,2	441673	79,2	208441
sol-20	126	198173,75	3826,25	140	79,2	79,2	441194	79,2	208441
sol-21	136	192183	9817	141	82,5	85,8	418315	75,9	242298
sol-22	133	194183	7817	141	79,2	85,8	418315	75,9	240918
sol-23	132	195933	6067	141	82,5	85,8	418315	75,9	240458
sol-24	136	195183	6817	141	82,5	85,8	419935	75,9	242542
sol-25	133	197183	4817	141	79,2	85,8	419935	75,9	241163
sol-26	132	198933	3067	141	82,5	85,8	419935	75,9	240703
sol-27	136	193715	8285	141	82,5	85,8	417716	75,9	241771
sol-28	133	195715	6285	141	79,2	85,8	417716	75,9	240391
sol-29	132	197465	4535	141	82,5	85,8	417716	75,9	239932
sol-30	121	196715	5285	140	79,2	82,5	414177	75,9	235120
sol-31	118	198715	3285	140	79,2	82,5	414177	75,9	233740
sol-32	117	200465	1535	140	79,2	82,5	414177	75,9	233281

Fig. 5-9 represents the value of order delivery time and order benefit for each solution. Fig. 5-10 depicts the values of SN, plant1 and plant2 workload.

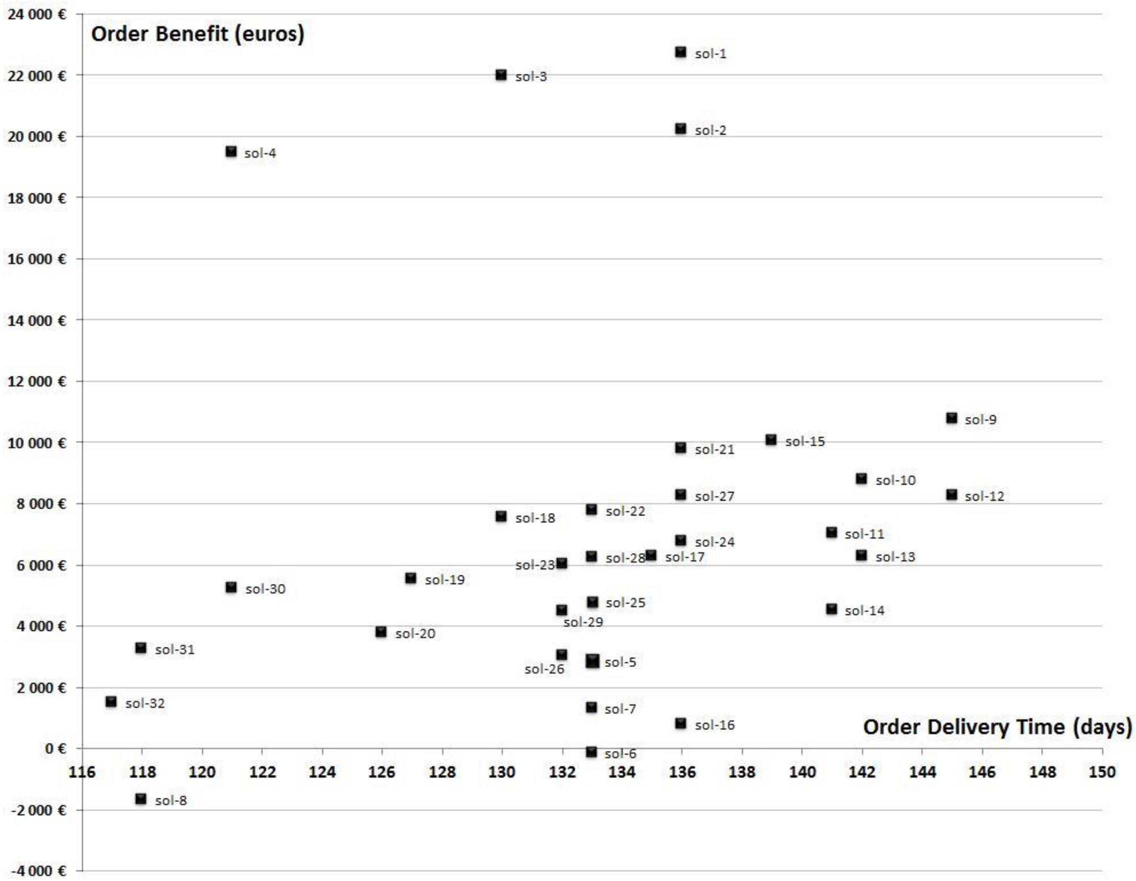

Fig. 5-9 Order delivery time and order benefit for each simulation run

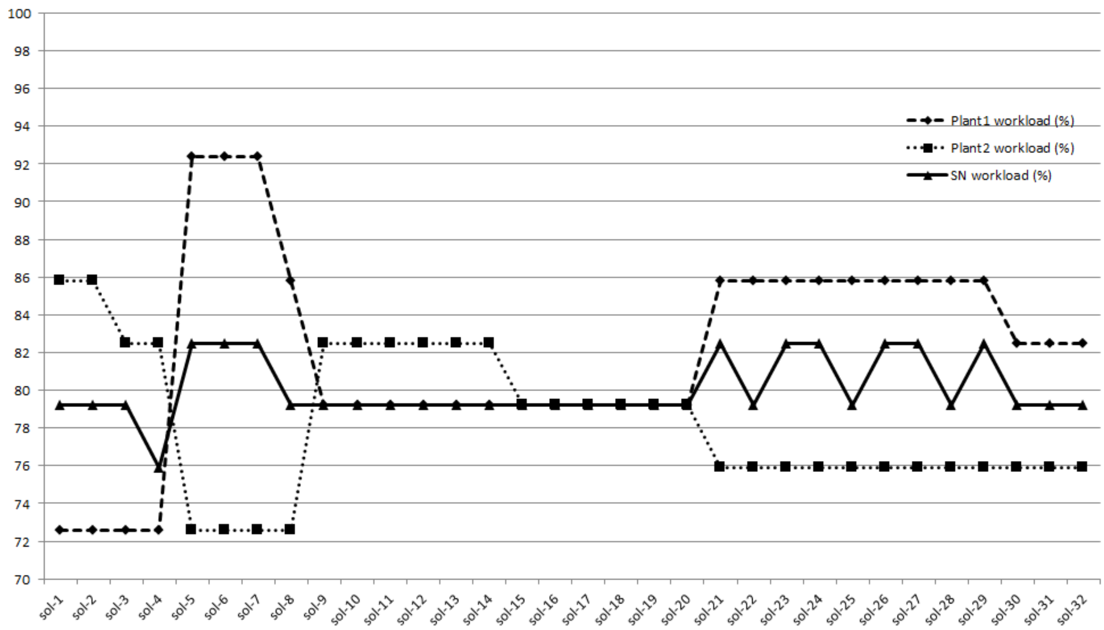

Fig. 5-10 Workload results

This simulation experiment has permitted the central decision maker to value the different alternative solutions and its impact over KPIs. When comparing the simulation results, the difference between each solution of the set is significant:

- 28 days in delivery time between solution 32 with 117 days and solution 12 with 145 days (or solution 9).
- €24,398 in benefit between solution 1 (€22,746) and solution 8 (€-1,652).
- A difference of 19.8% in the workload value between plants in solution 6 (19.8%) and in solution 15 (0%), for instance.

In order to make a decision, the customer needs the milling machine before 132 days. In this case, very few solutions are acceptable: 3, 4, 8, 18, 19, 20, 23, 26, 29, 30, 31, 32. In terms of benefits, solution 8 has to be discarded because it implies a loss. Solutions 3 and 4 imply high benefits, and solutions 18, 19, 23 and 30 imply medium benefits. In terms of the workload between both plants, solutions 18, 19 and 20 imply a workload that is totally leveled between the two plants. However, solution 4 assumes a minimum SN workload with 75.9%.

So a good solution that satisfies both the customer and the central decision maker is solution 3 or solution 4. Solution 4 has been chosen because:

- The value of its benefit is the second most important of the set of solutions (€2,500 less than solution 3).
- Its delivery time is 121 days and it respects the due date fixed by the customer. Moreover, it is 9 days less than the delivery time for Solution 3.
- The SN workload value is the lowest of the set of solutions. When compared to solution 3, which gives the most benefits, solution 4 implies a lower SN workload by 3.3%.

V. Conclusions

This paper describes a DSS to solve the supply network configuration and the operations scheduling problems for the machine tool industry. A novel relational database structure capable of considering alternative operations (purchasing, production, and transport) and alternative BOMs (upgrading, reconfiguring custom products) has been introduced and the steps of an algorithm for complete enumeration to determine all the feasible solutions have been presented. Then a simulator based on multiagent technology evaluates the different KPIs by collaborative decision making. The experimental results for a Spanish company that assembles highly customized machine tools in several European plants, which receives a specific order, are presented with the real data in order to find a decision that satisfies all the SN members.

Capítulo 6 Algorithm for complete enumeration based on a stroke graph to solve the supply network configuration and operations scheduling problem

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Purpose: The purpose of this paper is to present an algorithm that solves the supply network configuration and operations scheduling problem in a mass customization company that faces alternative operations for one specific tool machine order in a multiplant context.

Design/methodology/approach: To achieve this objective, the supply chain network configuration and operations scheduling problem is presented. A model based on stroke graphs allows the design of an algorithm that enumerates all the feasible solutions. The algorithm considers the arrival of a new customized order proposal which has to be inserted into a scheduled program. A selection function is then used to choose the solutions to be simulated in a specific simulation tool implemented in a Decision Support System.

Findings and Originality/value: The algorithm itself proves efficient to find all feasible solutions when alternative operations must be considered. The stroke structure is successfully used to schedule operations when considering more than one manufacturing and supply option in each step.

Research limitations/implications: This paper includes only the algorithm structure for a one-by-one, sequenced introduction of new products into the list of units to be manufactured. Therefore, the lotsizing process is done on a lot-per-lot basis. Moreover, the validation analysis is done through a case study and no generalization can be done without risk.

Practical implications: The result of this research would help stakeholders to determine all the feasible and practical solutions for their problem. It would also allow to assessing the total costs and delivery times of each solution. Moreover, the Decision Support System proves useful to assess alternative solutions.

Originality/value: This research offers a simple algorithm that helps solve the supply network configuration problem and, simultaneously, the scheduling problem by considering alternative operations. The proposed system allows an easier generation of many different alternatives for the supply network configuration.

Keywords: Stroke graph, Supply network configuration, Alternative operations, Complete enumeration

I. Introduction

A supply network (SN) is a network of organizations involved through upstream and downstream relations in which several processes and activities are carried out to produce value in the form of products and/or services for the end customer. To face increasing demand in customized products, SNs must offer a product or service with a minimum cost and a short lead time by considering global constraints and future market opportunities.

To do so, supply chain management must be based on two pillars: supply chain integration and coordination (Stadtler, 2005). Integration, in turn, is based on three factors: partners' selection, the network's inter-organizational and organizational collaboration, and leadership. Coordination is based on the use of information and technologies, and addresses processes and advanced planning. For SNs to be able to coordinate efficiently, the literature contemplates two phases at the strategic level: supply chain design (Mohammadi Bidhandi et al., 2009) or supply chain redesign (Nagurney, 2010), and supply network configuration (SNC) (Salvador et al., 2004).

Graves and Willems (2005) were the first to introduce the SNC problem, whose objective is to determine the suppliers, products, processes and forms of transport that must be selected to minimize the costs involved. In general, this problem contemplates different possible configurations because, for instance, raw material can be purchased from different suppliers (Wang et al., 2004), products can be produced or assembled on different machines, or products can be delivered by different forms of transport (Li y Womer, 2008). Selecting a configuration implies reaching a compromise between the costs involved and the service levels to be offered to the customer. The literature includes a large number of mathematical models which address the SNC problem. We refer readers to the following reviews (Goetschalckx et al., 2002; Mula et al., 2011). The literature includes some case studies such as the work of (Li y Womer, 2008) which not only deals with the configuration problem, but also includes considerations at the tactical and/or operational level.

In relation to scheduling problems, lots of works are available in the literature: capacitated resources, sequence-dependent setup times (Xiaoyan y Wilhelm, 2006), lead time concepts (Sahling et al., 2009), multi-stage production (Seeanner y Meyr, 2012), products substitution (Chern y Yang, 2011; Lang, 2009), multi-site scheduling (Alvarez, 2007), which are just some of the characteristics that might be considered.

However to the best of our knowledge, the single product, multi-site, multi-stage, supply network configuration and operations scheduling problem considering alternative operations has not yet been resolved by contemplating complete enumeration by a stroke graph.

This article proposes the use of a stroke graph structure to enumerate all the feasible solutions for the SNC and operations scheduling when a new customized firm order arrives. The stroke graph proposed is based on the stroke concept (Garcia-Sabater et al., 2013). Complete enumeration needs different transformations of the stroke graph to then determine the total costs and delivery times of each feasible solution. A selection mechanism, that selects a set of feasible solutions to be simulated, is introduced and the specific simulation tool to solve the problem is briefly described.

The structure of the paper is as follows: Section 2 describes the case study. Section 3 proposes the complete enumeration procedure. Section 4 describes the Decision Support System that supports the algorithm and the simulation tool that assesses finding solutions. Finally, Section 5 draws conclusions and provides future research lines.

II. Case study description

The case study proposed in this article is based on a multinational company that designs, assembles and transports milling machines. The environment in which the company works might be classified as engineer-to-order, where unique products are designed to customer specifications. This company has several plants around Europe that are capable of producing parts and assembling subsystems to make the product ordered by the customer and to then transport it to the customer's plant. The products delivered to the customer are milling machines customized according to customer requirements, comprising more than 300 components and subassemblies.

Unfortunately, this company does not serve a constant and regular demand throughout the year, but generally receives sporadic unitary orders. Such discrete demand affects its operations management. This company works according to the "mass customization" philosophy. Given its sporadic demand, and with a view to being able to quickly respond to customer requirements, it must keep a stock of those components commonly used in the majority of the products with possibilities to be ordered. Given the short delivery time expected by the market, the company is moving to a switch-to-order (Saiz y Castellano , 2008) environment for a high-demand product. When the product is not in stock and reconfiguration is expensive, the company has to be supplied for all the products. The company has dozens of suppliers for each plant and some can supply the same product with different lead times and delivery costs. Moreover, suppliers offer to deliver the product with different due dates (using various and alternative forms of transportation, and charging an extra amount given the urgency of the order).

According to its supplier's different offers, the company has to decide where the required subsystems will be assembled in order to obtain the final product. These assembly stages can be carried out in a single unique plant, or the first phase can be done in one plant and the final assembly stage done in another plant. This implies transport operations among plants.

In the case study presented in this paper, and given the large size of the involved products, it is also necessary to consider that limited resources in each plant is available space. Each plant has different areas where the various assembly operations are undertaken. These areas may be occupied for certain periods according to former programming plans.

As a basic working hypothesis, this work assumes that the products already sequenced can neither be amended nor their schedules and due dates modified. Therefore, as resources have been assigned and scheduled with a defined sequence, the available resources capacity considers an assignment prior to these operations. Then, production planning must not only assign operations to the plants that have production capacity, but must also determine when each operation must begin and end. It is worth stressing that all the operations can be done in the same area in the same plant.

This problem consists in scheduling, that is by defining when and where the production of the different operations required to deliver the end product in the customer's plant and to respect the due date actually takes place. If the due date is not met, the firm has to pay penalties. Given the possible purchasing and assembly alternatives (Maheut y Garcia-Sabater, 2011), or the BOM themselves, the problem must consider all the possible alternative operations. It is worth stressing that the firm does not consider operations which generate different products (for example, trim problems (Eisemann, 1957) or co-production problems (Vidal-Carreras et al., 2012)).

Stakeholders' expectations not only center on seeking a solution at the lowest cost or the solution with the shortest delivery time, but they have determined some key performance indicators (KPIs) that can be assessed only with a simulator. For this purpose, we go on to propose a heuristic procedure based on complete enumeration to determine all the alternative feasible solutions and to assess them.

III. An algorithm based on complete enumeration

The algorithm herein presented helps to determine all the feasible alternative solutions for producing a single end product.

All the operations are represented using the stroke concept (Garcia-Sabater et al., 2013): a stroke represents any localized operation that transforms (or transports) a series of localized products (preferably measured as SKUs) into another series of localized products (also preferably measured as SKUs). This localized operation and, therefore the stroke representing it, has an associated cost and due date, and consumes a certain amount of resources. Products must consider the site where they are stored. Hence a specific nomenclature has been designed; for example, product "P01" stored in plant PA is called P01@PA.

Different strokes types are characterized as indicated below:

- Assembly and transport strokes have a minimum of one stroke input and have a single stroke output (Maheut y Garcia-Sabater, 2011). Reconfiguration operations are considered an assembly stroke and only the main product obtained is considered (co-products are neglected).
- Purchase strokes have a single stroke output, but have no stroke input.

For this problem, we hypothesize that:

- Strokes must be of only the assembly, purchase or transportation types. Strokes with several outputs cannot be considered in a single stroke.
- At least one of the products can be obtained by different strokes (in other cases, there are no alternatives).
- Product inventory levels are not planned. Those with levels high enough for operations must not be considered. Others have to be ordered with a purchase stroke.
- All SKUs must be an output of at least one stroke. This implies that a SKU has to be obtained by a purchase stroke, or by an assembly or transportation stroke.
- All the SKUs must be an output of at least one stroke, except the end product.
- The end product is the only SKU that is not the input of any other stroke.

Solving the MILP model with commercial mathematical programming software is feasible. However given the characteristics of the case study and the stakeholders' expectations, a heuristic procedure is proposed to generate all the feasible solutions. The proposed algorithm consists in five steps:

- Step 1: Incorporating selection strokes
- Step 2: Transforming the structure with strokes into a direct hypergraph
- Step 3: Generating the complete set of arc vectors by enumeration
- Step 4: Determining each feasible solution
- Step 5: Assessing feasible solutions

III. 1. Step 1: Incorporating selection strokes

The standard form of modeling strokes using mathematical programming is to employ a mixed integer linear programming model as in (Maheut et al., 2012). In this case, the mathematical programming is able to use the structure with strokes by deciding how many different strokes can be performed in each period. The conceptual representation of the stroke is presented in Figure 1.

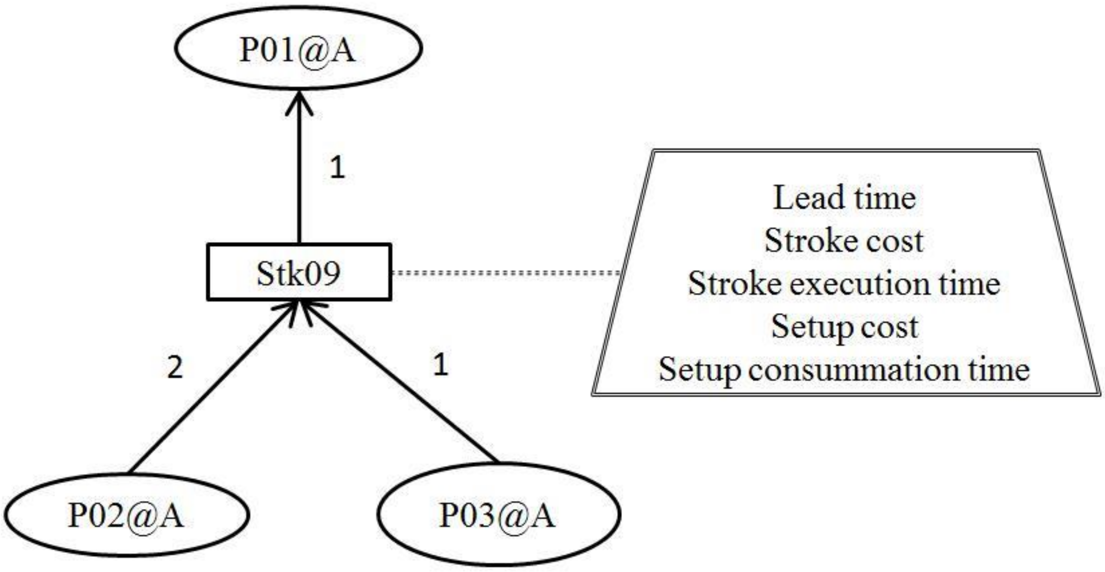

Fig. 6-1 Example of a conceptual representation of one stroke (Maheut y Garcia-Sabater, 2011)

In Fig. 6-1, when one unit of stroke is performed, Stroke Stk09 consumes 2 units of SKU P02@A, one unit of P03@A and generates one unit of P01@A. In our case, only the lead time and the stroke cost need be considered because operations last at least one day (the planning period). The traditional stroke graph is proposed in Fig. 6-2.

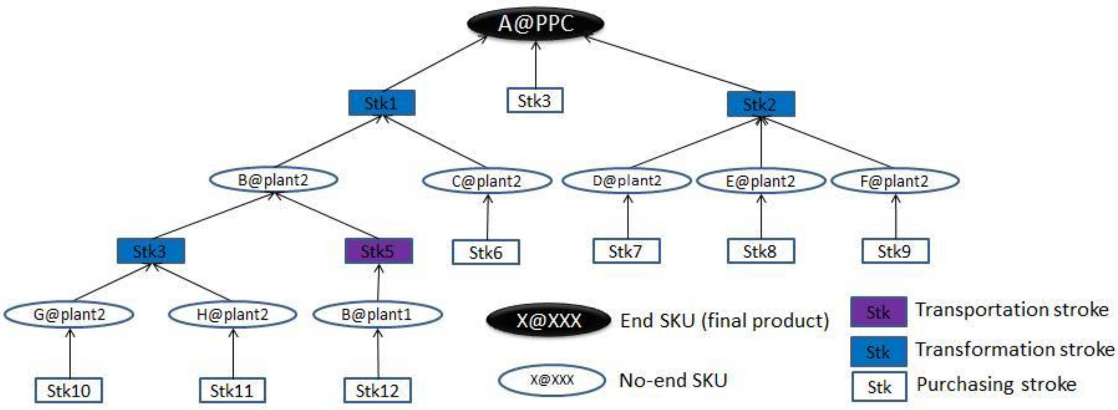

Fig. 6-2 Traditional stroke graph structure

In order to transform the stroke graph into a graph structure which enables complete enumeration, selection strokes and phantom SKUs must be incorporated to know where there are alternatives during algorithm execution (Figure 3). Alternatives exist basically when a SKU can be generated by at least two strokes.

When a SKU is the output of “Z” strokes, “Z” selection strokes and “Z” phantom SKUs must be incorporated. By definition, selection strokes are decision strokes and Phantom SKUs are dummy products, which are considered only for algorithm purposes. Selection strokes have the SKU as output and one phantom SKU as input. These input products are not real and, as seen in Fig. 6-3, they receive a name that reflects that they are phantom SKU from a physical one.

The last phase in this step is to associate the phantom SKU as output for each stroke.

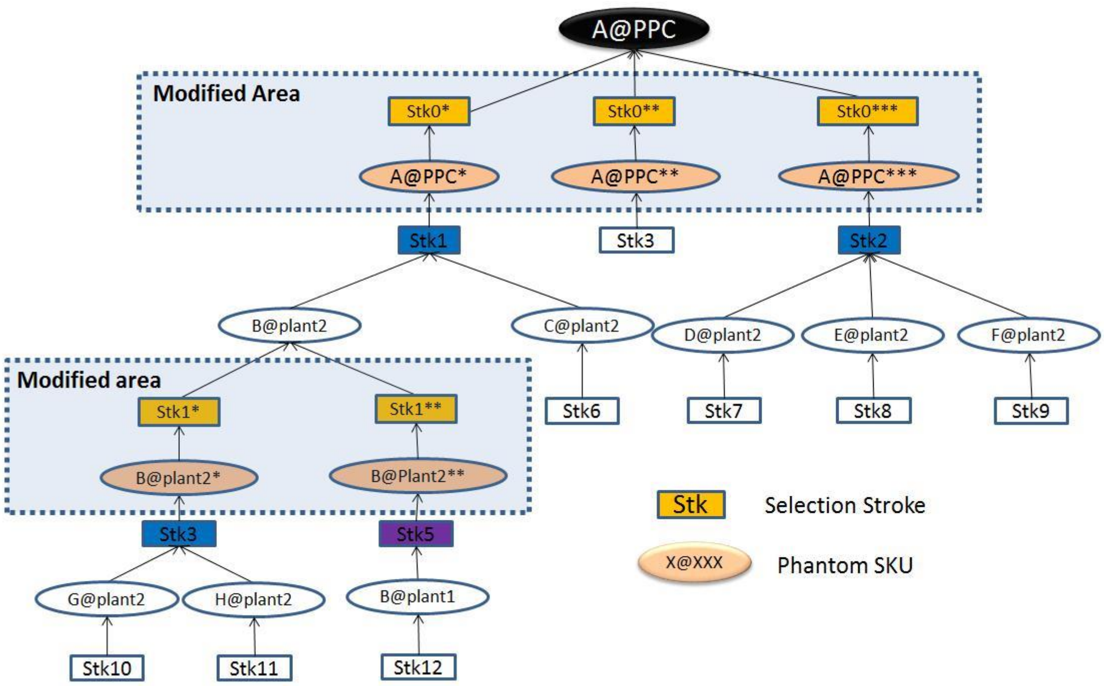

Fig. 6-3 Stroke graph structure incorporating selection strokes and phantom SKUs

III. 2. Step 2: Transforming the structure with strokes into a direct hypergraph

The next step consists in transforming the structure with strokes into a direct hypergraph. The hypergraph considers four different types of nodes, each of a different nature and two types of oriented arcs:

- Source nodes: these nodes have no input arcs, but have one output arc.
- Selection nodes: these nodes have at least two selection input arcs.
- Operation nodes: these nodes have at least one input arc, but no selection nodes.
- Terminal node: this node represents the end product. It can be a selection or an operation node, but cannot be a source node. Once again, this node has no output arcs.
- Selection arcs: these arcs have a selection-type destination node.
- Operation arcs: they have an operation-type destination node.

Step 2.1: Transforming each SKU into a node. The first transformation phase fundamentally consists in transforming each SKU (phantom or not) into a node.

Step 2.2: Creating source nodes with purchase strokes. Those SKUs obtained by a purchase stroke are transformed into source nodes.

Step 2.3: Transforming assembly and transportation strokes into operation arcs. The third transformation phase consists in associating each stroke input (which is now a node) with its operation node (stroke output) through a direct operation arc.

Step 2.4: Transforming selection strokes into selection arcs. The fourth transformation phase consists in associating each stroke input (which is now a node) with its selection node (stroke output) through oriented selection arcs.

The direct hypergraph obtained is the next one (Fig. 6-4):

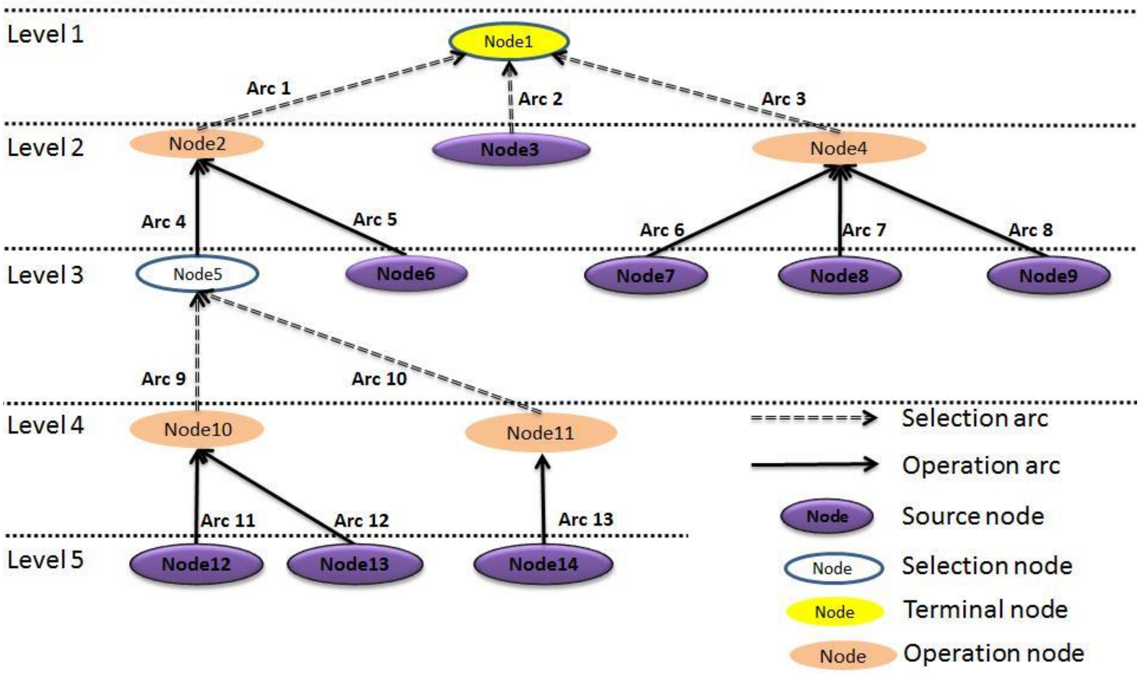

Fig. 6-4 The nodes-arcs structure

As observed in Fig. 6-4, nodes and arcs belong to different levels and are enumerated in a certain manner that enables an ordered enumeration for algorithm purposes. The transformation phase implies assigning the cost and times of strokes to nodes and arcs. This mechanism is as follows:

- Selection arcs and selection nodes have associated null times and costs.
- Source nodes inherit the resource consumption and costs of the purchase strokes that originate them.
- Operation arcs inherit the lead time and stroke cost of the transportation and assembly strokes that originate them.

Costs and lead times are translated into the new structure (see Fig. 6-5) and the assessment presented in Step 3.5 is described herein.

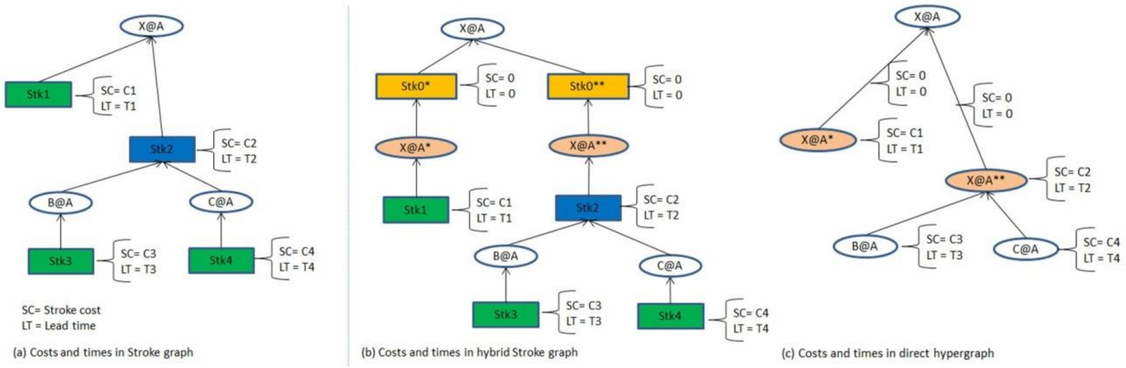

Fig. 6-5 Costs and lead times assignment in the different graph structures

III. 3. Step 3: Generating the complete set of arc vectors by complete enumeration

Generating the set of feasible solutions by complete enumeration consists in generating all the binary arc vectors. Then, infeasible and redundant solutions are erased. The set of feasible solutions is then obtained as the set of arc vectors and node vectors that activates the terminal node.

The three substeps required are described as follows:

Step 3.1: Generating the binary arc vectors. Since the objective is to generate all the feasible solutions, if the problem consists in N selection nodes and M selection arcs, 2^M different binary vectors can be enumerated and just N vectors as a maximum can be feasible. This first sub-step consists so in generating the two 2^M binary arc vectors where:

- Operation arcs are activated in each arc vector.
- Selection arcs are activated by complete enumeration.

Step 3.2: Eliminating the redundant binary arc vectors. As the set of solutions has been enumerated completely, some of the arc vectors generated are redundant because they have too many selection arcs activated. Consequently, the following binary arc vectors must be eliminated:

- Arc vectors that have more than one activated selection arc for the selection node input.
- Arc vectors that have more than N activated selection arcs.

Step 3.3: Eliminate some infeasible arc vectors. Once the redundant arc vectors have been eliminated, some arc vectors represent infeasible solutions because the combination of the activated selection arcs does not activate the terminal node. Consequently, the following arc vectors must also be eliminated:

- Arc vectors with no selection arcs activated, when they exist.
- Arc vectors with one selection arc activated at one level of the graph and no selection arcs (if they exist) activated at the lower levels.
- Arc vectors with a deactivated selection arc at one level and a minimum of one activated selection arc at a lower level.

Once the arc vectors have been generated by complete enumeration and some of the redundant and infeasible vectors have been eliminated, the next step is to use the arc-node structure to check the feasibility of each arc vector and to then reduce the feasible vectors to the simplest form in order to assess them.

III. 4. Step 4: Generating each feasible solution

In order to check that arc vectors are feasible solutions, each binary node vector has to be used to check that the terminal node can then be activated. Next, unnecessary activated arcs and nodes must be deactivated to obtain the simplest vectors. The steps are described as follows:

Step 4.1: Initializing the binary node vector at 0.

Step 4.2: Activating source nodes in the binary node vector.

Step 4.3: Updating the graph. As arc vectors are not yet generated, the next step is to update the binary node vectors. For node = M to 1,

> Step 4.3.1: If the node is of an operation-type, all the node's input arcs are activated and the input nodes of these arcs are activated, then the node is activated.
>
> Step 4.3.2: If the node is of a selection-type, at least one of the node's input arcs is activated and the input node of the activated arcs is activated, then the node is activated.

Step 4.4: Eliminating infeasible solutions. If the terminal node is deactivated, the solution is erased.

Step 4.5: Deactivating unnecessary arcs. For arc = N to 1, all the arcs are deactivated in turn:

> Step 4.5.1: If the terminal node is activated, return to step 4.5 (the next arc is deactivated).
>
> Step 4.5.2: If the terminal node is deactivated, then that arc is re-activated; return to step 4.5.

Step 4.6: Deactivating unnecessary source nodes. For node = M to 1, if the node is of the source type, it is deactivated.

Step 4.6.1: If the terminal node is activated, the next arc is deactivated.

Step 4.6.2: If the terminal node is deactivated, that arc is re-activated.

III. 5. Step 5: Assessing each feasible solution

In this step, the set of feasible and simplest solutions is generated and the next step is to assess them. Steps 1 and 2 generate the direct hypergraph and, as presented in Fig. 6-5, costs and times are now assigned to nodes and arcs.

Step 5.1: Calculating the cost associated with each solution. The cost associated with the solution is the summation of the cost of each activated arc and node.

Step 5.2: Calculating the earliness and tardiness of beginning and ending each arc and node by considering resources availability. This step is done precisely and directly by the simulation tool during each run. Nevertheless, a procedure based on a traditional earliness and tardiness calculation of each node has been specifically designed to obtain an approximation of these times. The feasible solutions showing the worst time behavior with that approximated method are not considered to assess the exact tardiness of the project. Due to length restrictions and to the limited scope of the paper, the complete procedure has not been introduced into this paper.

This algorithm has been programmed in Java. In the case study, an application case considering 34 purchasing strokes, 8 assembly strokes and about 10 alternative strokes (alternative purchase operation and alternative BOM) has been tested. The algorithm based on complete enumeration has been implemented within a Decision Support System, which includes a simulation that evaluates the different KPIs handled by the supply network for each alternative solution.

IV. The Decision Support System (DSS)

The DSS of the case study contains a database based on the stroke concept, a simulation model, which functions to transform data, and also the algorithm described herein.

When a new order arrives, different control mechanisms check that the delivery of the end product can be achieved. One of them proposes to stakeholders the incorporation of transportation strokes like transshipments to consider the transport of goods between plants. Another verifies, for instance, the possibility that all the SKUs that can be in the feasible BOMs are obtained with at least one stroke.

The main difficulty, which is where previous research has not provided results, lies in considering alternative operations. To this end, stakeholders propose alternative operations by introducing new strokes into the database.

IV. 1. An objective function to select feasible solutions

Having introduced all the strokes into the database, successfully performed the various implemented mechanisms to check the data and performed the algorithm based on complete enumeration, stakeholders receive a set of solutions with their associated cost and time. Next, these solutions have to be simulated in a specific simulator designed to solve the problem.

The different KPIs to be achieved at the end of the simulation execution are: lead time, delivery time, service level, plant workload level, machine cost, etc.

However, with the increased feasible solution number due to alternative operations, prolonged total resolution times given the need to simulate each solution, and as many solutions are identical in the KPIs value, a selection mechanism has been developed.

Stakeholders assumed that the two critical factors to select a better solution were the total cost and lead time associated with each solution. For each solution, a function is used to select a limited set of solutions. The various parameters used in the selection function are presented in Table 1.

Tabla 6-1 Parameters notation

$\emptyset \in [0,1]$	*Weight of the cost value in the objective function*
$\alpha = 1 - \emptyset$	*Weight of the lead time value in the objective function*
V	*Value of the function for the solution considered*
C^S	*Cost of the solution considered*
C^{max}	*Maximum cost of all the feasible solutions*
T^S	*Lead time of the solution considered*
T^{max}	*Maximum lead time of all the feasible solutions*

An objective function of selection (1) is used as follows:

$$V = \frac{C^S}{C^{\max}}\phi + \frac{T^S}{T^{\max}}\alpha \qquad (1)$$

In Fig. 6-6, a screenshot of the experiment setup page to fix the different weights used in the objective function is presented.

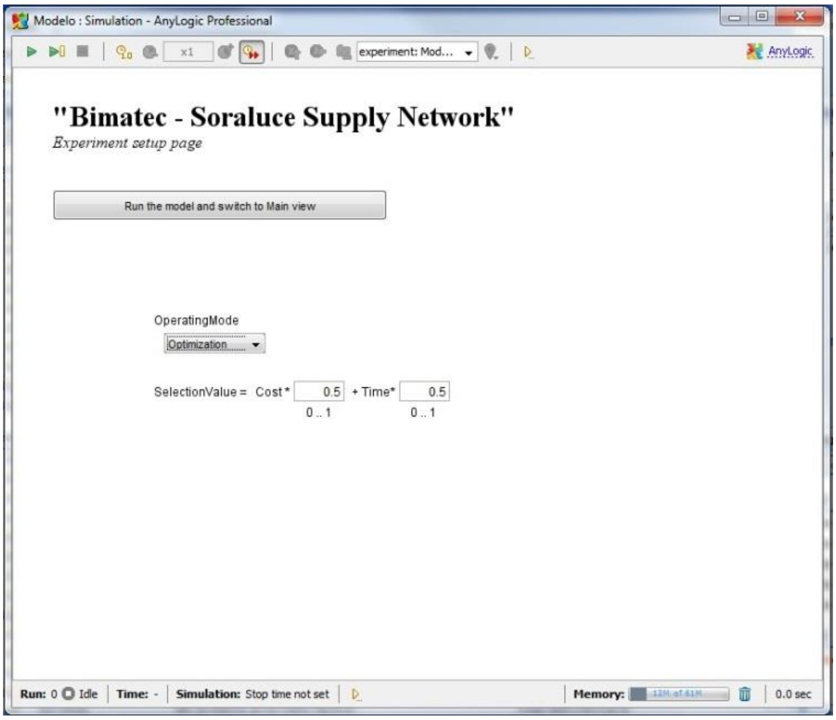

Fig. 6-6 The experiment setup page

Based on the classification, stakeholders decide the set of solutions to be simulated in the simulation model.

In our case, with a set of 30 alternatives, it took about 4 minutes to identify and assess all the feasible solutions. Based on the classification of the objective function values, stakeholders decide the set of solutions to be simulated in the simulation model. As each simulation run lasts about 10 minutes, they obtain the options to select all the solutions or part of them.

IV. 2. Simulation of the solutions

After selecting the set of solutions to be simulated, the associated strokes performed in each solution are identified. Then an instance of the SN for the order is build. This mechanism to transform solutions is performed to allow stakeholders to physically observe the network.

To do this, the strokes to be performed to complete the order are obtained from the arcs activated in the chosen solution, so it is easy to observe where to execute each operation. With these data, a Supply Network Strategy Customer Service is generated. The SN is configured for each solution, the simulation is run, and a more realistic scheduling plan is generated.

A screenshot of the model designed in the AnyLogic® software is shown in Fig. 6-7.

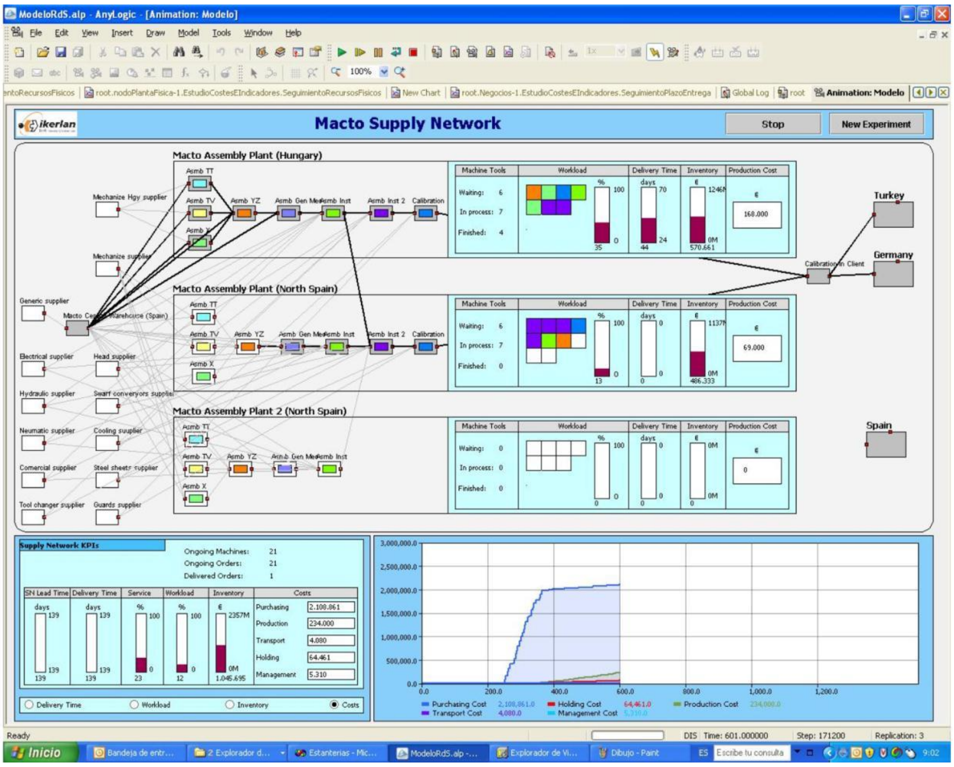

Fig. 6-7 Simulator interface

In the interface, three main parts can be observed:

- The SN configuration at the top. Suppliers are on the left, three plants considered in this instance are in the centre, and customers are on the right. Each plant is divided into the various main processes. Lines in bold denote that there is a material flow among the different processes, suppliers and customers in the simulated solution.
- The different KPIs of the SN are below the SN representation. Numerically KPIs values are on the left and, on the right, KPIs are graphically represented.

Then, stakeholders make a multicriteria decision based on the value of the different KPIs obtained after each run.

V. Conclusions

In this paper, a complete enumeration algorithm based on a stroke graph is used to generate all the feasible solutions. Each time a new order arrives, the proposed procedure offers stakeholders all the feasible solutions which are needed to be evaluated in a specific simulator. Then, a selection function and the simulation tool are introduced.

As a further research line, algorithms that consider multi-products must be developed in an initial step. Another research line extends the algorithm to consider the strokes that are not only assembling process, but also splitting ones. Further research is required to solve the problem in a distributed manner, and stakeholders can appreciate considering a possible re-scheduling activity as in (Lloret et al., 2008) in order to determine if order delivery lead times can be reduced.

Capítulo 7 The Generic Materials and Operations Planning (GMOP) problem solved iteratively: a case study in multi-site context

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Abstract. This paper addresses the Generic Materials and Operations Planning (GMOP) problem, a multi-site operations planning problem based on the “stroke” concept. The problem considers a multinational company subject to positive and negative backlogs imposed by using returnable racks that have to be filled by end products and transported to customers, alternative operations (purchase, transformation and transport), different BOM structures given the different operation types (injection operations, assembly operations) performed in the various factories of the supply chain, and capacitated production resources. This paper describes and defines the “stroke” construct that mathematically models the relationships between operations and materials. The mathematical modelling approach is provided, as is a brief description of an operations planning tool that has been implemented. Furthermore, some results obtained in a first-tier level supplier of the automotive industry have been introduced.

I. Introduction

One of the most well-accepted definitions in the literature of supply chain management (SCM) is that SCM is a task that involves integrating organisational units through the supply chain (SC) and coordinates the flow of material, information and financing for the purpose of fulfilling customer demands (Stadtler y Kilger, 2002). Dudek (2004) states three SCM objectives: improve customer service; lower the amount of resources to serve customers; improve the SC's competitiveness. Improving competitiveness lies on two main pillars: integrating the SC and coordinating it Stadtler, 2005a).

Many managers tend to think that Enterprise Requirement Planning (ERP) systems will solve their planning issues, but despite their name, ERP systems are usually transaction-based systems rather than planning systems. Traditional production planning methods, such as Material Requirements Planning (MRP), consider only availability of materials, and completely ignore factors such as capacity limits and SC configurations (Caridi y Sianesi, 1999). In most software, alternative operations can be introduced as data, but the optimisation methods available do not consider them simultaneously. Moreover, packaging and its planning is a special concern in some industries and, to the best of our knowledge, ERP cannot plan them in any detail. Furthermore, operations planning functions in large companies are usually executed by different organisational units at distinct locations. Generally, excess inventories, poor customer service and insufficient capacity utilisation are due to the lack of coordination between these operations planning functions. Broadly extended ERP systems have led to the emergence of the so-called Advanced Planning and Scheduling Systems (APS), which may be viewed as “add-ons” of the ERP system to plan and optimise the SC. For this support, APS uses optimisation techniques to model and determine the quantities to be produced, stored, transported, and procured by respecting the SC's real constraints (Garcia-Sabater et al., 2012a; Günther y Meyr, 2009).

The commonest name with which to consider the mathematical model that simultaneously solves the materials and operations planning problem is the Multi-level Capacitated Lot-Sizing Problem (MLCLSP). All in all, most works on the MLCLSP still assume that BOM is made up of assembly products. A series of problem variants based on amending the structure of BOMs may also be found in practice and in the literature. In (Garcia-Sabater et al., 2013), an extensive literature review about the MLCLSP and the need to use the stroke concept in the GMOP problem is introduced. In (Maheut y Garcia-Sabater, 2011), a variant of the GMOP problem is introduced, which considers scheduled receptions and the initial stock level. Nevertheless, to the best of our knowledge, a case study about the multi-site, multi-level, capacitated operations planning problem with lead times that simultaneously considers alternative operations (purchasing, transport - replenishment, transshipments and distribution - and production) and returnable packaging has not yet been studied.

This paper proposes an alternative modelling technique that stresses what is known to be done rather than the result of the action (the product). The proposed modelling method is useful given its simplicity and generality. Furthermore, its proposal is feasible since the mathematical programming solving technology has considerably improved in the last 10 years. The model's objective is to minimise total costs by fulfilling lead times and by considering alternative operations and returnable racks. The model has been designed for a first-tier level company of the automotive sector and operations plans are performed daily.

II. The "stroke" concept

To consider this proposal, it is necessary to specify some concepts. Products must consider the site where they are stored at and also their packaging. This implies loss of generality, which is compensated by simplified data loading. For example:

- Part item "01" stored in factory A will be called P01@A,
- Rack "01" filled with 12 "02" part items stored in factory B will be called R01#12P02@A,
- Empty rack "01" in factory C will be considered R01#00@C.

Each stroke corresponds to a specific located operation (Maheut et al., 2012). It is characterised by the use of located resources. A set of products is assigned to each stroke, which is consumed when a stroke unit is executed. This set (known as "stroke input") can be null, unitary or multiple, while its coefficients (the Gozinto factor) can be above one unit. A set of SKUs is assigned to each stroke, which is produced when a stroke unit is carried out. This set (called "stroke output") can consist in several different items, a single item or none, and its coefficients (amount of each item produced) can be above one unit (Garcia-Sabater et al., 2013). Moreover, lead times, setup times and costs, time consummation and the costs of performing one stroke unit are assigned to the stroke and not to the result of the operation. Resources are associated with each stroke, but not with the product (or the series of products) obtained.

III. Mathematical formulation of the GMOP problem

Due to software limitations, the problem is solved on an iterative basis. Therefore, the GMOP problem was modelled by considering that each stroke level, or each stroke, was independent of the rest. The GMOP model presented herein has been, therefore, slightly modified to represent this new approach. To mathematically formulate the problem, it is necessary to define the nomenclature presented in Tabla 7-1 Sets and indices. Table 2 contains the notations per parameter and Table 3 presents the notations per variable.

Tabla 7-1 Sets and indices

Symbol	*Definition*
$i \in P$	*Index set of products (includes product, packaging and site)*
$r \in R$	*Index set of resources (includes product and site)*
$k \in Z$	*Index set of strokes (includes stroke and site)*
$j \in J$	*Index set of sites*
$t = 1 \ldots T$	*Index set of planning periods*
Z_r	*Set of strokes that are performed in resource r* $(Z_r \subseteq Z)$
FP	*Set of end-products* $(FP \subseteq P)$

Tabla 7-2 Parameter notation

Symbol	*Definition*
D_{it}	*Demand of product i in period t (due date)*
CA_{it}	*Acquired compromised in product i in period t (due date)*
X_{it}^{rec}	*Planned reception for products i in period t*
H_i	*Non-negative holding cost per period for storing one unit of product i*
Y_i^0	*Initial inventory of product i*
P_i^F	*Benefit of delivering product i*
P_i^P	*Cost of purchasing product i*
TO_{kr}	*Capacity of resource r required for performing one stroke k unit (in time units)*
TSO_{kr}	*Capacity required of resource r required for the setup of stroke k (in time units)*
K_{rt}	*Capacity available of resource r in period t (in space units)*
M	*A sufficiently large number*
CO_k	*Cost of performing one stroke k unit*
CS_k	*Cost of the setup of stroke k*
SO_{ik}	*Number of product i units produced by performing one stroke k unit (stroke output)*
SI_{ik}	*Number of product h units required for performing one stroke k unit (stroke input)*
$LT(k)$	*Lead time of stroke k*
B_i	*Initial backlog of product i*
$C_{it}^{\beta+}/C_{it}^{\beta-}$	*Cost of positive/negative backlogging for one unit of i in period t*

Tabla 7-3 Variable notation

Symbol	*Definition*
z_{kt}	*Quantity of strokes k to be performed in period t*
y_{it}	*Inventory of product i at the end of period t*
o_{it}	*Quantity of i that it is to be delivered at the end of period t*
q_{it}	*Quantity of demand of product i at the end of period t that it is not to be delivered*
w_{it}	*Requirements of product i at the end of period t*
δ_{kt}	*Binary variable which indicates if stroke k is set up in period t*
$\beta_{it}^{+}/\beta_{it}^{-}$	*Positive/negative backlog of product i in period t*

The GMOP problem adapted for an iterative resolution can be formulated as shown below:

$$Maximize\, F(o,z,y,\delta)=\sum_{i\in P}\sum_{t=1}^{T}\left(P_{it}^{F}\cdot o_{it}-P_{it}^{C}\cdot w_{it}\right)-\sum_{i\in P}\sum_{t=1}^{T}\left(\beta_{i,t}^{+}\cdot C_{i,t}^{\beta+}+\beta_{i,t}^{-}\cdot C_{i,t}^{\beta-}+H_{it}\cdot y_{it}\right)-\sum_{k\in Z}\sum_{t=1}^{T}\left(CO_{k}\cdot z_{kt}+CS_{k}\cdot\delta_{kt}\right) \quad (1)$$

Subject to

$$o_{it}+q_{i,t}=D_{i,t} \quad i\in P, i\in FP, t=1,\ldots,T \quad (2)$$

$$y_{it}=y_{i,t-1}+X_{it}^{rec}+\sum_{k\in Z}\left(SO_{ik}\cdot z_{k,t-LT(k)}-SI_{ik}\cdot z_{kt}\right)-CA_{i,t}-o_{i,t} \quad i\in P, i\notin FP, t=2,\ldots,T \quad (3)$$

$$\beta_{it}^{+}-\beta_{it}^{-}=\beta_{i,t-1}^{+}-\beta_{i,t-1}^{-}+X_{it}^{rec}+\sum_{k\in Z}\left(SO_{ik}\cdot z_{k,t-LT(k)}\right)+q_{i,t} \quad i\in FP, t=2,\ldots,T \quad (4)$$

$$y_{i,1}=Y_{i}^{0}+X_{i,1}^{rec}+\sum_{k\in L_0}\left(SO_{ik}\cdot z_{k,1}-SI_{ik}\cdot z_{k,3}\right)-CA_{i,1}-o_{i,1} \quad i\in P, i\notin FP \quad (5)$$

$$\beta_{i,1}^{+}-\beta_{i,1}^{-}=B_{i}^{0}+X_{i,1}^{rec}+\sum_{k\in L_0}\left(SO_{ik}\cdot z_{k,1}\right)+q_{i1} \quad i\in FP \quad (6)$$

$$w_{i,t}=\sum_{k}\left(SI_{ik}\cdot z_{k,1}\right)-X_{i,t} \quad i\notin FP, t \quad (7)$$

$$z_{kt} - M \cdot \delta_{kt} \le 0 \quad k \in Z, t = 1,...,T \tag{8}$$

$$\sum_{k \in Z_r} \left(TO_k \cdot z_{kt} + TS_k \cdot \delta_{kt} \right) \le K_{rt} \quad r \in R, t = 1,...,T \tag{9}$$

$$z_{kt} \in \mathbb{Z}_0^+ \quad k \in Z, t = 1,...,T \tag{10}$$

$$o_{i,t}, q_{i,t}, w_{i,t}, y_{it}, \beta_{it}^+, \beta_{it}^- \ge 0 \quad i \in P, t = 1,...,T \tag{11}$$

$$\delta_{kt} \in \{0,1\} \quad k \in Z, t = 1,...,T \tag{12}$$

Objective (1) is to maximise the profit of delivering products minus the sum of the storage costs, the stroke execution costs, the stroke setup costs, and the positive (classical) and negative (serving in advance) backlogging costs. Equation (2) splits external demand into real sales and the demand that is to be delayed. Equations (3) and (5) provide the continuity equation of the inventory levels. The inventory level at the end of a period considers the inventory level at the end of the previous period, planned receptions, product demand, and the products generated and consumed after executing those strokes with their associated lead times. Equations (4) and (6) provide the continuity equation of the backlogging levels. Two types of backlogs exist: the traditional positive backlog (also called Delay at the shipment level or the underdelivery level) and the negative backlog (also called Serve in Advance or the overdelivery level). Given the difference with inventory levels, Backlogging levels are generally applied to the product in the inventory at customers' locations. Backlog levels are the determined inventory levels of products based on demand plans, but they do not have to be physical inventory levels in customer plans. This concept is regularly used in the automotive industry because products are sent in packaging (pallets or racks). In this case, if demand is regular and not proportional to the packaging capacity because of the cost of negative backlogging and the policy of optimising resources, packaging is fulfilled and a negative backlog level is generated. Constraint (9) evaluates the quantity of products *i* that should be acquired in order to fulfill requirements. Constraint (8) is introduced to know if stroke *k* is produced in *t* by, therefore, employing the capacity associated with the setup (setup forcing). Constraint (9) is a capacity constraint that limits the use of resource *r* in period *t* by considering both the setup and operations times. Constraints (10), (11) and (12) define the range of variables.

The model is solved iteratively for each product with internal or external demand. The value of *o* will be converted for the following iterations into a constant *CA* since it has been accepted. The value of w will be converted into new demand that will be fulfilled in subsequent iterations.

IV. Case study

This model is implemented if it is particularly motivated by the problem faced by a company manufacturing plastic products from two factories located in Spain and which sells the product in this country. Production management develops a 3-month operations plan by considering the inventory level, resources capacity, routes and packaging availability to fulfill demand.

A specific operations planning tool has been deployed by the ROGLE research Group. The development process of the information system has been carried out completely. The system not only includes the model presented herein, but also other features related with SC activities, like Demand Planning or Scheduling tasks. The software runs beyond the official ERP system. To obtain data from it and to generate a parallel database that stores official company data and the rest of parameters that need to be used, specific connections were created using XML files. Users interact with the software by using standard browsers (to activate and input data) and spreadsheets (to analyse and use the results).

The operations plan consists in listing those operations with quantities to be performed with the different resources in the various factories for each time period of the horizon in order to serve customers in terms of time and quantity. Basically, operations are:

- Purchase operations, which determine the amount of raw material (plastic powder) to be purchased in each period by considering different lot sizes.
- The raw material is injected into a press injection machine and different products are obtained depending on the mould used.
- After injecting the obtained products, they are assembled on an assembly line to obtain the end products.
- End products must be stored in filled returnable racks and are transported to the customer's site.

Fig. 7-1 displays a sharp drop in backlog levels. Throughout the horizon, a negative backlog is maintained because customers force the company to maintain a safety backlog level. Thanks to the operations planning tools, the company has been able to cut its overdelivery costs, while demand levels remain constant. In fact, this reduction might be considered the effect of simply applying the MRP concept.

With the software, we solved the GMOP problem by employing LP Solve IDE. We tested performance in a full-sized case study problem with seven different factories with approximately 500 end products, 30 resources and more than 700 different operations for distinct instances. The results show an average running time of 6 hours, for instance using a Pentium IV 1.22 GHz processor, 2 GB RAM and Windows XP as the OS.

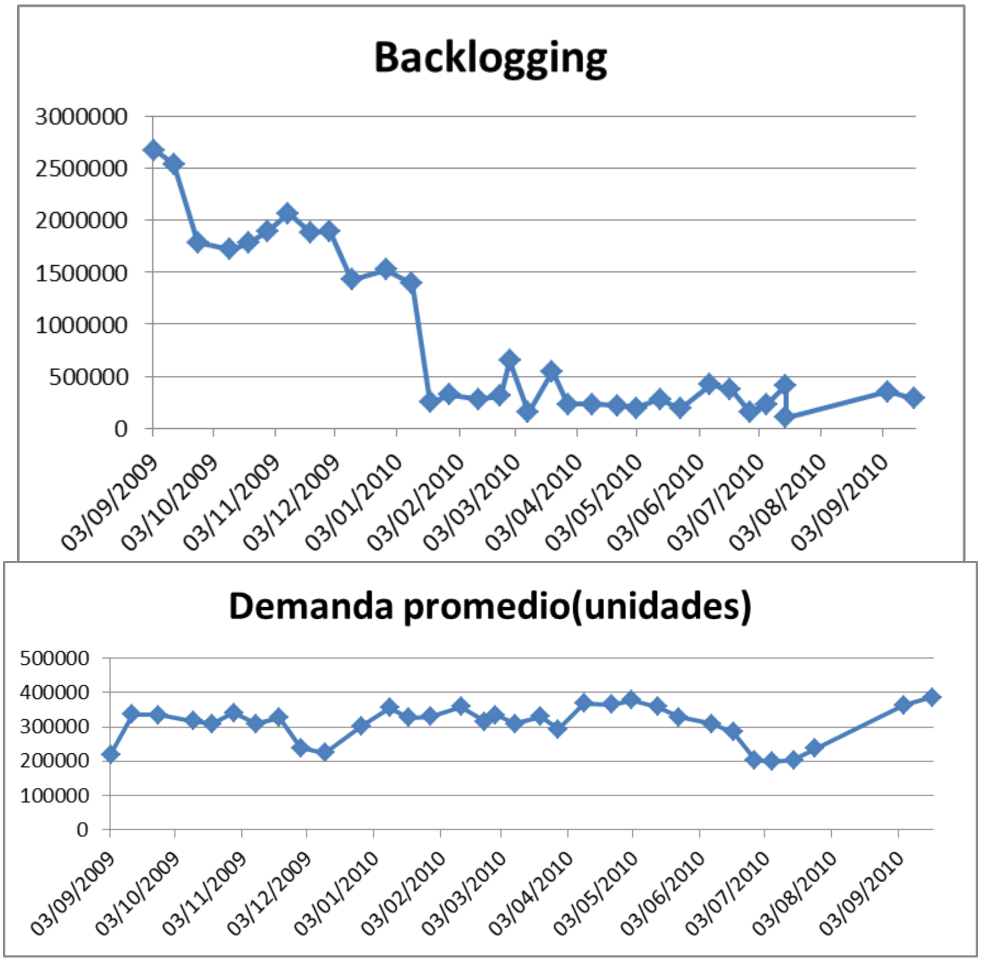

Fig. 7-1 Demand and Backlog levels

V. Conclusions

A form of modelling the relationship between operations and the materials required to manufacture a product has been considered. This way of defining the relationships between operations and materials suggests a compact mathematical programming model to plan operations in an SC. Apart from capacity constraints, this GMOP model also takes into account direct and reverse BOMs, multi-site, alternative operations by considering packaging, and briefly introduces one operations planning tool designed and used by one multinational company at the first-tier level of the automotive industry.

Two important research lines for the near future include the design of specific heuristics for the problem considered herein, and the incorporation of the central stroke concept for modelling and solving the distributed problems. The incorporation of variants such as uncertainty (if it is stochastic or uses fuzzy methods) is another future research line.

Capítulo 8 A supply chain operations lot-sizing and scheduling model with alternative operations

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Abstract. The aim of this paper is to propose a Mixed Integer Linear Programming (MILP) model for operations lot-sizing and scheduling (assignment and sequencing) in the supply chain of an international company which produces and delivers customized products through several geographically distributed assembly plants. The model schedules the purchase of raw materials in the various plants considered, lateral stock transshipments, shipments to customers and the various operations required to assemble the product. We contemplate different alternative production operations, such as product substitution (upgrading), alternative procurement and transport operations. It also addresses the different lead times associated with these operations. Specific constraints such as space availability on each plant and workforces are contemplated. A novel approach based on the stroke concept is applied to the MILP model to consider alternatives.

I. Introduction

A supply chain (SC) is a network of organizations involved through upstream and downstream relations where different processes and activities are carried out to produce value in the form of products and / or services for the end customer. In order to face the increase in demand, SCs must offer a product or service with a minimum cost and a short lead time. To do so, Stadtler (2005) considers that SC management must be based on two pillars: SC integration and coordination.

For SCs to be able to coordinate efficiently, the literature contemplates two phases at the strategic level: SC design (Mohammadi Bidhandi et al., 2009) or SC redesign (Nagurney, 2010), and SC configuration. Graves and Willems (2003) were the first to introduce the SC configuration problem. In general, this problem contemplates different possible configurations because, for instance, raw materials can be purchased from different suppliers, products can be produced or assembled on different machines, or delivered by different forms of transport (Li y Womer, 2008). Selecting a configuration implies reaching a compromise between the costs involved and the service levels to be offered to the customer. The literature includes a large amount of mathematical models which address the SC configuration problem. We refer readers to the following review: (Mula et al., 2012b). The literature includes some cases such as the work of (Li y Womer, 2008) where the tactical and / or operational level characteristics can be considered by the configuration problem.

In relation to lot-sizing and scheduling problems, one of the first models put forward was that of Wagner-Whitin (Wagner y Whitin, 1958), which proposes lot-sizing for a single product. Afterwards, work was done on the capacitated lot-sizing problem (Karimi *et al.*, 2003). Later, other concepts were introduced: sequence-dependent setup times (Haase, 1996), lead time concepts (Hnaien et al., 2008), multi-stage production (Tempelmeier y Buschkühl, 2008), products substitution (Lang y Lang, 2010) or other multi-site scheduling problems into scheduling models (Lloret et al., 2008). Nevertheless, to the best of our knowledge, the multi-site, multi-stage, capacitated lot-sizing and scheduling problem with lead times has not been studied by considering alternative operations for purchasing, transport (replenishment, transshipments and distribution) and production.

This article proposes an MILP model to optimize lot-sizing and scheduling (assignment and sequencing) of SC operations with the arrival of a new firm order. The model proposed is based on the stroke concept (Garcia-Sabater et al., 2009a; Garcia-Sabater et al., 2009b) (a similar concept to the Resource-Task Networks (Pantelides, 1994)) to consider purchase, transport and production alternatives in the SC. The model's objective is to minimize total costs by fulfilling lead times.

The structure of the paper is as follows: section 1.2 describes the aims of the model; section 1.3 presents the basic assumptions of the model. Section 1.4 formulates the MILP model for supply chain lot-sizing and scheduling. And finally, the last section draws conclusions and provides future research lines.

II. The supply chain operations lot-sizing and scheduling model with alternative operations

The SC operations lot-sizing and scheduling model with alternative operations that considers lead times (SCOLSS-AO) is a multi-site, multi-level and multi-period problem with transport among plants (transsshipments) that considers alternative production routes and products substitution. It contemplates intermediate (or half-finished) items and finished goods, as well as different resources.

When new firm orders arrive, SC configuration and multi-plant scheduling are performed to deliver the product to customers. SC scheduling must consider restrictions in all the plants. Furthermore, setup times, costs and all the possible alternatives, i.e., replenishment, production / assembling and transport alternatives, must be studied.

Since it is assumed that products already sequenced cannot be amended, and as resources have been assigned and scheduled with a defined sequence, the available resources capacity considers an assignment prior to these operations.

In general, the objective of the model is to determine some operations scheduling which minimizes costs by fulfilling customers' expectations in terms of the characteristics of the product to be delivered and the due dates. In detail, the model provides: (i) the different products and SC configurations that respond to the strategy selected; (ii) the supplier that best responds to each strategy efficiently; (iii) the costs of each configuration; and (iv) the due date of the product ordered for each configuration. In short, when a new order arrives, the model must assign the production of the various modules to each plant and resource, generate the raw materials purchase order to suppliers and manage the transshipments among plants.

III. Assumptions

The SCOLSS-AO is a deterministic model that considers a P set of product, a W set of sites, a Z set of operations (known as strokes) and an R set of resources.

Each product is defined with both their packaging and site in mind. A stock-keeping unit (SKU) corresponds to each product. Consequently, two products in different sites are considered as two different items. Two products in the same site but in different packaging are considered as two different SKUs. Demand refers to an SKU with specific characteristics, which is accomplished with the assembly of several modules that are produced basically with a raw material purchased from several suppliers. Demand has to be served on a predetermined due date at a given site without backlogs. Substitution of SKUs is considered (through upgrading or because of the suppliers' capacity to provide similar components).

Each stroke corresponds to a determined located operation. It is characterized by the use of located resources. Two technically identical operations performed in two different sites are considered as two different strokes. A set of SKUs is assigned to each stroke, which is consumed when a stroke unit is executed. This set (known as "stroke input") can be null, unitary or multiple, while its coefficients (the Gozinto factor) can be above one unit. A set of SKUs is assigned to each stroke, which is produced when a stroke unit is carried out. This set (called a "stroke output") can consist of several different items, a single item or none, and its coefficients (amount of each item produced) can be above one unit. Lead times are considered and assigned to each stroke. Setup times and the associated costs are invariable in time, but depend on the sequence of the stroke considered (consequently, on the set of resources employed). The scheduling (assignment and sequencing) of strokes is performed in each period. There can be different setups in one same period. The existence of alternative operations is considered. Some modules can be produced in different resources and / or sites.

Resources are localized, immovable and heterogeneous. In resources, strokes have been assigned and sequenced in accordance with previous orders. Thus for each resource, the production capacity corresponding to the different strokes needed for these orders has been reduced. Resources have different limits of the capacity available in each period. The consumption of the production capacity in each resource varies in terms of both the strokes performed in it in each period and the setup changes contemplated. Setups must be complete during each period.

IV. Formulation

Tabla 8-1 contains the notations for the constants, sets and indices used for formulating the SCOLSS-AO.

Tabla 8-1 Sets and indices

Symbol	*Definition*
$i \in P$	*SKUs*
$r \in R$	*Resources*
$k \in Z_{k \in Z}$	*Strokes including dummy stroke 0*
$0 \in Z$	*Dummy stroke for modelling time during which a resource is not setup for any stroke*
$j \in J$	*Sites*
$t = 1 \dots T$	*Periods*
Z_r	*Set of strokes that are performed in resource r* $(Z_r \subset Z)$
Z_j	*Set of strokes that are performed in site j* $(Z_r \subset Z)$
L_X	*Set of strokes whose lead time is lower than* $X \in \{0,1,\dots,l\}$
P_j	*Set of SKUs in site j* $(P_i \subset P)$

Tabla 8-2 contains the notations per parameter.

Tabla 8-2 Parameter notation

Symbol	Definition
D_{it}	Demand for SKU i in period t (due date)
X_{it}^{rec}	Planned reception for SKUs i in period t
H_i	Non-negative holding cost per period for storing one unit of SKU i
Y_i^{max}/Y_i^{min}	Upper\Lower inventory limit for SKU i
Y_i^0	Initial inventory of SKU i
A_i	Space consummation for storing one unit of SKU i
A_k	Space consummation for performing one unit of stroke k
K_j^{sp}	Space capacity of site j (in space unit)
Γ_k	Workforce utilization for performing one unit of stroke k
K_{rt}^{lab}	Workforce capacity available of resource r in period t (in the workforce unit)
CO_{kt}	Cost of stroke k in period t
$CS_{k1,k2}$	Setup cost that is incurred when the setup state changes form stroke k1 to k2
$\theta_{k,1} = \delta_{k,k,1}$	Binary parameter that indicates whether stroke k is set up at the beginning of the first period
SO_{ik}	Number of SKU i units produced by making one unit of stroke k (stroke output)
SI_{ik}	Number of SKU i units required for making one unit of stroke k (stroke input)
$LT(k)$	Lead time of stroke k
M_r	Number of strokes performed in resource r

Tabla 8-3 contains the notations per variable.

Tabla 8-3 Variable notation

Symbol	Definition
x_{kt}	Quantity of strokes k starting in period t
y_{it}	Inventory of SKU i at the end of period t
v_{kt}	Auxiliary variable: the larger it is, the later the stroke is scheduled in period t
$\delta_{k1,k2,t}$	Binary variable which indicates whether stroke k2 is set up immediately after stroke k1 in period t
$\theta_{k,t}$	Binary variable which indicates whether stroke k is set up at the beginning of period t

By assuming, for instance, that the maximum lead time is 3, then $X \in \{0,1,2,3\}$.Thus, there are three lists $L_X \in \{L_0, L_1, L_2, L_3\}$. The SCOLSS-AO can be formulated as shown below:

$$Minimize\, F(x,y,\delta,\theta) = \sum_{i\in P}\sum_{t=1}^{T}\left(H_i \cdot y_{i,t}\right) + \sum_{k1\in Z}\sum_{t=1}^{T}\left(CO_{k1,t}\cdot x_{k1,t} + \sum_{k2\in Z} CS_{k1,k2}\cdot \delta_{k1,k2,t}\right) \quad (1.1)$$

subject to

$$y_{it} = y_{i,t-1} + X_{it}^{rec} + \sum_{k\in Z_i^+}\left(SO_{ik}\cdot x_{k,t-LT(k)}\right) - D_{it} - \sum_{k\in Z_i^-}\left(SI_{ik}\cdot x_{kt}\right) \quad i\in P, t=4,\ldots,T \quad (1.2)$$

$$y_{i,X} = y_{i,X-1} + X_{i,X}^{rec} + \sum_{k\in L_{X-1}}\left(SO_{ik}\cdot x_{k,X-LT(k)}\right) - D_{iX} - \sum_{k}\left(SI_{ik}\cdot x_{k,3}\right) \quad i\in P, X=1,\ldots,3 \quad (1.3)$$

$$Y_i^{\min} \le y_{i,t} \le Y_i^{\max} \quad i \in P, t = 1,\ldots,T \tag{1.4}$$

$$\sum_{k \in Z_j} \sum_{\tau = t - LT(k)}^{\tau = t} A_k \cdot x_{k\tau} + \sum_{i \in P_j} A_i \cdot y_{it} \le K_j^{sp} \quad i \in P, t = 4,\ldots,T \tag{1.5}$$

$$\sum_{k \in Z_j \wedge k \in L_{X-1}} \sum_{\tau = X - LT(k)}^{\tau = t} A_k \cdot x_{k\tau} + \sum_{i \in P_j} A_i \cdot y_{i,X} \le K_j^{sp} \quad j \in J, X = 1,\ldots,3 \tag{1.6}$$

$$\sum_{k \in Z_r} \Gamma_k \cdot x_{kt} \le K_{rt}^{lab} \quad r \in R, t = 1,\ldots,T \tag{1.7}$$

$$\Gamma_{k1} \cdot x_{k1,t} \le K_{rt}^{lab} \left(\theta_{k1,t} + \sum_{k2 \in Z_r} \delta_{k1,k2,t} \right) \quad r \in R, k1 \in Z_r, t = 1,\ldots,T \tag{1.8}$$

$$1 = \sum_{k \in Z_r} \theta_{kt} \quad Z_r \mid r \in R, t = 1,\ldots,T \tag{1.9}$$

$$\theta_{k,t} + \sum_{k1 \in Z} \delta_{k1,k,t} = \theta_{k,t+1} + \sum_{k2 \in Z} \delta_{k,k2,t} \quad k \in Z, t = 1,\ldots,T \tag{1.10}$$

$$v_{k2,t} \ge v_{k1,t} + 1 - |M_r| \left(1 - \delta_{k1,k2,t}\right) \quad k1, k2 \in Z_r, k1 \ne k2, t = 1,\ldots,T \tag{1.11}$$

$$x_{kt}, v_{kt} \in \mathbb{Z}_0^+ \quad k \in Z, t = 1,\ldots,T \tag{1.12}$$

$$y_{it} \ge 0 \quad i \in P, t = 1,\ldots,T \tag{1.13}$$

$$\delta_{k1,k2,t} \in \{0,1\} \quad k1, k2 \in Z, t = 2,\ldots,T \tag{1.14}$$

$$\theta_{kt} \in \{0,1\} \quad k \in Z, t = 2,\ldots,T \tag{1.15}$$

Objective (1.1) is to minimize the sum of the storage costs, the stroke execution costs and those costs associated with sequencing strokes. (1.2) provides the continuity equation of the inventory levels. The inventory level at the end of a period considers the inventory level at the end of the previous period, planned receptions, product demand and the execution of those strokes with associated lead times. (1.3) presents the continuity equation for the first periods given the lead times (in this case, the maximum assumes 3 periods). (1.4) offers a limit for the maximum and minimum inventory levels for each item. (1.5) to (1.6) present the limits of the space resource. These limits imply that the sum of the space consumed by executing strokes *k* (a similar concept to the WIP stock) in each plant, plus the space consumed by the inventory levels of items *i* in the considered plant, cannot exceed a certain limit. (1.7) offers the availability limit of the workforce resource as a result of executing the different strokes in each resource. Equation (1.8) ensures that the execution of stroke *k* in the considered resource occurs only in period *t* if stroke *k* is a setup in the resource at the end of period *t*-1, or a change in the setup state is made in period *t*. Equation (1.9) implies that only one stroke is in the setup at the end of period *t*. Equation (1.10) conserves the setup state (Lang, 2009). Constraint (1.11) enables the creation of a sequence of the strokes for each resource throughout each period thanks to the use of variable $v_{k,t}$. If $v_{k1,t} > v_{k2,t}$, then stroke *k1* will be sequenced after stroke *k2* during period *t*. Equations (1.12) to (1.15) define the domains of the considered variables.

We have solved the SCOLSS-AO problem by employing the Gurobi optimizer 4.5. We tested the performance on a full-size case study problem on 2 different sites with approximately 60 products. We studied alternative operations, working under various space and workforce resource constraints and including transshipments between the 2 sites for different instances. The results showed an average running time of 1 minute per instance with an Intel Core i7 3.22 GHz processor, 24 GB RAM and Windows 7 as OS.

V. Conclusions

The model presented in this paper has been created to plan and schedule the supply chain operations activities in an international company with distributed plants. The novelty of the MILP model is its capacity to schedule alternative operations in a multi-site context, such as transshipments, shipments to customers, product substitution and alternative operations considering lead times. Moreover, in order to model alternatives, a novel approach based on the stroke concept is introduced and applied to the MILP model.

Although it lacks a practical application given the limited extension of a paper, a real application will be presented in an extended paper.

Further research has been identified throughout this work as follows: (i) extending the model by including backorders; (ii) designing specific heuristics for the problem considered herein, and incorporating the central stroke concept for modelling and solving distributed problems; and (iii) incorporating variants such as uncertainty (whether it is stochastic or uses fuzzy methods) is another future research line.

Capítulo 9 A parallelizable heuristic for solving the Generic Materials & Operations Planning in a Supply Chain Network: a case study from the automotive industry

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Abstract. A trend in up-to date developments in multi-site operations planning models is to consider in details the different ways to produce, buy or transport products in a multi-site context and the distributed decision-making process for operations planning. One of the most generic approaches to support global op-timization in those supply chain networks by considering all the different opera-tions alternatives and product structures is the Generic Materials & Operations Planning (GMOP) Problem. This problem can be modelled by a Mixed Integer Linear Programming (MILP) model capable of considering production, trans-portation, procurement tasks and their alternatives and other relevant issues such as packaging. The aim of this paper is to introduce the implementation of a parallelizable heuristic method for materials and operations planning and its ap-plication to a case of a Supply Chain Network (SCN) of the automotive industry with several plants geographically distributed. The approach uses variants of the GMOP model to overcome traditional MRP systems' limitations. The heuristic has been designed in order to allow its easy parallelization.

Keywords: Operations Planning; MRP; Generic Materials & Operations Plan-ning; Mixed Integer Linear Programming, Supply Network, Automotive Industry

I. Introduction

Multi-site operations planning in a Supply Chain Network (SCN) is the process that consists in determining a tentative plan about the operations that must be performed on the available capacitated resources geographically distributed in each time period all along a determined horizon time. The planning of these operations not only determines inventory levels of certain products in given locations, labor levels or the use of productive resources but must also determines which located operations, called strokes (Garcia-Sabater et al., 2013; Maheut y Garcia-Sabater, 2011) must be performed to implement the operations plan.

Generally, SCNs are composed by several facilities located in different sites that must serve a set of end products to different customers (Mula et al., 2012b). Despite belonging to the same SCN or to the same company in some cases, sometimes, the different members themselves do not communicate their exact costs and capacity data (Dudek y Stadtler, 2005). This implies that central planning is impossible and operations planning must be coordinated in a distributed way between the different members of the SCN.

In the literature, lots of mathematical models that simultaneously solve the materials and operations planning problem in a multi-site context are presented and part of them are reviewed in (Garcia-Sabater et al., 2013). The Multi-level Capacitated Lot-Sizing Problem (Kanyalkar y Adil, 2007; Torabi y Hassini, 2009) is the most widely covered, but other authors call it the Supply Chain Operations Planning Problem (de Kok y Fransoo, 2003) or they include other adjectives when defining it; for example, dynamic (Buschkühl et al., 2009). Nevertheless, to the best of our knowledge, GMOP is the only model that simultaneously considers multi-site, multi-level capacitated operations planning problems with lead times, alternative operations (purchasing, transport -replenishment, transshipments and distribution- and production) and returnable packaging. Moreover, the GMOP model that solves in a decentralized way has not yet been studied.

In this paper, a parallelizable heuristic method for operations and materials planning is introduced. Its application in a SN of the automotive industry composed by different facilities geographically distributed is presented. The proposed method is to plan operations in a decentralized manner using agents that take decision based on the results of several MILP model variants to solve the GMOP problem (Garcia-Sabater et al., 2012a; Maheut et al., 2012).

Section 2 introduces the SCN description and the different operations carried out in it. Section 3 describes the proposed system and the proposed heuristic method briefly and partially. Section 4 proposes a description of the implementation process of the planning approach. Finally, Section 5 introduces a conclusion and future research lines.

II. Supply Chain Network Description

The SCN considered in this paper is composed by several plants geographically distributed in Spain. Plants are responsible of processing, treating, assembling and transporting metal parts in different returnable packaging to different customers, mainly car assembly plants of the automotive sector in Europe.

In this case study, global operations planning tasks is a critical process because some of the different SCN members have grown during the last decade and have currently different plants able to perform the same operations or produce the same products in the different locations considering different constraints and costs. Consequently, one of the main concerns of the SCN is to adapt its plans in order to consider all the feasible ways to serve the customers minimizing costs and respecting due dates.

Global operations planning must consider all the operations, tasks that are performed to procure, transform and transport the materials in order to serve a determined end product to the final customer. In the literature, production operations, transport operations and purchasing operations are the most high value added operations considered. Nevertheless, others high value-added operations must be considered like operations considering returnable packaging (Pinto et al., 2007; Scheer, 1994) or alternative operations (Escudero, 1994; Lin et al., 2009) because they can substantially affect total SCN cost if they are considering. This is, to the best of our knowledge, one of the major concerns for practitioners that the literature has not dealt with extensively.

The emergence of alternative operations in this case study is a direct consequence of the different processes that take place in the different plants. Stamping, cutting, chemical treatment, painting, assembling, dismantling, and finally (un)packaging operations are some of the operations performed in the SCN where alternatives can exist. Besides transport between plants is a very important process since it is necessary to consider the return and transshipments of the returnable packaging. This consideration is necessary since customers demand is not only in quantity of products on each due time, but also customers demand requires a specific packaging.

In addition, each plant has its own work schedule and capacitated resources, and these factors are usually unknown to the others. Moreover, each plant does not want to share information about inventory levels and costs.

III. Advanced Planning and Scheduling Module Description

III. 1. The designed procedure for collaborative decision making

The designed system is an Advanced Planning and Scheduling (APS) system. The SCN planning module consists of different types of agents: one warehouse agent, some plant agents and some supplier agents (Fig. 9-1). Agents do not have any artificial intelligence but are able to communicate and make decisions based on specific criteria established preliminarily.

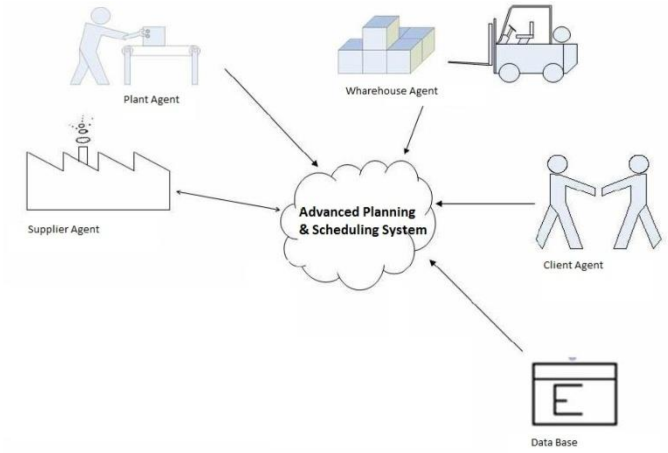

Fig. 9-1 General scheme of the APS System

The warehouse agent knows at all times the inventory levels of products in all the SCN. This agent is the central coordinator and is responsible for transporting finished products between different plants and to the final customers.

The operations planning process starts when a new customers' demand forecast is received (extracted for the MRPs of the different SCN members). First, it is asked to the warehouse agent if the customer-requested product is available in stock in one of the various SCN plants.

If there is sufficient material in at least one of the site, the agent plans how to transport the material to the customer based on specific criteria (cost, due date, run out time in each plant, etc). The decision is made based on the result of a MILP model that considers transport stroke and some constraints about working calendars and truck fleet. Otherwise, the warehouse agent has to act as coordinator and must achieve to get all the material respecting the due date.

To do so, the warehouse agent generates an ordered list of the needed materials. This ordered list is a "bag of material" where there is a quantity of material per request and its due date. For the first product of the list, the warehouse agent asks the different plant agents capable of producing this product. Plant agents can be a plant, a set of resources or even a single specific resource and they are responsible for its assigned internal operations.

Each plant agent then executes its MILP model to determine how much and when can be available the amount of products ordered. Each proposal is offered to the warehouse agent. The latter chooses the option with lower costs.

If the chosen agent plant needed raw material to produce the product, it transmits the information to warehouse agent and this product enters in the tail of the sorted list of material to order.

The agents, before ordering raw material to manufacture an ordered product, will require the product to the warehouse and, if there is not enough, the plant agent of the product will ask the supplier agents the raw material and the possible due dates according to the capacity already assigned.

When the bag is empty, the warehouse agent transfers to different SCN members and the suppliers a personalized plan with the operations to be performed with its corresponding due date.

Currently the model does not include a specific transport agent but it is planned for future expansion of the system to take it into account, including more specific constraints.

The operations plan will be used by the different SCN members to create detailed production plans (due dates, delivery dates and lot size), which will be the starting point for sequencing and temporalize. A screen of the tool designed is introduced in Fig. 9-2.

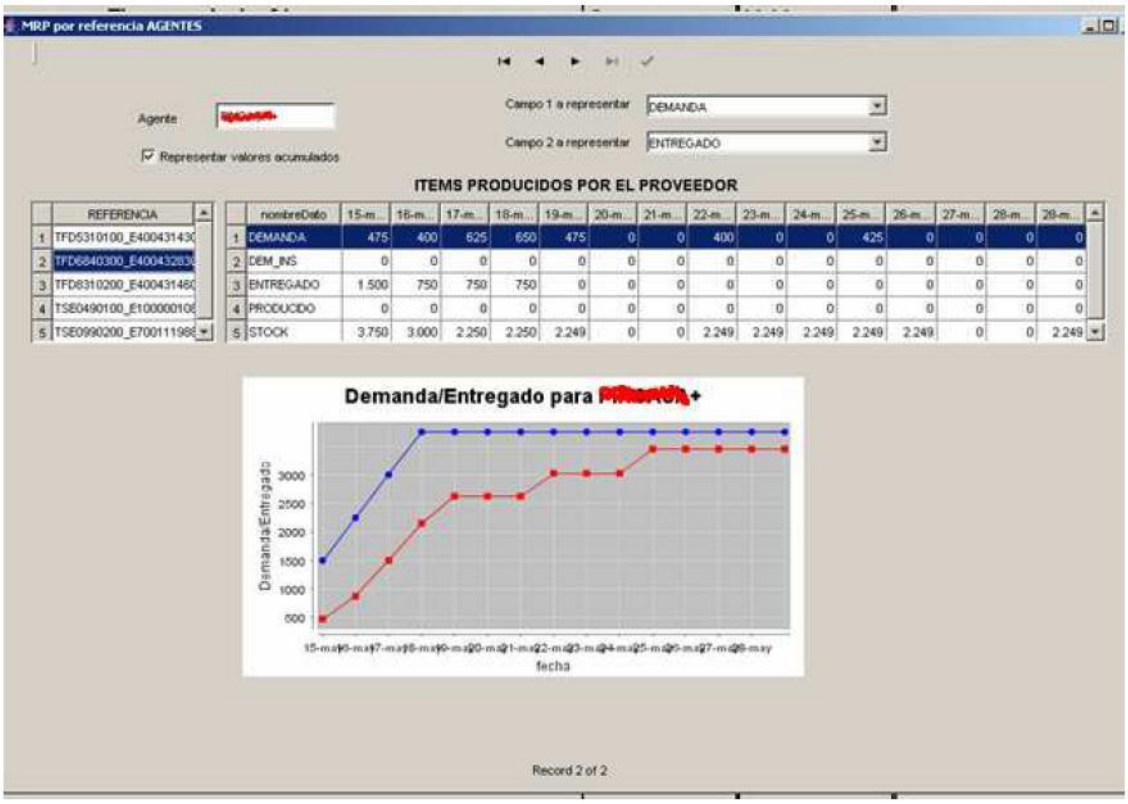

Fig. 9-2 Some results of the planning tool

III. 2. The MILP Model

The MILP models used for each SCN agent are variants that solve the GMOP problem including backlogs. Each time the warehouse agent requests a product, the associated MILP model is executed to check if it has sufficient capacity for the production of goods (in the requested quantity). Each resource has a limited available capacity, so the agent could not have in certain case the sufficient capacity to serve the order.

In the case the agent do not have enough capacity, the timing or a new amount of product to be serve on time will be determined. The mathematical models are encapsulated in each agent and they are run whenever the agent is solicited.

Procurement strokes are only considered with supplier agent because different alternative procurement operations exist. Because of length constraint, the complete model will not be introduced herein. One generic variant is described in (Maheut *et al.*, 2011).

IV. Advanced Planning and Scheduling Module Implementation

IV. 1. Implementation approach

Before tool implementation, the company had its own Enterprise System (ES) which managed an MRP System. In practice, MRPs results were limited to advance the major components production and to merely attempt to maintain one day of demand in stock for each one.

The biggest problem the company faced was that the number of late deliveries had grown in recent years. The reason for this was that the group had grown considerably and had to face and consider an increasing number of end products and production stages. Besides production processes had become more complex with more loading units types, with different facilities to take into account, and with resources, materials and packaging alternatives to be considered.

The existing ES was used to support a certain type of transactions. Plant managers claimed they had sufficient information, and their only complaint was that they did not have sufficient resources (in inventory and machines) to deal with sudden changes in demand.

During implementation, the structure of the existing information system did not change. XML files were created from the existing database (which was supported by conventional BOM files and Routing Files) and were sent to feed the proposed APS system.

During the tool implementation process, the data quality in the ERP systems improved substantially because the facilitator of the new APS (which was in charge of the IT systems) placed pressure on managers to maintain it without our intervention.

After each APS execution, users received the operations plans in Excel spreadsheet files based on an XML format which were designed to suit their requirements.

IV. 2. Implementation Organizational Aspects

Probably one of the major pitfalls in the tool implementation process was that no organizational change occurred. Given the leadership characteristics of the facilitator of IT, we decided to replace the information flow given to users without informing them about the new APS tool.

Thus, tool implementation was transparent to most users who never perceived that they were actually making major changes. The only noted change was that users observed that the data were of a much better quality and that minor changes could be applied to spreadsheet files as they received them. It can be stated that the tool was well-accepted since it was not known to exist as such.

IV. 3. Results in practice

The implementation process comprised two phases. In the first phase (before Christmas), the head of information systems checked the quality of the results. As he was highly committed to data quality, the data improved substantially. This led to a 33% reduction in delay levels, but also to a 50% increase in stock levels. In the second phase (after Christmas), users began to run operations plans. At that time, delays disappeared completely and only delays due to client requests after deadlines were the source of delays.

Arguably, this reduction was due not only to the use of GMOP models, but also to the MRP system which, until then, had never executed good data quality. However, the use of GMOP models also allows stakeholders to handle packaging flows and alternative operations by generating feasible operations plans and by cutting delays each time without having to consider more machinery resources.

After several years of implementation, the operations planning tool is still executed daily in the company until the present-day. The group's Logistics Manager soon changed after the introduction of the new APS, and the IT facilitator was removed some months afterward. However, the system continues to work, although the company owners now seek a more general (off-the-shelf and state-of-the-art) commercial ERP system. The main problem they now face is to find one that meets their expectations (that considers alternative operations and returnable packaging).

V. Conclusions

The proposed system has been successfully implemented in a real SCN. Experiments have been realized to evaluate the different alternatives, taking into account not only the validity of the results in terms of quality but also into account the computation times. The results obtained are practical in the proposed implementation and also revealed to be interesting because it appeared some light features of the system that were not foreseen. The problem has more than 600 end products (considering different types of packaging) and more than 15 agents.

A future research line would be to identify other strategies for ordering products in the bag and evaluate the best strategy in terms of total SCN costs against a centralized MILP model. Another future research line would be to introduce fuzziness in some parameter in case of demand or available capacity data uncertainty.

Capítulo 10 Coordination mechanism for MILP models to plan Operations within an Advanced Planning and Scheduling system in a motor company: A case study

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Fecha	In press

Abstract. The aim of this paper is to present a coordination mechanism between MILP models for planning operations within an integrated planning tool. The mechanism presented allows co-ordinate planning models between different do-mains (procurement, production, transportation), the different planning horizons (mid-term, short-term and very short-term) and between the different planning periods. This mechanism has been design to ensure coordination and integrity be-tween the different plans while meeting the expectations of the different stake-holders involved in the planning process of an automotive plant. The proposed mechanism was implemented in an Advanced Planning & Scheduling system for an engine assembly company.

Keywords. MILP, Coordination Mechanism, Advanced Planning & Scheduling, Satisfaction, Case Study

I. Introduction

Supply Chain Management is defined in (Stadtler y Kilger, 2002) as the task of integrating organizational units through the supply chain (SC) and of coordinating the flow of material, information and financing for the purpose of fulfilling the client's demands. Coordinating the SC is, in turn, based on: using information and technology to improve the flow of information and materials; process orientation in order to accelerate the execution of processes and associated activities; and Advanced Planning (Stadtler y Kilger, 2005). Advanced Planning of the SC addresses decisions regarding SC design, its mid-term coordination and the short-term planning of processes. Advanced Planning systems attempt to fulfill the aforementioned objectives by using specific software (Fleischmann *et al.*, 2005).

Many managers tend to think that Enterprise Requirement Planning (ERP) systems will solve their planning issues. Yet despite its name, ERP systems are usually transaction-based systems rather than planning systems (Chen, 2001).

The broad extension of ERP systems has brought about the emergence of the so-called Advanced Planning & Scheduling Systems (APS) which may be viewed as “add-ons” of the ERP system to plan and optimize the SC (Rashid et al., 2002).

The appeal of APS to manufacturers is obvious: companies can optimize their SCs to cut costs, improve product margins, lower inventories and increase manufacturing throughput (Lee et al., 2002). APS extract data from the ERP systems, and support decision making. Once the decision has been made, it is sent back to the ERP system for its final execution. For this support, APS use optimization techniques to model and determine the quantities to be produced, stored, transported, and procured by respecting real constraints of the SC (Günther y Meyr, 2009). APS might help with the management of the whole SC, specifically its operations (Parush et al., 2007).

There are many commercially available software programs with well-differentiated characteristics (David et al., 2006). The various software modules cover all the segments of the operations planning throughout the SC, in all the planning horizons. However, the use of advanced planning tools in the automotive industry is minimal.

Many Lean companies now use ERP/MRP methods to communicate demand through SC, and hybrid situations have become common in the automotive industry (Riezebos et al., 2009). Indeed, the need to coordinate capacitated transport and production together with low stock levels, and its relation with lean systems, is probably no small concern. MRP does not offer planning tasks in this sense (Drexl et al., 1994); instead, it supports planning, but only to a limited extent (Chung y Snyder, 2000).

In (Garcia-Sabater et al., 2012a), the APS that solves the operations planning using integrated models to solve at each time level is presented. However, because of the constantly increasing complexity of operations (number of derivatives to be produced, number of customers and/or suppliers to be served, new restrictions, etc..), these integrated models become terribly difficult to resolve in adequate resolution time. For this reason, during the implementation of the tool, small models were generated for each domain and each horizon. This explosion is the creation of coordination mechanisms for the models to find an optimum result close to the integrated model result. And that is the purpose of this paper, to present the coordination mechanism that was implemented. The mechanism has not only allows coordination at two levels (horizons and domains) but also integrates the temporal aspect of the previous planning to deliver results expected by users.

Section 2 introduces a brief problem description. Section 3 proposes the coordination mechanism. And finally, Section 4 proposes a conclusion.

II. Problem definition

An overview of the planning needs in this case study is presented. The framework presented by Meyr et al. (2005), as seen in Fig. 10-1, was used to cover the main system areas.

In the company, mid-term corresponds to the mid-term planning horizon with bucket periods of weeks, while short-term planning corresponds to a short-term planning horizon with daily buckets. Lastly, the daily scheduling tasks are solved with a 2-day horizon with variable buckets.

The structure of this section goes through the different planning levels, and covers domains such as the Supply Chain Planning matrix modules. The particular characteristics of the different APS modules implemented are highlighted.

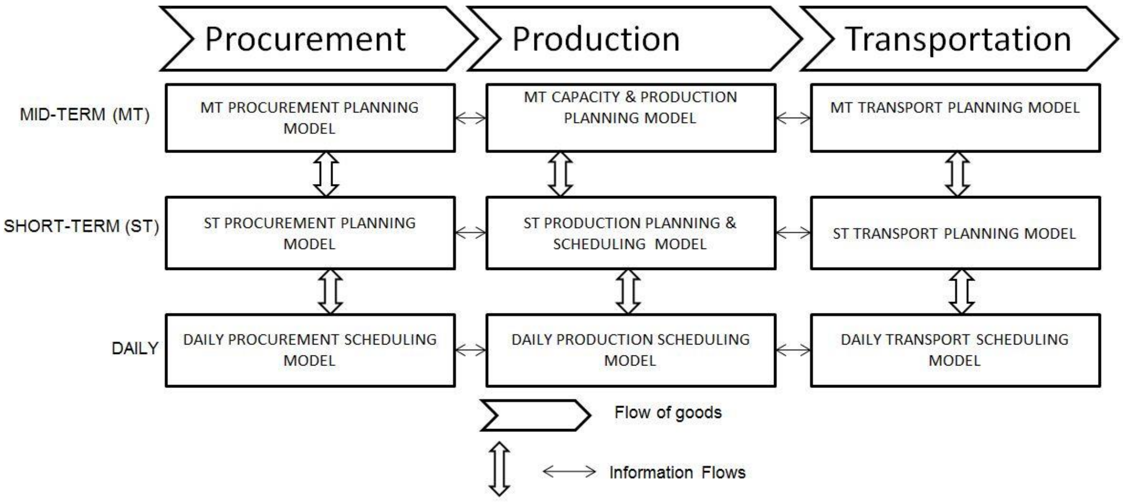

Fig. 10-1 Coverage of the mathematic models implemented in the APS in this case study

II. 1. The Mid-Term Planning

Mid-term planning (MTP) is usually divided into two main modules: Master Planning and Demand Planning. Demand Planning has been not treated in this case study since it was defined by the other firm's levels. The MTP synchronize the whole network flow of materials on a mid-term basis and interact with the 4-week operations planning.

In our work, the MTP is solved with three MILP models. To better understand the planning tasks, objectives, constraints and decisions to be taken at this level, a summary is proposed in Table 1.1. This table describes it by separating the functional areas of procurement, production and distribution that are considered in the same model.

The MTP process is in four models:

- MT transportation planning model that aggregated transportation plans for all the products.
- MT capacity production model that determines production rates and the working calendars for all five production lines and the assembly line.
- MT production plans that determines production levels and set stock levels at the end of each week for each line.

MT material requirements model for short-distance suppliers and a MT detailed material procurement model for long-distance suppliers.

Tabla 10-1 MTP Characteristics

	MT Procurement Planning Model	*MT Production Planning Model*	*MT Capacity Production Planning Model*	*MT Transportation Planning Model*
Tasks	*Raw material requirement planning for short-distance suppliers* *Ordering raw material for long-distance suppliers*	*MT production planning*	*MT capacity production planning*	*Component Transport Planning (FTL)*
Objectives	*Minimize raw material stock levels*	*Minimize storage costs* *Maximize the stability of the plans*	*Minimize total operating costs (minimization of productive days and extra days production)*	*Maximize component delivery fulfillment*
Constraints	*Working calendars* *Lead time of long-distance suppliers* *Raw material in transit*	*Working calendars* *Production rates* *Safety stocks levels* *Storage capacity limits* *Availability of raw materials and components*	*Previous Working calendars* *Previous Production rates*	*Working Calendars* *FTL Strategy* *Forecast Demand Fulfillment*
Decisions	*MT material requirements plan for short-distance suppliers* *MT detailed material procurement plan for long-distance suppliers*	*MT production plans for each line*	*MT capacity production plans (new working calendars; adjustments in production rates capacity)*	*MT Transport plan*

II. 2. Short-Term Planning (STP)

The STP process must satisfy the requirements of the logistics department, but must also take into account the constraints that the production department defines. Both these departments have contradictory objectives and different constraints, and the trade-off that usually occurs in real meetings has to be considered with the implemented model.

Using the same approach as for the MTP, Tabla 10-2 summarizes the case of the STP and some of the characteristics considered.

In this case study, the STP process is performed by three main models.

- ST transport model aimed at optimizing products and component shipping costs.
- ST production and schedule model aimed at ensuring stability, leveling and cutting setup costs and inventory costs.
- ST material requirements model aimed at scheduling production quantities to short-distance suppliers, and at ordering shipping quantities to long-distance suppliers.

In each case, the objective is to minimize total costs.

Tabla 10-2 STP Characteristics

	ST Procurement Planning Model	ST Production Planning Model	ST Distribution Planning Model
Tasks	Ordering materials for short-distance suppliers Material requirements planning	Engine production planning Detailed Component production plans	Engine transport planning Component transport planning
Objectives	Minimize raw material stock levels	Maximize production leveling Minimize inventory faults Minimize set-ups costs	Maximize engine delivery fulfillment Minimize backlog costs
Constraints	Working calendars FTL strategy Truck and rack capacity	Safety stock level constraints Maximum stock level limits Max/Min number of derivate products manufactured Daily production capacity Availability of raw materials and components	Working calendars FTL Strategy Truck and rack capacity Demand fulfillment
Decisions	ST material requirements plan	ST engine production plan ST detailed component production plans	ST transport plan

III. The coordination mechanism

In the APS, each model cannot be executed in a separate way. The first step is the MTP. Then the STP is performed and then the SSTP. In order to maintain consistent results, the different plans should be related with the other results/plans in three dimensions (hierarchy, domain and temporal). Fig. 10-2 represents the relations among planning models. The notation is the same like in (Garcia-Sabater et al. 2012). Variables from other plans (from both previous executions and previous stages) are converted into parameters in subsequent models.

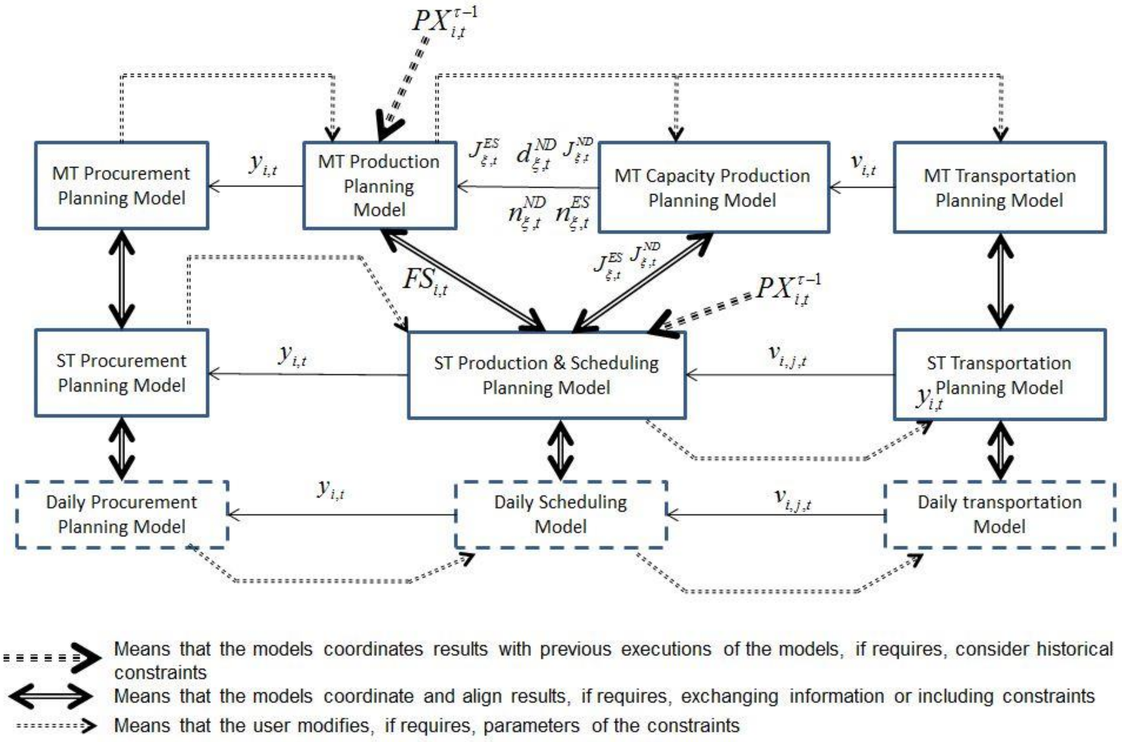

Fig. 10-2 Coordination mechanism between planning models

III. 1. Hierarchical coordination

The integration of the different hierarchical models (downward and upward coordination) has been done using constraints and objective parameters that limit the “autonomy” of each decision level and ensure an integration and cohesion between plans.

Downward coordination MTP and STP is done for production plans with the so-called Intended Stock $FS_{i,t}$. It helps coordinate MTP with STP since it was (together with limited capacity) the relation that states what is to be produced by looking at the future beyond the first 4 weeks.

Upward coordination is considered in some cases. For example, the stakeholders can manually include new constraints in the mid-term models, such as limiting the number of derivatives or limiting raw material availability in specific periods, if necessary however those constraints are typically for the STP models.

III. 2. Domain coordination

The coordination mechanism (business functions integration) between the different domain models in each planning horizon has been done using parameters and the possibility to incorporate constraints. It allows business functions to relate to each other.

In our case study, the approach consists in giving valuable information to align plans. For example, between transport models and productions models, the coordination mechanism consist in the downstream exchange of information (e.g. accumulated shipping quantities, accumulated production quantities).

Upstream coordination consists in the integration of restrictions about accumulated quantities when plans are infeasible. Another concern is about some raw materials that arrive from (long distance) suppliers. In some cases, upstream coordination consists in establishing a frozen period. So some changes are not allowed.

This coordination is a major concern since objectives between domains can be conflictive and some constraints are, in some cases, not compatible. Besides, it is far more difficult to solve models with more restrictions because the number of integers and binary variables can be quite high.

III. 3. Temporal coordination

A temporal coordination mechanism had to be design because some of the KPIs used by the company deal with the leveling of the production levels of each derivates and the plans' stability (Build to Schedule).

For instance, in the capacity production plan in the MTP, it exists a limit about the maximum number of production rate ($\mathrm{K}_{\xi,\mathrm{t}}$) changes and working calendars parameters changes during a whole year.

Moreover, production models need to relate to the previous decisions. This integration is considered with the parameter $PX_{i,t}^{\tau-1}$ that represents previous production quantities for each product. This data has been specifically considered into the APS. This temporal mechanism ensures a control of the stability of the plans which is commonly control with the KPIs like the Build To Schedule. Stability is not only a matter of planning stable plans; indeed, today's plan has to be similar to the plans of previous days. This concept is basic in the automotive sector and, in fact, there are specific performance measurements that are used only to evaluate stability. This is mainly justified by the fact that the SC cannot, or finds it difficult to, respond to major changes in production levels (Hüttmeir et al. 2009).

IV. Conclusion

As a general conclusion of this research work, a new coordination mechanism considering three dimensions (hierarchy, domain and temporal) is proposed in this paper. The mechanism allows the stakeholders of different business functions to generate plans that are used each day. The mechanism proposed has been successfully implemented in an Advanced Planning & Scheduling system for a motor company.

Further research has been identified throughout this work, as follows: (i) Providing users the ability to know which data (demand, stocks, production rates, etc.) is inaccurate would be the next good step to take; (ii) designing a more data-resilient model and a resolution procedure are to be built (iii) incorporating uncertainty in data (it may be stochastic or uses fuzzy methods) is another future research line.

Capítulo 11 Conclusiones

I. Introducción

En este último capítulo de la tesis se recogen las conclusiones alcanzadas tras la realización del trabajo. Para ello se considera adecuado resumir por objetivos cada una de las conclusiones extraídas. A lo largo de las tareas de investigación que se han realizado, se han tenido que ir tomando decisiones, dejando muchas líneas de investigación para futuros trabajos. Así, se pretende finalizar esta tesis doctoral presentando las más interesantes.

II. Resultados

Los principales resultados alcanzados en la presente tesis doctoral se sintetizan en los siguientes puntos:

- Revisión de la literatura científica y la detección de los huecos de investigación existentes entre las necesidades empresariales y la literatura científica, en cuanto a los modelos de datos para considerar de una forma unificada la mayor parte de los tipos de operaciones y materiales así que sus alternativas.
- Estudio de las necesidades de las empresas de diferentes industrias, proporcionando conocimientos empíricos sobre algunas características criticas de la planificación de las operaciones en entornos multi-planta.
- Despliegue y el análisis de las matrices asociadas al modelo de datos propuesto basado en el concepto stroke para su uso en modelo de programación matemática.
- Propuesta de diferentes variantes de modelos de programación matemática para resolver el problema genérico de planificación y de programación de las operaciones considerando Listas de Materiales alternativas, co-productos, by-productos y embalajes así como operaciones alternativas de transporte en un entorno multi-planta.
- Desarrollo e implantación de mecanismos de coordinación para coordinar modelos de programación matemática en diferentes niveles de planificación así como en diferentes dominios de planificación.
- Desarrollo de un algoritmo para resolver el problema de programación de las operaciones con sus alternativas y de configuración de red de suministro basándose en el modelo de datos basado en el concepto stroke.
- Reflexión sobre los requisitos e implicaciones a la hora de implementar herramientas basadas en este modelo de datos basado.

Por otra parte, los resultados científicos se pueden valorar en función de la participación activa del doctorando en proyectos de investigación relacionado así como en los trabajos generados a los largo de esta tesis doctoral:

- 4 trabajos publicados: 1 artículo en revista indexada JCR (*Flexible Services and Manufacturing Journal*), de 2 artículos en revistas indexadas SJR (*Dirección Y Organización; IFIP Advances in Communication and Technology Journal*) y de 1 capítulo de libro en el editorial *Springer*.

- 4 trabajos en proceso de publicación: 1 artículo en revista indexada JCR (*European Journal of Industrial Engineering*), 1 artículo en revista indexada SJR (*Journal of Industrial Engineering and Management*) y 2 capítulos de libro en el editorial *Springer*.
- 2 trabajos en revisión: 1 artículo en segunda revisión para una revista indexada JCR (*Production Planning & Control*) y 1 artículo en segunda revisión para una revista indexada SJR (*IFIP Advances in Communication and Technology Journal*).

Otro resultado interesante de esta tesis doctoral es que algunos de los resultados presentados anteriormente han permitido resolver problemas reales, como por ejemplo:

- El uso en la planta de Ford Motor Company en Almusafes (Valencia) de la herramienta que se presenta en el 0.
- El uso para la multinacional vasca SORALUCE que ensambla maquinas herramientas de la herramienta de apoyo a la decisión que se presenta en el Capítulo 5.
- El uso en el grupo F Segura de la herramienta integrada introducida en el Capítulo 9.

III. Futuras líneas de investigación

Las principales líneas de investigación futura se centran en:

- Estado del arte sobre todas las técnicas de optimización utilizada para el diseño, la configuración o reconfiguración de redes de suministro.
- Diseño de modelos descentralizados y distribuidos para la planificación de las operaciones en sistemas multi-sitio.
- Desarrollo de procedimientos y modelos que tengan en cuenta la incertidumbre de datos básicos en la planificación de operaciones.
- Desarrollo de modelos que pretendan la estabilidad, y midan sus efectos, en la planificación de operaciones.
- Desarrollo de procedimientos heurísticos usando el concepto del stroke en el caso particular de las líneas de ensamblaje y desensamblaje.
- Estudio de los sistemas de bases de datos actuales que se usan en los ERP y los APS y la propuesta de una nueva arquitectura así como los algoritmos de transformación necesarios para que sean capaces de usar el concepto stroke.
- Desarrollo de modelos de simulación que representen con el máximo nivel de detalle razonable situaciones reales en las que se exija una coordinación de las operaciones de una red de suministro.
- Realización de los experimentos y análisis de los datos obtenidos en las simulaciones en Anylogic para al menos dos tipologías de empresas (fabricación de bienes de consumo y fabricación de bienes de equipo)
- Desarrollo de algoritmos y modelos de programación matemática para la planificación de las operaciones de redes de suministro resilientes.
- Desarrollo de algoritmos y modelos de distribuidos para la planificación de las operaciones de redes de suministro resilientes.

- Diseño y la implantación de un Sistema de Apoyo a la Decisión (*Decision Support System*, DSS) para la simulación y optimización de una red de suministro del sector de bienes de equipo.
- Diseño y posible implementación de una herramienta distribuida para la optimización de las operaciones en una red de fabricación del sector automovilístico.
- Incorporación de variantes como la incertidumbre (que sea estocástica o usando métodos borrosos (*fuzzy*) en el caso de datos de demanda o de la capacidad productiva disponible.

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