Trabajo de Fin de Grado
Grado en Ingeniería en Tecnologías Industriales

Framework for spare parts management. Methods to improve decision making.

(Marco de referencia para la gestión de repuestos. Métodos para la mejora del proceso de toma de decisiones)

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Dep. Organización Industrial y Gestión de Empresas I
Escuela Técnica Superior de Ingeniería

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

Sevilla, 2017

El Secretario del Tribunal

A mi familia

A mis profesores

Index

Resumen

Motivación y Objetivo del Trabajo

Este trabajo surge en un marco de colaboración con la Universidad de Brescia, mediante el intercambio de información con uno de sus alumnos y el seguimiento en paralelo de los departamentos homólogos correspondientes. Este intercambio se facilita tanto por el uso del inglés para la realización del trabajo, como por los conocimientos de italiano adquiridos en el Politécnico de Milán durante una estancia anual donde el tema de investigación presentado aparece de forma recurrente.

En el sector industrial, especialmente en aquellas empresas con activos que requieren grandes inversiones y alto grado de especialización, nos encontramos con el problema de la gestión de repuestos, cuya gestión tiene un notable impacto en el desempeño final de la organización.

Cualquier fallo en la maquinaria conlleva un paro en la producción principal, y este parón depende del tiempo de diagnóstico, reparación o cambio de pieza. Siendo piezas de alta especialización esto puede implicar fabricar el repuesto desde cero con sus implicaciones: Caída del nivel de servicio, menores tasas de producción, roturas de stock, pérdidas... Se podría pensar que la solución es mantener un nivel de stock de piezas de repuesto de manera que se reduzcan estos Lead Time, pero se debe tener en cuenta que mantener un stock de piezas de repuestos con riesgo de obsolescencia alto, costes de mantenimiento de inventario elevado y de alguna manera "secundarios" para la producción, puede significar unos costes excesivos.

La clave está en buscar el balance que permita minimizar los costes conjuntos y encuentre el modo de proceder óptimo.

En la literatura se estudia el problema de gestión de repuestos, pero se hace de manera demasiado focalizada, estudiando y actuando sobre cada pequeño proceso decisional en vez de tratar de atacar el todo.

Este ha sido el objetivo de este trabajo, ofrecer una metodología completa, que englobe todos los procesos de gestión, que aporte herramientas y modelos, que encontrando su justificación en la literatura, proporcionen un respaldo y un soporte objetivo a los protocolos de acción a la hora de la toma de decisiones.

Trabajando con repuestos

Al trabajar con repuestos, y no con productos destinados al cliente, se parte de varias diferencias y suposiciones clave a la hora de trabajar:

La demanda no la impone el cliente, sino las políticas de mantenimiento de la empresa.

Para lograr la funcionalidad de una máquina, se puede escoger entre dos opciones cuando una determinada pieza se rompe, cambiarla o repararla, esta decisión no es trivial y cambiará la forma de trabajar, entre otras cosas la cantidad de piezas iguales para simplificar los problemas de mantenimiento.

En general, información sobre la fiabilidad no está disponible en el grado de detalle necesario especialmente al tratarse de equipos nuevos. Se puede monitorizar las máquinas pero esto conlleva unos recursos dedicados, las relaciones entre fallos suelen ser desconocidas.

Si algún equipo vital es caro se tiende a mantener sus componentes en stock en vez de equipos completos y se prefiere la reparación a la sustitución cuando sea posible.

Conceptos clave en este trabajo

SKU: Stock Keeping Unit. Son aquellas piezas que se mantienen en el inventario, se las identifica mediante un código que ayuda a su seguimiento.

LRU: Line replaceable unit. Aquellos componentes listos para su recambiando in situ, en la línea de producción, lo que disminuye los Lead Time de reparación.

SRU: Shop-repleceable unit. Similares a las anteriores pero en vez de tratarse de recambios completos son partes de un mayor LRU.

MRO: Todas las operaciones asociadas al mantenimiento y reparación, desde diagnóstico hasta las tareas administrativas asociadas.

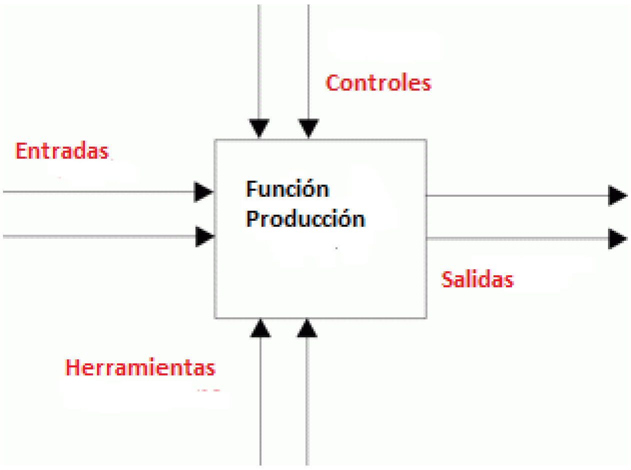
Mantenimiento Correctivo: Operaciones de mantenimiento que se realizan después de que se produzca un fallo.

Mantenimiento preventivo: Operaciones de mantenimiento que se producen para mantener la máquina en una determinada condición sin necesidad de que se produzca un fallo.

¿Cómo se realizará la metodología?

Para la creación de la metodología se ha optado por un lenguaje intuitivo, claro y visual, que permite al usuario la comprensión del proceso con varios niveles de detalle. El lenguaje escogido es IDEF 0 (Integrated Definition for Function Modeling).

Permite la representación multinivel del proceso. En este caso se ha escogido desarrollar los niveles IDEF 0, IDEF 1 e IDEF 2. Representa cada función, con sus entradas y salidas, de manera que las conexiones quedan claras; además, añade los mecanismos y herramientas necesarios (entrando desde abajo); así como las restricciones y controles (entrando desde arriba) como observamos en la siguiente imagen.



En el nivel IDEF 0 se presenta la metodología global dentro de una sola caja, con el máximo nivel de agregación. En IDEF 1 se descompone en los cuatro procesos principales y sus conexiones, y por último cada uno de los procesos se subdivide en IDEF 2, mayor nivel de detalle y menor nivel de agregación.

<u>Selección de los cuatro procesos principales</u>

De la literatura podemos extraer cuatro grandes pasos, o problemas a abordar a la hora de lidiar con la Gestión de repuestos.

1. **Gestión de la gama de piezas de repuesto (Assortment Management)**. Gestión de la variedad de productos. ¿Qué piezas se tienen? ¿Cuáles deben estar registradas, clasificadas y seguidas? Mediante información de los proveedores, el uso de herramientas de gestión informatizada, da lugar a las partes clasificadas y priorizadas dentro de una base de datos.
2. **Previsión de la Demanda (Demand Forecasting)**. Previsión de la demanda de piezas de repuesto. ¿cuántas piezas se van a necesitar? ¿Cómo es la demanda de cada una de las piezas anteriores? ¿En cuáles se deben invertir recursos para mayor precisión de pronóstico? Por medio de la información en las bases de datos, la planificación de operaciones y unas restricciones, este proceso proporciona la tendencia de la demanda futura de las piezas deseadas.
3. **Gestión de Suministros (Supply Management)**. Gestión de los proveedores. Se plantean las distintas posibilidades para el abastecimiento, se establece la política deseada y os contratos necesarios para garantizar el suministro de las piezas vitales, ya sea por medio de la reparación o compra.

4. **Control de Inventario (Inventory Control)**. El problema más estudiado en la literatura de gestión de repuestos, establecer el nivel de Stock de cada pieza de manera que se minimicen los costes garantizando un determinado nivel de servicio.

En su estudio Driessen et Al. [23] proponen un 5º, la previsión del flujo de piezas del taller de reparación (Parts Return Forecasting), se ha considerado que este paso no está al nivel de los anteriores, y se ha incluido como parte de la Previsión de la Demanda, ya que al final está tasa de retorno, influirá ya que es otra posibilidad a la hora de satisfacer la demanda de repuestos.

Conceptos teóricos necesarios y ejemplos en la literatura

Gestión de la variedad de piezas de repuesto:

Para la gestión de este primer paso es necesario introducir unos conceptos y métodos que permitan la comprensión de los casos prácticos y las herramientas de las que se habla.

CMMS: Gestión de mantenimiento asistida por ordenador, se trata de una base de datos en la que se introducen los detalles de mantenimiento de las distintas piezas. Integra toda la información de manera que permite el seguimiento y la unificación de la información.

ERP: Sistema de planificación de recursos empresariales, integran todos los aspectos empresariales en una única solución global, de manera ideal. Viene de la integración de MRP (Material Resource Planning), CIM (Computer Integrated Manufacturing) y CRM (Customer Relationship Management). Integra producción, logística y ventas mediante flujos de información.

Herramientas para la clasificación de las partes:

Para clasificar los repuestos de manera que sea posible decidir cuales se incluyen en la base de datos y como se les caracteriza, existen varios métodos tanto cuantitativos como cualitativos.

ABC: Se basa en el principio de Pareto, que establece que el 80% de los efectos lo provocan el 20% de las causas. Clasifica las partes en tres grupos dependiendo de la tasa del coste anual total que supuso la pieza.

FSN: Clasifica las partes dependiendo de la frecuencia con la que se requieran a partir de un ratio, se dividen en Fast, Slow o Not Moving.

Otros ejemplos serían **AHP, ANN**, todos desarrollados en el trabajo.

Los anteriores son ejemplos de métodos cuantitativos a continuación uno cualitativo.

VED: Divide las piezas en Vitales, Esenciales, y Deseables, se basa en la importancia de la falta de una determinada pieza.

Ejemplos en la literatura analizados:

Autor(es)	Año	Compañia	Metodología				
			ABC	NN	VED	FSN	Otros
Patrovi and Anandarajan [49]	2002	Farmaceútica	X	X			
M. Braglia et al. [13]	2004	Tissue production and converting	X				AHP
Syntetos et al. [62]	2009	Productos Electrónicos	X				
Bacchetti et al. [6]	2010	Electrodomésticos					Hierarchical multi-criteria
P. Joui et al. [37]	2011	Simulación					Multi-criteria
Molenaers et al. [41]	2012	Petroquímica			X		Multi-criteria
Vaisakh P. S. et al. [64]	2013	Química			X	X	
J. Chen & T.Chen [19]	2016	Simulación	X				Multi-criteria

Previsión de la demanda:

Dos conceptos previos, que serán información necesaria para el pronóstico de la demanda son:

- **MTBF** (Mean Time Between Failures): Tiempo medio entre fallos. Es una medida de fiabilidad, proporciona el tiempo medio entre dos fallos consecutivos. Si es conocido aporta información sobre cuantas piezas de repuesto se necesitarán en un periodo concreto de tiempo.
- **MTTR** (Mean Time to Repair): Tiempo medio de reparación. Medida básica en mantenimiento, representa el tiempo medio asociado a la reparación de un componente.

Incluye detección de avería, identificación del problema y reparación. A mayor MTTR, mayor se vuelve la necesidad de disponer de la pieza en stock, sino el parón en producción será significativo.

Toda estimación de la demanda futura, se basa en la información histórica en la base de datos, si se ha implementado un sistema como CMMS o ERP en la empresa, esa información estará integrada como parte del sistema. Después la extrapolación se realizará por medio de herramientas estadísticas.

Para evaluar la caracterización de la demanda se evalúan dos parámetros:

- **ADI** (Average inter-demand interval): El tiempo medio entre la demanda de dos piezas de repuesto.
- **CV** (Coefficient of Variation): La desviación estándar de la demanda dividida entre la demanda media.

Para la predicción de la demanda existen numerosos métodos empleados en diversas situaciones, por ejemplo las Medias Móviles, Ajuste Exponencial, Método de Croston, el método de Syntetos y Boylan o el 2S (Two step forecast). Todos explicados en el trabajo, su aplicación depende de cada caso, a continuación se mostrarán algunos ejemplos de la literatura.

Para comparar el resultado entre los métodos anteriormente mencionados existen varios medidores del error como:

- **MAPE**: Error absoluto percentual medio.
- **RMSD**: Desviación cuadrática media.
- **MSE**: Error cuadrático medio
- **A-MAPE**: Uno de los más usados, ajuste del cásico MAPE.
- **PB**: Compara dos métodos y devuelve el porcentaje de tiempo en el que uno es major que otro.

Ejemplos en la literatura

Se han encontrado los siguientes casos representados en la tabla adjunta, en la que se muestran los métodos empleados para el pronóstico de la demanda:

Autores	Año	Compañia	Metodología												
			CR	**SES**	**NNA**	**BPN**	**SBA**	**SY**	**TSB**	**ZF**	**NF**	**2S**	**ES**	**MA**	**GM**
T. R. Willemain et al. [69]	1994	Equipos Eléctricos Motores Salud Veterinaria Alimentos	**X**	**X**											
M. R. Amin-Naseri & B. R. Tabar [44]	2008	Petroquímica	**X**		**X**		**X**								
F.L.Chen et al. [19]	2009	Semi conductor				**X**								**X**	**X**
W. Romeijnders et al. [54]	2012	Componentes aeronáuticos					**X**		**X**	**X**	**X**	**X**	**X**	**X**	
ºM. Z. Babai et al. [5]	2014	Aeronaves & Automoción	**X**	**X**			**X**	**X**	**X**			**X**			

Gestión de Suministros:

Conceptos teóricos:

Cuando se trata del control de aprovisionamiento, se pueden considerar varias fuentes posibles: Reparación interna, reparación externa, uno o varios proveedores externos. La primera decisión a la que se enfrenta el usuario es la de reparar o no una pieza, la herramienta usada para este discernimiento es:

LORA (Level of Repair Analysis): Determina para cada componente si debería ser descartado o reparado y dónde, tratando siempre de minimizar los costes asociados. Debe tener en cuenta las capacidades del taller de la organización, los recursos disponibles, los intentos de reparación fallidos y las opciones de reparación externas.

A través del LORA, sus resultados revelan si las capacidades del taller interno son adecuadas o por el contrario excesivas o insuficientes.

Control de Inventario:

En control de inventario nos encontramos ante la imperiosa necesidad de introducir el concepto de Lote económico (EOQ), la cantidad a pedir de manera que se minimizan los costes, que vendría dado por la expresión:

$$Q *= D\sqrt{\frac{2AD}{r * v}}$$

A= Coste de Lanzamiento.

D=Demanda en el periodo T.

$r * v$ = Costes de mantenimiento en inventario.

Se puede diferenciar en dos tipos de sistemas:

Revisión continua:

- **Política (s, Q):** Cuando el inventario baja del punto de pedido establecido s, se pide la cantidad fija Q. Estos valores dependen del Lead Time de aprovisionamiento.
- **Política (s, S):** Cuando el inventario baja de un nivel dado s, se pide la cantidad suficiente de manera que se alcanza el nivel S.
- **Política (S-1, S):** Similar a la anterior, de manera que cuando se demanda una pieza el sistema reacciona volviendo al nivel deseado.

Revisión periódica de inventario:

- **Política (T, S):** El inventario se revisa periódicamente en intervalos de tiempo T, se ordena la cantidad necesaria para alcanzar el nivel S deseado.
- **Política (T, s, S):** El inventario se revisa periódicamente en intervalos de tiempo T, si el nivel de inventario está por debajo del punto de pedido s, se ordena la cantidad necesaria para alcanzar el nivel S deseado.

En general los sistemas de previsión continúa conllevan mayor número de recursos dedicados que logra una mayor precisión.

Casos en la literatura:

Autores	**Año**	**Compañia**	**Política stock**			
			(S-1, S)	(s, Q)	(s, S)	**Otros**
J. Ashayeri et al. [5]	1996	Piezas de servicio informática				EOQ
K. Cobbaert et al. [19]	1996	Fábricas de cableado		**X**		EOQ
R. Botter et al. [10]	2000	Componentes electrónicos	**X**			(R, s, Q)
K. P. Aronis et al. [3]	2004	Paquetes de circuitos	**X**			
M. Braglia et al. [13]	2004	Producción y conversion de tejido	**X**			EOQ
P.L. Chang et al. [18]	2005	Semiconductores				(r, r, Q)
E. Porras et al. [49]	2007	Refinería de petróleo	**X**		**X**	(s, nQ)
M. Bevilacqua et al. [10]	2008	Producción alimenticia	**X**			(s, nQ)
Syntetos et al. [63]	2010	Válvulas Industriales		**X**		
Nenes et al. [46]	2010	Distribuidor ruedas				(R, S)

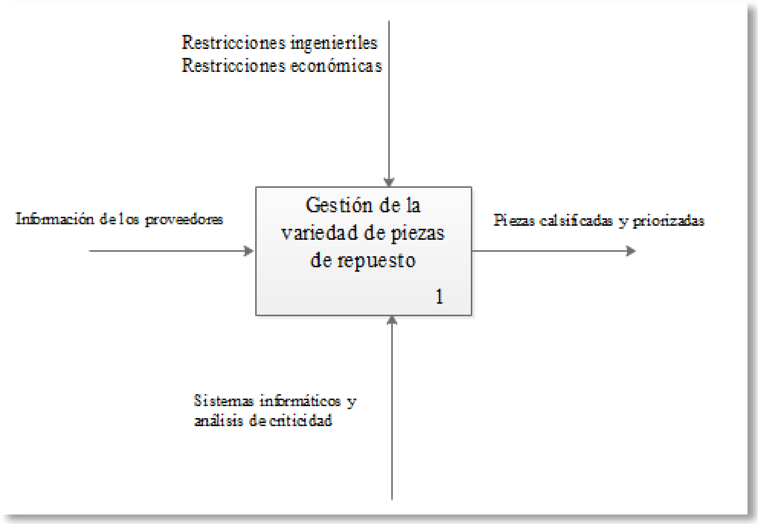
Cabe destacar el uso del modelo (S-1, S) que permite a las empresas gestionar los stocks de costes muy elevados. El modelo de lote económico se aplica más generalmente cuando el valor de la pieza no es tan elevado o el riesgo de obsolescencia es bajo.

Desarrollo de la metodología

1º Gestión selección de piezas de repuesto

Una pieza se puede incluir en la selección antes o después de ser necesitada por primera vez, si se incluye antes existe la posibilidad de que esa pieza nunca se use durante su vida útil. Los recursos invertidos en recopilar información, establecer contratos con proveedores potenciales y otros costes operacionales habrán sido en vano. Sin embargo, si no está incluida la pieza y se necesita el tiempo perdido en recopilar los detalles puede dar lugar a la interrupción de la producción. Este proceso decide si se incluye en la selección una determinada pieza y la clasifica respecto a unos parámetros que determinan su importancia.

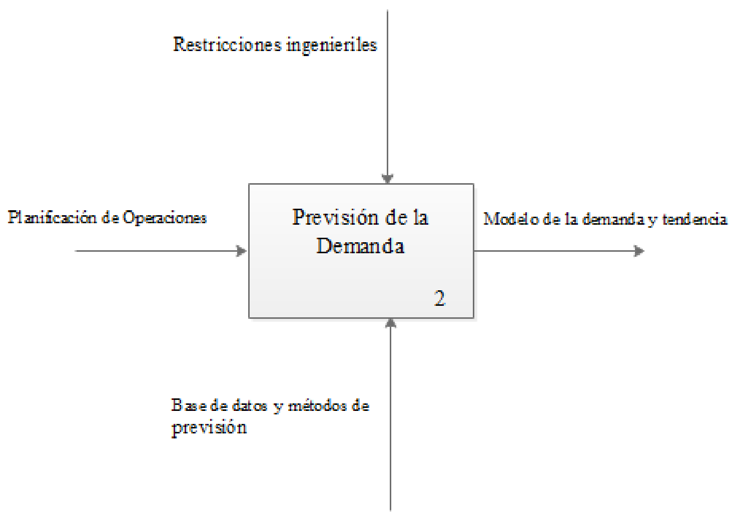
La información necesaria vendrá dada por los detalles técnicos de las piezas estudiadas, así como por la información del proveedor. La información será manejada por herramientas CMMS y ERP previamente introducidas, y a través de los métodos de la sección anterior se clasificarán. Las restricciones que debe cumplir el proceso serán el propósito y los recursos a los que se destina la pieza, características ingenieriles y económicas. El producto es el flujo de piezas incluidas en la selección clasificadas, por orden de prioridad.



2º Previsión de la demanda

El pronóstico de la demanda es la fase encargada de proporcionar la tipología y número de piezas de repuesto necesarias. Mediante estimaciones se prevé el flujo de piezas necesarias.

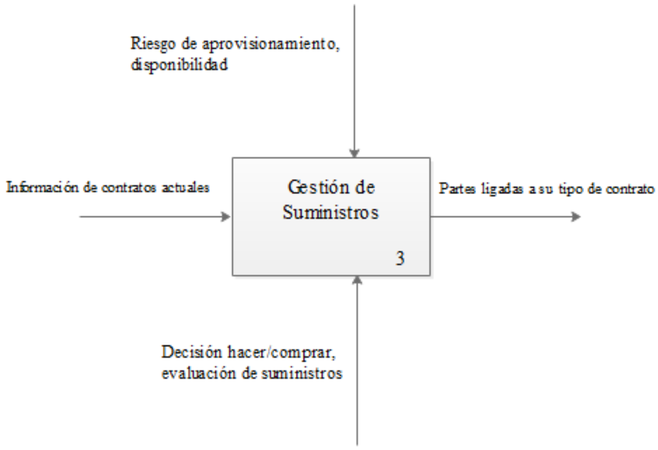
Este proceso recibe la información del proceso anterior, la programación de operaciones. Las herramientas para el pronóstico son los métodos presentados en la literatura y las bases de datos históricos y las restricciones ingenieriles.



3º Gestión de Suministros

Esta fase se encarga de asegurar la disponibilidad de fuentes de aprovisionamiento de LRU o SRU en un momento de tiempo determinado, con unas condiciones de Lead Time y servicio determinadas.

La información necesaria se obtiene de los contratos actuales que maneja la empresa, se decide entre las diferentes posibilidades ya introducidas de "make or buy", las restricciones a tener en cuenta es el riesgo asociado a la falta de disponibilidad de alguno de los proveedores y sus posibles consecuencias. Como producto del proceso obtendremos las piezas ligadas a sus contratos detallados de aprovisionamiento.

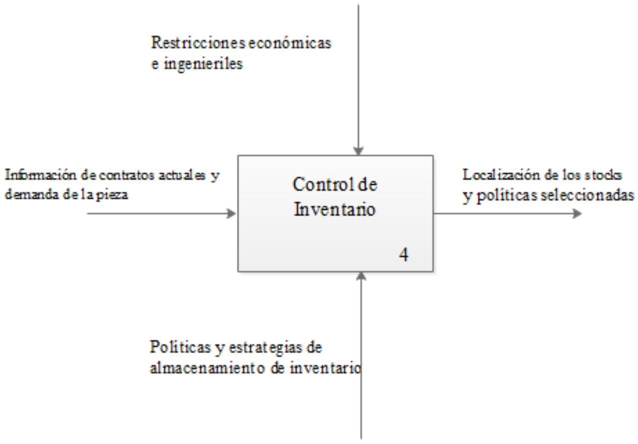


4º Control de Inventario

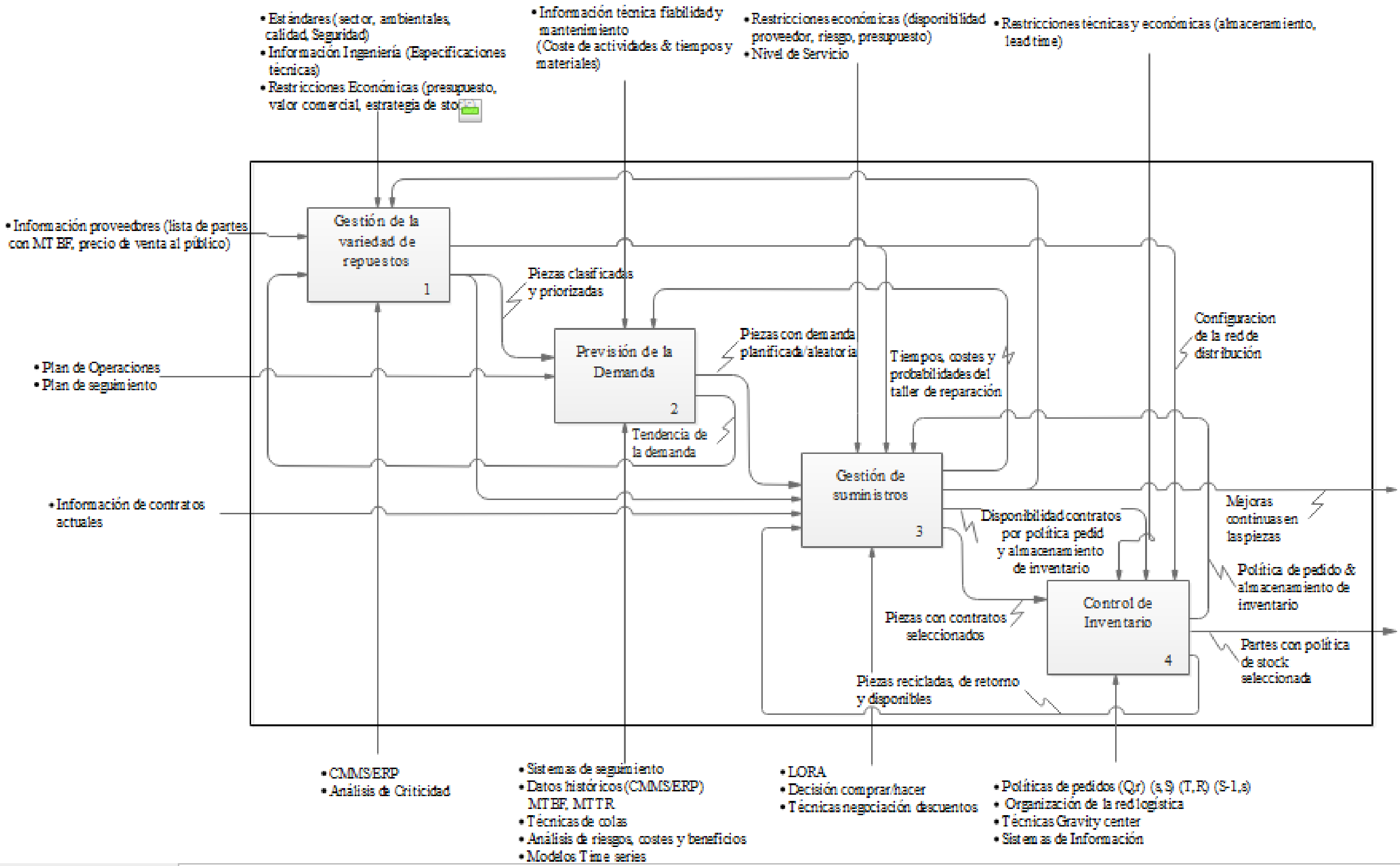
El inventario de piezas de repuesto debe lidiar con la elección de qué, dónde y en qué cantidad almacenar. Las políticas de control de inventario deben ser evaluadas y seleccionadas en función del valor, precio, y la probabilidad de fallo de la máquina asociada la pieza de repuesto.

Recibe el flujo de información acumulada en las fases previas, como los contratos de aprovisionamiento o el pronóstico de la demanda. Los recursos o políticas han sido introducidos en la sección previa, así como algunos ejemplos de su uso, a estos debemos añadir la teoría de colas que ha sido propuesta como método con potencial a explotar a la hora de alojar el stock por W.J Kennedy et Al. (2002).

El producto de este proceso es la combinación de las anteriores influencias y su representación final con la decisión sobre el tipo de política adoptada y el lugar de almacenaje.



Integración del primer nivel de la metodología



Como se puede apreciar, las relaciones entre los cuatro procesos principales no son simplemente secuenciales, la realimentación debe ser continua, de manera que el flujo de información este actualizado y se adapte dinámicamente a la cambiante situación empresarial.

El proceso Gestión de la variedad de repuestos (Assortment Managenement) recibe retroalimentación tanto del pronóstico de la demanda, como de los contratos con los proveedores, información que utilizará para la clasificación de cada parte, a su vez influye en cada uno de los otros procesos que toman la información que proporciona.

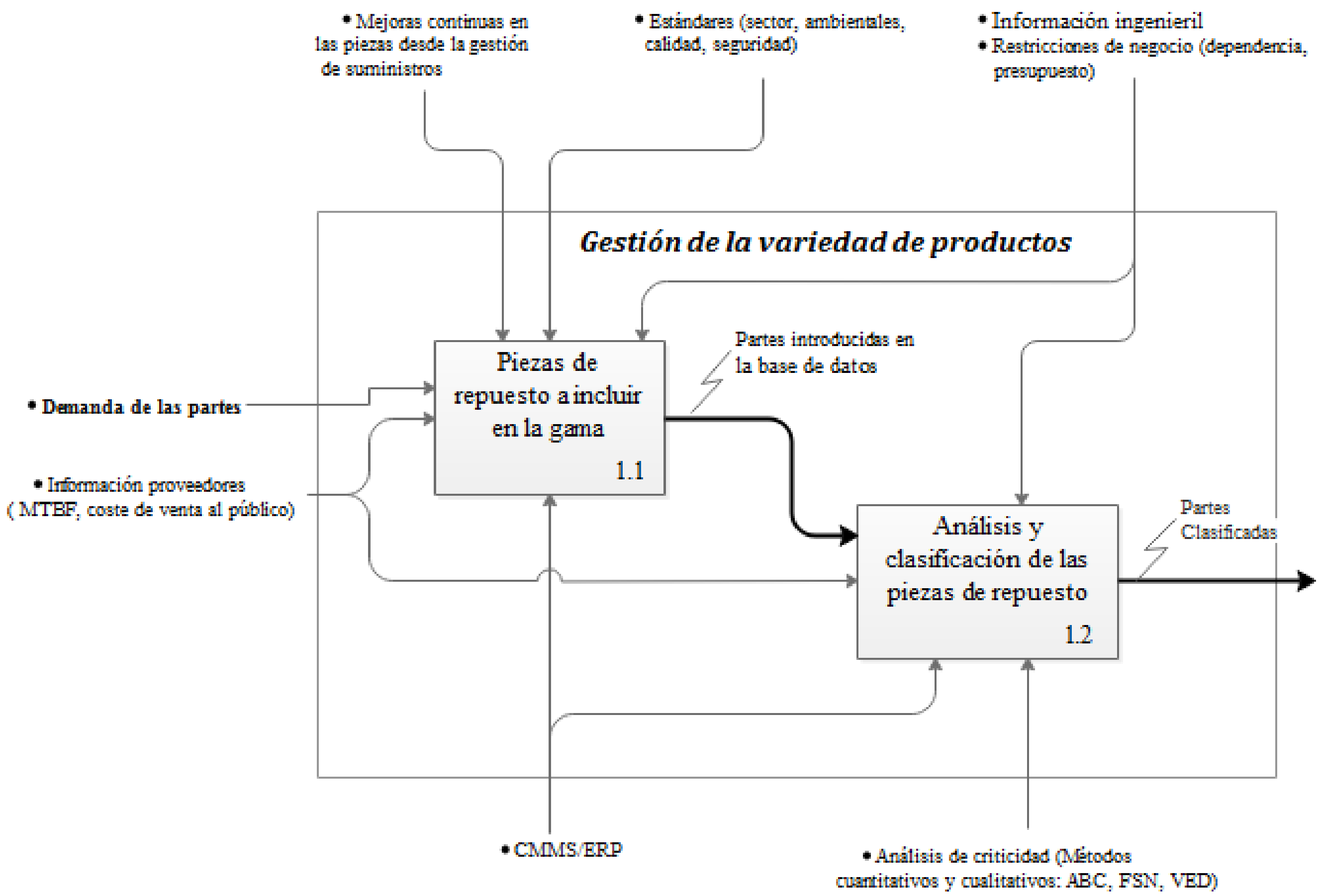
Se puede observar como el proceso Previsión de la Demanda (Demand Forecasting) interacciona con los procesos sucesivos, siendo vital el pronóstico del número de piezas que se necesitará para determinar el nivel de stock o asegurar el aprovisionamiento.

Todas estas interacciones se muestran en forma de flecha de manera que se puede seguir de manera intuitiva las relaciones, que añadidas a las expuestas anteriormente conforman el primer nivel de la metodología.

<u>Nivel 2 de la metodología</u>

A continuación avanzamos un paso en el nivel de detalle de cada uno de los cuatro procesos antes presentados. Se proporciona la visión interior de manera que aporta información acerca de las etapas necesarias dentro del proceso decisional.

Gestión Variedad de Productos (Assortment Management)

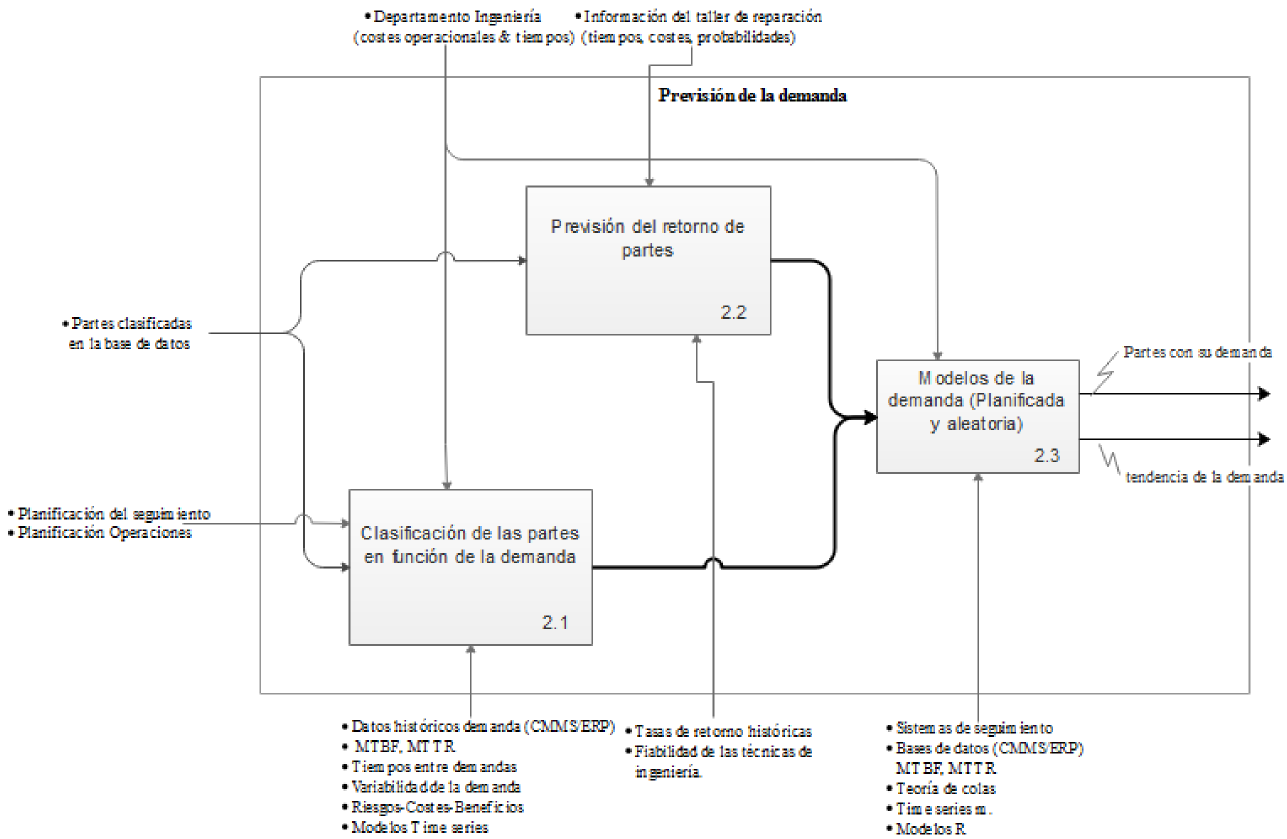


Este proceso se subdivide en dos partes, cada una corresponde a las dos tareas principales del proceso:

1. **Piezas a incluir en la gama de repuestos**: encargada de decidir si una pieza entra a formar parte de las piezas seleccionadas para el seguimiento, si entran a formar parte de la gama de productos a controlar. Herramientas: CMMS/ERP
2. **Análisis y clasificación de las piezas de repuesto**: encargada del análisis y clasificación de las partes seleccionadas previamente. Para muchas plantas industriales la clasificación se vuelve vital para controlar las enormes variedades de producto que manejan. Las piezas de repuesto se diferencian en los efectos que tiene una rotura de stock, en el tipo de demanda y el valor de la pieza. Herramientas: Métodos clasificación explicados en la sección teórica: ABC, VED...

Previsión de la demanda (Demand Forecasting)

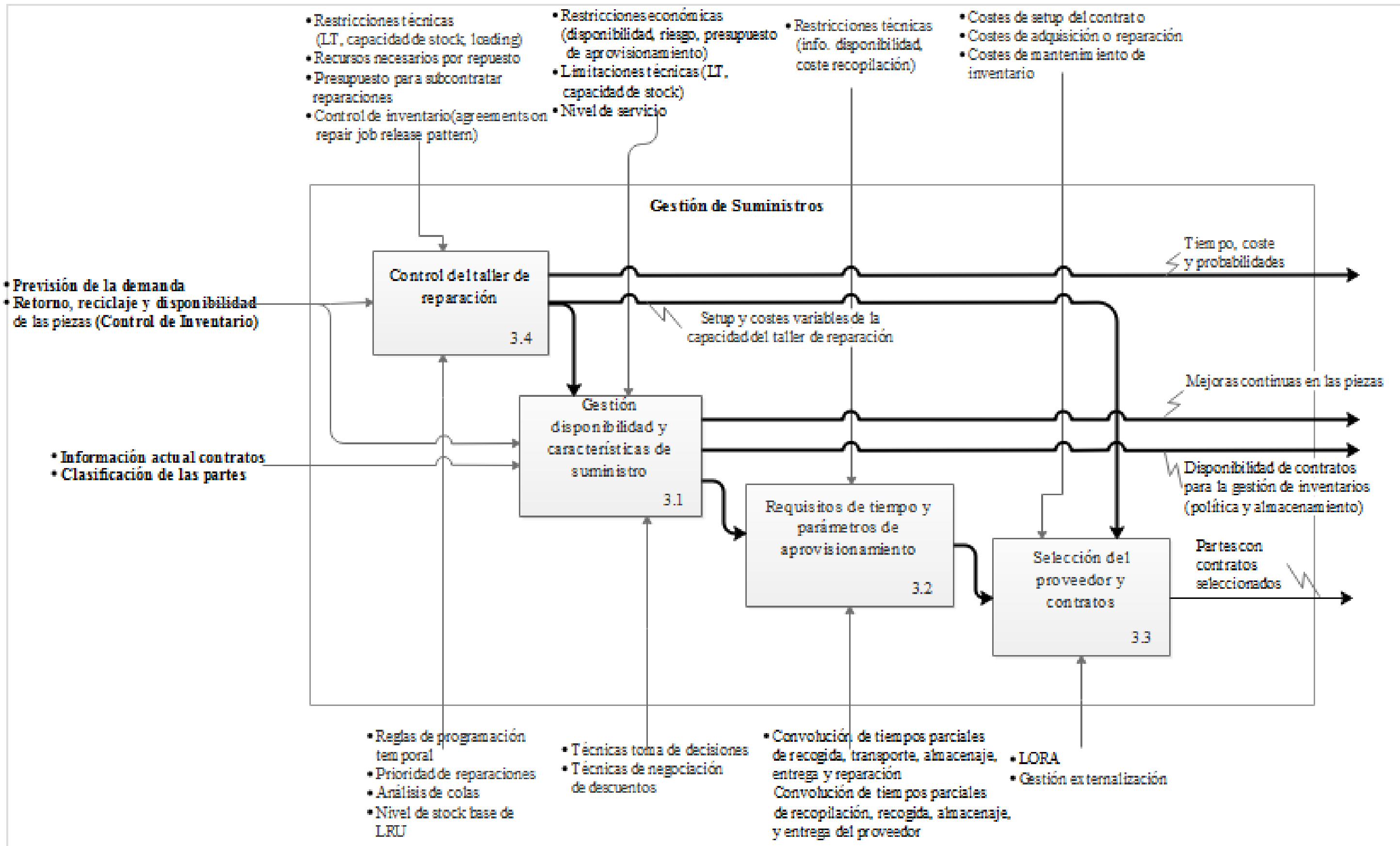
Se debe caracterizar la demanda futura con tres propósitos, para determinar el número de partes a almacenar, para determinar la capacidad necesaria del taller de reparación y para proporcionar la información necesaria al actualizar los contratos de aprovisionamiento.



Se ha dividido el proceso en tres etapas diferenciadas:

1. **Clasificación de las piezas de repuesto en función de la demanda:** Dependiendo del ADI y CV de cada pieza, con la información transmitida del proceso anterior, se procede a la caracterización de la demanda entre nivelada, intermitente, errática o irregular.
2. **Tasas de retorno de las piezas de repuesto**: Las piezas reparadas, una vez listas para su uso, cubren una parte de la demanda, por tanto se debe mantener un seguimiento de esta fuente de entrada, con la posibilidad de que una pieza sea descartada o se pueda reparar.
3. **Modelos de demanda planificada y aleatoria:** Con la información de los pasos previos se procede al pronóstico de la demanda de las piezas, que servirá como feedback para el primer proceso, y de información necesaria para la Gestión de suministros y Control de Inventario. Existen varios métodos ya introducidos en las secciones previas.

Gestión de Suministros (Supply Management)



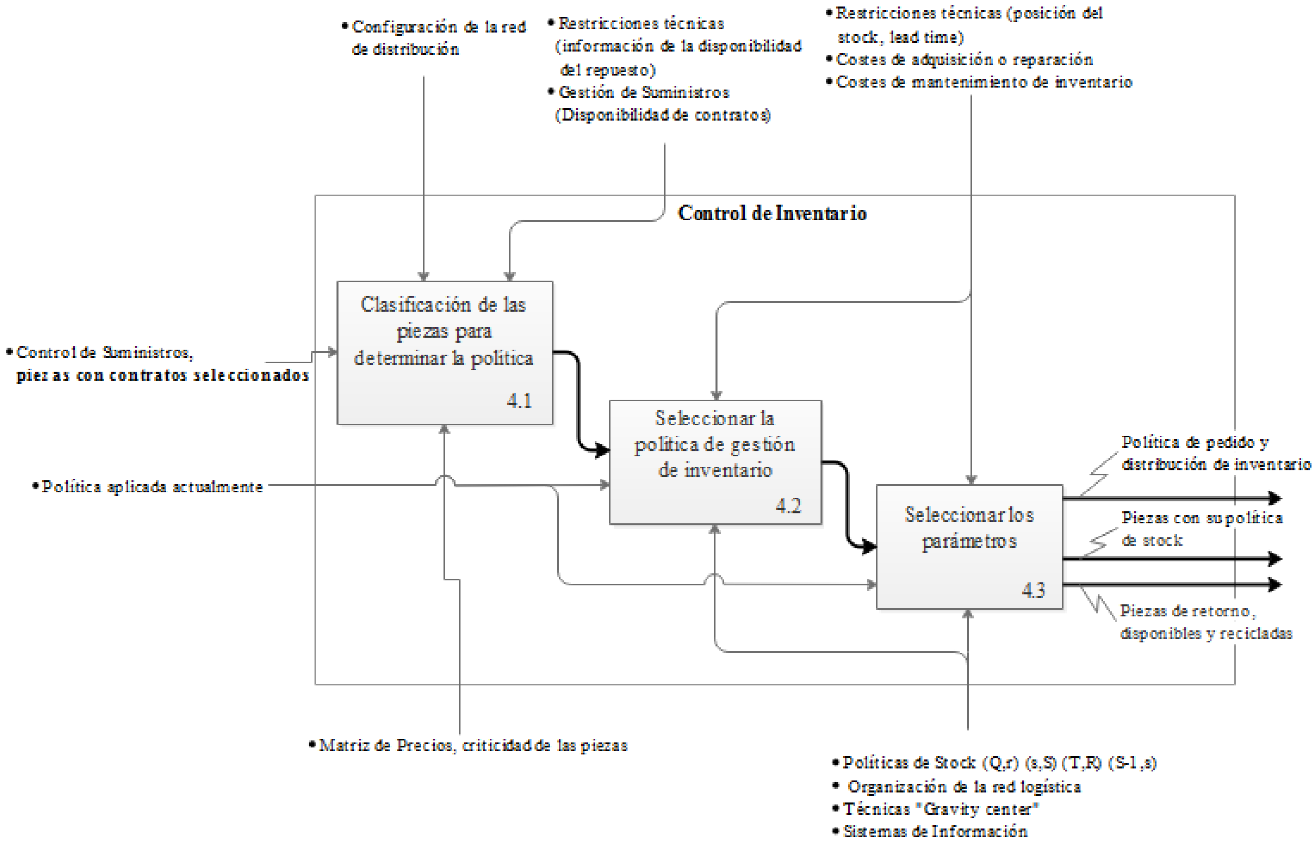
El objetivo de la gestión de aprovisionamiento es asegurar la disponibilidad a lo largo de la producción de las piezas de repuesto necesarias al nivel establecido. No está regulado el tiempo que un fabricante debe producir piezas de repuesto para un determinado producto, hecho que puede causar falta de disponibilidad, por ello la necesidad de los contratos que fijan periodos en los que el aprovisionamiento se garantiza.

Se ha dividido este proceso en las siguientes etapas:

- **Control del taller de reparación**: Siendo una potencial fuente de piezas de repuesto, en este proceso se establece la capacidad necesaria, a través de los recursos destinados se determina el tiempo de espera. Se estima la carga de trabajo de reparación a partir de las tasas de fallo y el pronóstico de la demanda. Se determina el número de especialistas, turnos, el nivel de SRU a mantener en stock y las herramientas necesarias, los costes dependiendo de la capacidad (Información necesaria para la selección de los contratos).
- **Gestión disponibilidad y características de suministro**: Estudia las diferentes opciones para que el suministro necesario de piezas no se interrumpa, mediante un LORA se establece si la pieza se debe reparar o no, ya sea en el taller interno (una vez conocidas las capacidades) o recurriendo a algún recurso externo a la empresa. Del mismo modo se puede recurrir a la sustitución sin reparación de la pieza.
- **Requisitos de tiempo y parámetros de aprovisionamiento**: Se establecen los parámetros deseados que debe cumplir el proveedor: Lead Time, coste, calidad, nivel de servicio.
- **Selección del proveedor y contratos**: Una vez establecidas las necesidades de cada pieza, se procede a negociar el contrato con el proveedor: Descuentos, inspecciones de calidad, sanciones por incumplimiento de contratos, se estable una relación colaborativa, ya sea con un único proveedor o varios. En la firma de contratos se ha de tener en cuenta el tiempo que conlleva la burocracia y las negociaciones de un nuevo contrato al acercarse la fecha de vencimiento de manera que se garantice en la medida de lo posible que no se interrumpa la producción.

Control de Inventario (Inventory Control)

¿Qué? ¿En qué cantidad? ¿Dónde? Estas son las preguntas que debe responder acerca de las piezas a mantener en Stock. Es el proceso más estudiado en la literatura y a veces se reduce el sistema de gestión de repuestos a este único paso. Se ha considerado que al formar parte de una metodología integrada se asegura unos flujos de información actualizados y se facilita la carga decisional de este proceso.



Se divide el proceso en las siguientes tres etapas como podemos ver en la figura anterior:

- **Clasificación de las piezas para determinar la política de gestión de inventario**: Esta etapa se encarga de clasificación de las piezas para la posterior selección de la política de gestión de Inventario. La clasificación depende del precio, la rotación, el comportamiento de la demanda o la dificultad del suministro.
- **Selección de la política de gestión de inventario**: Se selecciona el tipo de política a aplicar, primero debemos diferenciar entre control de Inventario Estático o Dinámico de manera que podamos aplicar alguno de los métodos presentados en la teoría.
- **Seleccionar los parámetros**: Esta etapa final del proceso, recibiendo toda la información anterior establece los parámetros de la política de pedidos que seguirá la organización, periodo de revisión, punto de pedido, cantidad a ordenar.

Resultados del trabajo

El resultado principal de este trabajo es la metodología que se ha mostrado representada tanto por procesos como integrada. Se muestran las contribuciones de cada fase, sus relaciones representadas mediante flechas.

El objetivo de este trabajo era desarrollar y ofrecer un respaldo para la toma de decisiones en la gestión de sistemas de repuestos. La gestión de mantenimiento conlleva un grueso respaldo teórico, y el desarrollo de una metodología con una complejidad elevada, requiere la introducción de unos conceptos teóricos de manera que los pasos, las diferentes etapas sean comprensibles al lector. Se busca un equilibrio entre la minuciosidad de los detalles, y la fácil accesibilidad del lector al trabajo.

La metodología que se ha generado en este caso es de carácter general, de manera que intenta abarcar la diversidad de casos asociado al problema en cuestión. Esto significa sin embargo la necesidad de adaptación en cada caso de la metodología, la necesidad de adaptar todo lo propuesto tanto al presupuesto de la organización, a la información disponible y eligiendo la adecuada entre las herramientas propuestas.

Un resultado alternativo de este trabajo es la identificación de los problemas clásicos de la gestión de repuesto de manera que se relaciona con cuál de las etapas de la metodología es la responsable, cuál debe ser informada y cual consultada. Esta relación se muestra en la siguiente matriz RACI:

R: Etapa Responsable **A:** Etapas que afectan al problema **C:** Etapas a consultar **I:** Etapas a Informar.

Los problemas seleccionados de muestra son:

Stock de Seguridad (Safety Stock): Problema del stock de seguridad a mantener contra la incertidumbre de la demanda, o para cubrir el tiempo necesario en reponer las piezas usadas.

Flujo de piezas reparadas (Repaired material flow): Problema de decidir si se establece un taller de reparación o no.

Clasificación de los repuestos (Spare parts classification): Determinar la criticidad de una pieza es para muchos autores la base del mantenimiento, desde un punto de vista financiero, logístico y de fiabilidad.

Órdenes de compra (Order quantity): Cantidad óptima a pedir, la política de gestión de inventario.

RACI Matrix		Fases de mantenimiento de piezas de repuesto											
		Gestión variedad piezas de repuesto		Pronóstico de la demanda			Gestión de suministros				Control de inventario		
		Piezas a incluir en la gama de repuestos	Análisis y clasificación de las piezas de repuesto	Clasificación de las piezas de repuesto en función de la demanda	Tasas de retorno de las piezas de repuesto	Modelos de demanda planificada y aleatoria	Gestión disponibilidad y características de suministro	Requisitos de tiempo y parámetros de aprovisionamiento	Selección del proveedor y contratos	Control del taller de reparación	Clasificación de las piezas para la política de gestión de inventario	Selección de la política de gestión de inventario	Seleccionar los parámetros
Problemas clásicos	Stock de Seguridad	I	C,I	C,I	I	C,I	C,I	C,I	I,A	I	R,A	R,A	R,A
	Flujo de piezas reparadas	I	C,I	C,I	I	I	R,A	C,I	I,A	R,A	I	I	I
	Clasificación de los repuestos	C,I,A	R,A	C,I	I	I	I	I	C,I	I	I	I	I
	Órdenes de compra	I	C,I	C,I	I	C,I	I	C,I	I	I	C,I	R,A	R,A

Conclusiones y campos abiertos para futura investigación

El objetivo de esta tesis era la creación de una metodología que integrase los estudios realizados por distintos autores acerca de la gestión de repuestos, para ello se ha procedido mediante el análisis de ejemplos concretos y herramientas teóricas. Se ha de remarcar la falta de casos de estudio relativos a la tercera etapa de metodología, el trato con el proveedor, desde establecer el tipo de política hasta la elaboración de contratos. Destaca por el contrario la gestión de inventarios como la parte del problema más estudiada en la literatura.

Tras leer esta metodología futuros investigadores podrían tener a su disposición acceso a una mayor documentación de la que extraer avances para la misma. Ya sean herramientas, incorporación del internet de las cosas como vía de desarrollo que permita la conexión autónoma entre las máquinas y almacenes o proveedores por ejemplo.

Se ha desarrollado una metodología de carácter general, ya que se consideró más útil no centrarse en un único caso al carecer entonces de flexibilidad, por tanto el último escalón entre teoría y aplicación queda por salvar. Se deja abierta la adaptación práctica, una futura investigación podría mostrar ejemplos y resultados al personalizar e implantar en empresas de distintos sectores la metodología propuesta.

1 Introduction

1.1 Motivation

Many industries depend on high capital assets in their main primary process. Any lack of availability caused by downtimes would result in lost incomes, customer dissatisfaction and other possible inconvenience damaging the image of the company.

To reach efficiency within a company, diagnosis and maintenance time need to be minimize, and delays due to unavailability reduced.

The first solution that arises is to maintain spare parts for a prompt availability. However in case of expensive and rarely used parts, it would result in high inventory holding costs and high obsolescence risk. Balance is needed between the two sides of the coin to establish the optimal spare parts policy. Working with spare parts inventory does not only need expertise in the field of logistics and finance but also in maintenance and technical knowledge.

In the last decades, many studies have been developed with the aim of reaching conspicuous and suitable results in maintenance field. During the years, the scientific articles production in maintenance grew up due to the increasing interest for the subject, brought by the undeniable positive implications that the related studies allow to the firms.

However these studies are too specific, they do not reach the whole decision-making process that is faced when managing the spare parts supply chain. The manager of an industry has information available from these studies, but information is overloading and confusing because each author tackles one part of the problem. The aim of these thesis is a compilation of these studies, a final framework that would cover the necessity of a complete guide to the problem of spare parts management, providing the tools and information necessary to back up decision-making.

1.2 Objective

The objective of this paper is to provide a complete and innovative vision of the decision-making process involved in the spare parts supply chain. Despite the huge quantity of academic literature, especially in the field of inventory control for spare parts, there is the need for a compiling framework, adaptable to diverse situations that would provide tools for the decision making process. Due to the issues cause by a non-proper spare parts management, it has been recognize the importance of achieving a broader and clarifier framework of every step to follow by the Manager of Operations. A framework is proposed in which acknowledge how to manage and contextualized the critical phases of the process in order to provide decision support.

The ideal would be a methodology that could be both partially and completely adapted to an organization working with high capital assets. All decisions making process involve subjectivity, nevertheless a manager should not risk the result of the company guided only by instinct, providing this framework decisions would be backed-up by quantitative and qualitative tools.

The secondary target of this project is to extract different cases from the literature in which the reader can identify some of the problems regarding spare part management and a possible solutions or tools implemented.

1.3 Summary

The thesis is structured as follows:

Firstly, a brief description of the environment is offered; in order to provide an interpretation key for the entire work, to set the purpose, the methods for tools representation and usage and to keep as a preface the meaning of numerous terms of which it has made extensive use in the remaining work's stages.

In **chapter 2** are reported all the acknowledgments exploited to reach the main purpose of the thesis: a review of the literature contributions is offered and, in the detail, tools and methods that represent the basis of the work are briefly explained and contextualized. Afterwards, general process representation is indicated and the selection of the concepts reference is highlighted. Thus, chapter is structured reviewing basic decision-making tools, case studies analyzed and investigated in literature with all the resulting techniques reported and the proposed choices and order to represents processes.

In **chapter 3** it is provided the development of the work: starting from an aggregated level of detail, main decision phases have been acknowledged and reported through the IDEF0 representation methodology. At first, work basis and structure is justified providing an explication of the meaning that the method adopted gives to the levels. Following, main processes are selected and their functions presented acknowledging the information flow that involve the process steps toward and from each phase. Afterwards, the decision-making support is provided by a broad vision of the phases subjects of interest, with the presentation of all the interactions and relationships through the phases. In this way, it is made simple the approach to adopt for capturing all the strategical steps that a decision maker has to face in the spare parts management and issues linked to. After the main work steps are argued, the second level of the analysis is developed and, adopting the same approach, interaction and features of the tools are explained.

In **chapter 4** the results are presented and assessed arguing the contribution in different ways and providing the meaning and the value of the efforts. A RACI Matrix has been exploited in order to enhance the awareness on framework possible applications.

In **chapter 5** a conclusion and a brief summary are offered to enclose the job in a few simple concepts and present possible future development of the efforts accomplished.

2 PREVIOUS CONTEXT

2.1. Key Concepts

Before presenting the framework, there are some concepts that have been used to build up the model, therefore they need to be showed to the reader in order to reach full understanding of all the cause-effects connection between the process, and the logical thinking behind the methodology.

These concepts will be presented in this section devoted to them, and they own the most significant weight among all the technical vocabulary that will be used.

These concepts are: maintenance, spare parts supply, availability, and critical components. Below, necessary definitions related to these concepts will be given and their relations will be explained.

2.1.1 Differences working with maintenance spare parts instead of common parts

In order to assess the environment in which the analysis is developed, a brief description of maintenance concept is needed; to argue the features that make maintenance inventories different from WIP or finished product inventories. Below a list of key aspects has been developed:

- In this field, rather than customer usage, the demand for spare parts inventories is dictated by maintenance policies. As instance, to fix and allow the functionality of a machine that has a broken part is to repair the part; another possibility is that the part can be replaced. The decision of whether to repair or replace has profound implications like the decision of the amount of redundant equipment to design into a machine to simplify the maintenance issues;
- Information on reliability, generally is not available with degree requested or needed for the prediction of failure times, particularly in the case of new equipment. Machines could be monitored but such operations are particularly time consuming, and thus, expansive. The fact that part failures are often dependent enhance the difficulties of the operations, particularly if the dependence relation is not known;
- When a failure occurs the costs of the production stopped include quality as well as lost production, and these costs are difficult to quantify;
- Obsolescence may be a problem as the machines for which the spare parts were designed become obsolete and are replaced. It is difficult to determine how many units of a part for an

obsolescent machine to stock, and it may be difficult to replace a part that no one still keeps in stock.

- If the major unit of equipment is expensive components of equipment are more likely to be stocked than complete units, and repair may be preferred to replacement if it is possible. (39)

2.1.2 Terminology

- **SKU:** a stock keeping unit (SKU) is a product and service identification code for a store or product, often portrayed as a machine-readable bar code that helps track the item for inventory;
- **LRU:** is a modular component that is designed to be replaced quickly at an operating location (1st line). The different lines (distances) are essential for logistics planning and operation. LRUs can improve maintenance operations, because they can be stocked and replaced quickly from distributed nearby on-site inventories;
- **SRU:** shop-replaceable unit SRUs are similar in nature to line-replaceable units (LRUs), but rather than being complete functional units, represent component functions, such as circuit card assemblies, of a larger LRU;
- **MRO:** maintenance and repair operations, they are all the operations involve with maintenance, inspection, repairs and administrative tasks.

2.1.3 Review of basic decision making tools in logistics

In order to understand the decisions made during the process, the theoretical background extracted from literature is settled. The following is, basically, a compilation of methods and techniques that provides the manager with tools to make non-deterministic decisions that otherwise would be arbitrary.

This chapter is divided in two main sections, the first section in which all the theoretical aspects found in literature during the research are offered. The development of the model sets its basis on the concepts listed below, for this reason, it has been established to provide a concepts background and confer explanations of tools with a brief review of their operational mode. The second section deals with the results related to the case studies analysis. Firstly, summary tables are proposed to depict tools met, and then explanations of the cases are clarified.

Computerized maintenance management system

CMMS provides historic information for various types of work; availability of materials; costs by job, facility or type of work, and much more. The CMMS most basic function is to organize all equipment information into a workable database. It can increase effectiveness of planning, scheduling, and cost tracking considerably. Furthermore, it will establish an electronic information warehouse, which will be available for many other queries and reporting. CMMS is a centralized repository for maintenance related information. Ideally, a CMMS provides an easy to use interface to modules tying together purchasing, work requests, work orders, equipment records, labor resources, inventory, and history of work orders.

The effectiveness of a CMMS depends on how well the software accomplishes this integration, the acceptance of the user community, and the quality of the maintenance data loaded into the CMMS. A CMMS is a powerful tool that simplifies day-to-day activities in maintenance, planning and scheduling, inventory control and purchasing. It also provides event and history tracking facilities that will enable the overall performance to be monitored and optimizes the equipment and personnel resources.

Implementation process

In an organization, departments are under pressure to provide information fast and at a low cost for the company. Lack of information is a great handicap while working, especially for those who have to take decisions, the more information they get the merrier.

The importance of CMMS has increased dramatically in the past few years, especially in resource-based companies such as mining, oil and gas, pulp and paper, utilities, and heavy manufacturing. This is because lean companies realize the enormous savings potential due to improved equipment reliability, lower spare parts inventory, and higher operator productivity. The more sophisticated CMMS packages provide excellent analysis tools for lean manufacturers to identify problem areas, root causes, and actions required. Many problems can be avoided in the first place through various modules of CMMS.

Listed below the typical CMMS features:

- Minimal learning curve required;
- Quick easy to set-up;
- Easy to use with powerful features;
- Minimal time required for operating;
- Bulletproof software system that requires no computer experience to install or maintain even on a network.[24]

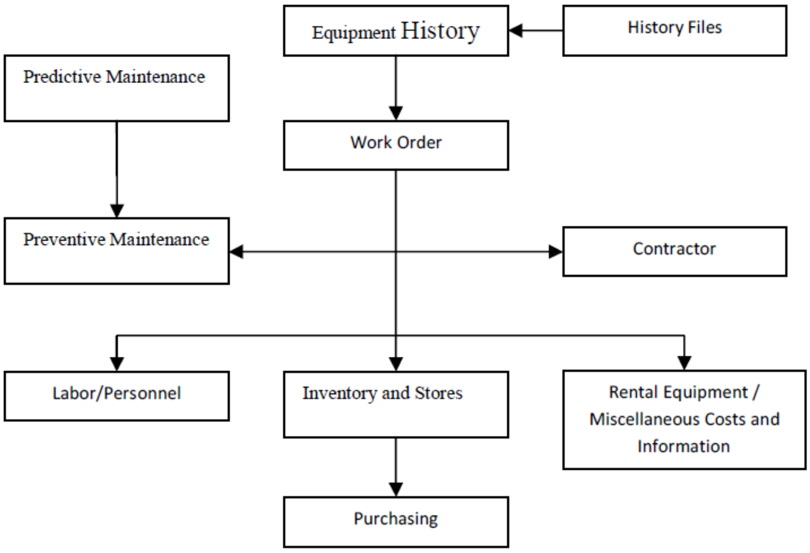


Figure 1 CMMS structure showing information fluxes and connections established in the system.

Enterprise Resource Planning

An ERP system is an integrated set of application software modules such as accounting, distribution, sales and marketing, material management, human resources, logistic and more. Instead of concentrating on specific functional areas separately, these modules work as an integrated unit by bringing the visibility of real-time information to all the departments, focusing on the business process as a whole.

It provides function to calculate safety stock (SS), make a demand forecast and determine the re-order point (ROP) for each item contained in the database based on the item's demand history (information that we place as an input on this step of the methodology). [50]

In their idealized form, Enterprise Resource Planning (ERP) systems integrate all business processes into one enterprise-wide solution. This is accomplished by having a centralized database that all business functional areas have access to (O'Leary, 2002)

ERP comes from the limitations of Material Resource Planning and Computer Integrated Manufacturing (CIM). Actually they focus more in the relationship with the customer. Customer Relationship Management (CRM).

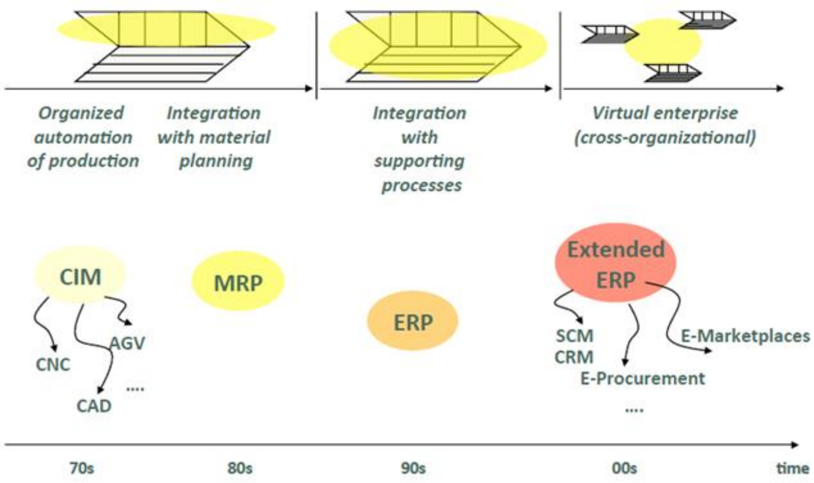


Figure 2 ERP figure, Information Systems, Politecnico di Milano, 2015

, Information Systems, Politecnico di Milano, 2015

ERP are classified in three tiers. First one supports big enterprises. Some examples enterprises that offer this ERPs are Oracle, SAP or Microsoft. The second one supports medium enterprises and they focus on vertical markets. Some examples of this one are Microsoft, Infor or Sage. And the last tier is not actually ERP, they offer solutions for small enterprises. In some enterprises there are two ERP integrated one for horizontal processes and one for vertical processes.

In the market there are available some open source solutions as: Compiere, Adempiere, Hipergate, OfBiz, ERP5. They have low impact on costs but the learning curve at the beginning could be considerably high. ERP is organized by modules, and it is needed to make sure that information is not redundant.

There are three types of structure: Suite, Module, and Function.

While implementing an ERP there ten tips to follow.

1. Focus on business processes and requirements first.
2. Take measurements to achieve a healthy ERP ROI.
3. Strong project management and resource commitment is key.
4. Commitment from organization executives.
5. Take time to plan up front.
6. Ensure adequate training and change management.
7. Make sure to understand why you are implementing ERP.
8. Focus on data migration early in process.
9. Leverage the value of conference room pilots (CRPs)
10. Chart the course.

ABC

The ABC method is based on the Pareto principle which says: for many events, roughly 80% of the effects come from 20% of the causes. This means that a minority of parts in this case are responsible for most the value.

The ABC classification is a frequently used analytical method for inventory classification into the three A, B and C groups. However, the traditional ABC classification considers only one criterion to classify inventory. Very often this criterion is **annual cost usage** obtained by multiplying annual requirements and unit price of the parts or the position cost (item in stock). The other criteria, besides annual cost, are: time of delivery, item criticality, accessibility, unit price, penalties costs etc. [54]

The A, B and C clusters are defined based on the traditional ABC analysis which gives group A the greatest importance and group C the least importance. In the process group A includes 10 ÷ 20 % of the total number of parts but has the greatest share (70 ÷ 80 %) in overall annual cost. Group B has a share of 15 ÷ 20 % in overall annual cost while group C has 60 ÷ 70 % of the total number of parts but its share is the smallest (5 ÷ 10 %) in the overall annual cost.

The inconvenient of this method is that only considers one criteria, nowadays we can see how multi-criteria methods are entering more and more because they provide a more complete analysis. However, the main advantage of ABC is its annual cost that are considerably lower in comparison with other methodologies. It needs periodical review to control price changes.

Building an ABC model

In order to exemplify the phases that composes the ABC tool usage, a list of actions has been provided in Figure 3. The activities in the scheme would allow an ordinated method to accomplish the categorization brought by the Pareto principle.

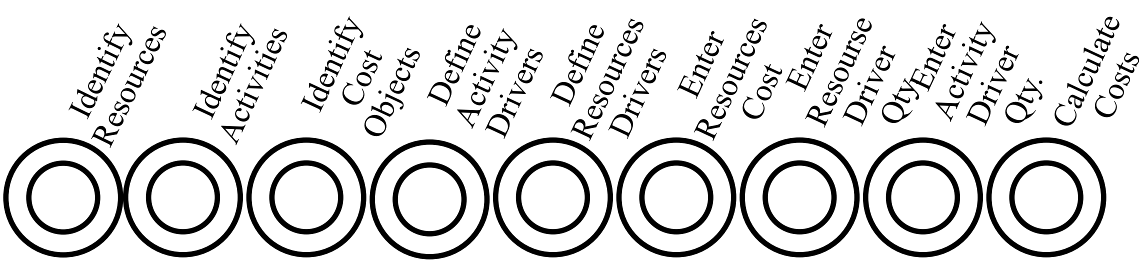


Figure 3 Proposal on criticality assessment steps

VED

VED method is a qualitative approach to classify parts. VED stands for Vital, Essential and Desirable. These are the three categories in which this method difference. A part is classified on base of its importance due to its absence. Some of the materials are important by their absence. In case they are not available, the whole production system may come to standstill and involve high cost of loss of production. The investment in these materials may be small but for non-availability of the item the costs or losses the company going to involve will be very high. These are critical items, which are required in adequate quantity. It is normally combined with ABC for more accuracy. [43]

FSN

FSN is based on the turnover ratio. In any manufacturing industry, not all items are required with the same frequency. Some materials are quite regularly required, yet some others are required very occasionally and some materials may have become obsolete and might not have been demanded for years together. FSN analysis groups them into three categories as Fast-moving, Slow-moving and Non-moving (dead stock) respectively. Inventory policies and models for the three categories have to be different. While performing this particular analysis the turnover ratio of each item has to be calculated because the items are sorted and analyzed according to the turnover ratio it possesses. [64]

To proceed with the analysis we need to have the following data: Name of the items, Annual demand of each item, Turnover Ratio, Unit price of each item, Annual Usage and cumulative annual usage of each item. The turnover ratio is calculated from the following formula **Turnover Ratio= Annual Demand/Average Inventory**. After that we calculate the **Annual Usage of each item= Annual Demand of each item x Unit Price of each item.** After this the percentage cumulative usage of each item is calculated, for the 2nd Item is the addition of the first and its own. Taking into account these values we classify as we mentioned before. Normally if the turnover ratio is below 2 the part is considered N.

FSN analysis helps an organization in the identification of the following

The items considered to be “active” may be controlled regularly on more frequent basis. Items whose stocks at hand are higher as compared to their rates of consumption. Non-moving items whose consumption is “nil” or almost insignificant.

AHP

The AHP is a powerful and flexible multi-criteria decision making tool for complex problems where both qualitative and quantitative aspects need to be considered. The AHP helps the analysts to organize the critical aspects of a problem into a hierarchical structure similar to a family tree. By reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, the AHP not only helps the analysts to arrive at the best decision, but also provides a clear rationale for the choices made. Briefly, the systematic procedure in using AHP is the following:

1. Define decision criteria in the form of a hierarchy of objectives. The hierarchy is structured on different levels: from the top (i.e. the overall objective) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives).
2. Weigh the criteria, sub-criteria and alternatives as a function of their importance for the corresponding element of the higher level. For this purpose, AHP uses simple pairwise comparisons to determine weights and ratings so that the analyst may concentrate on just two factors at the same time. The verbal judgements are then translated into a score via the use of discrete scales.
3. After that the judgement matrix has been developed, to calculate a priority vector to weigh the elements of the matrix. This is the normalized eigenvector of the matrix.
4. Evaluate the goodness of judgements with the inconsistency ratio I. This is a peculiarity of the AHP technique.[17] [43] [26]

In Figure 4 an example of AHP decisional structure has been reported; this frameworks provided by a study of M. Braglia et al. (2004), focuses the attention on spare parts classification developed through the criticality analysis of four spares features. The result is a classification as much as possible complete, taking into account all the strategical that may be worthwhile for the classification.

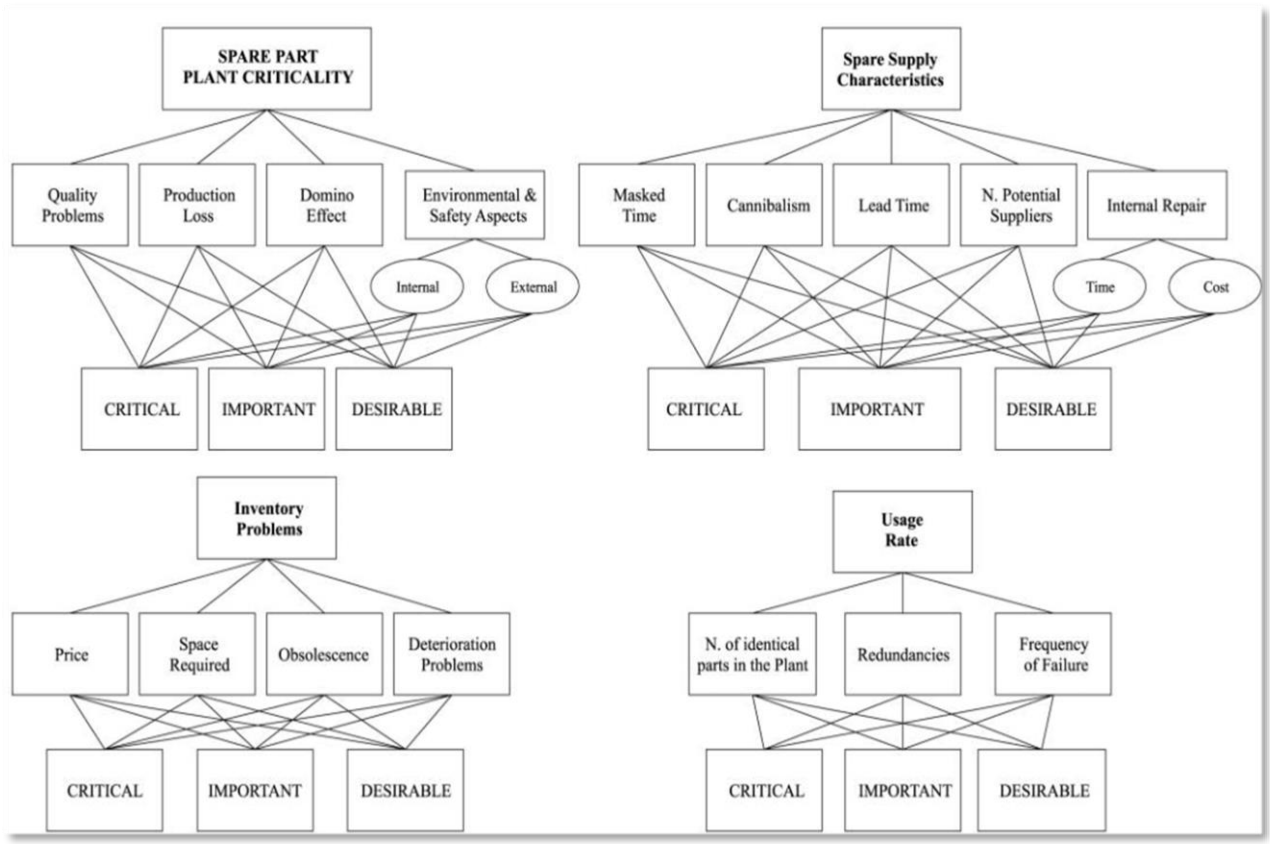


Figure 4 AHP models adopted in decision diagram nodes M. Braglia et al.

Artificial Neural Networks

ANN is a methodology that consist on applying Artificial Neural Networks to traditional ABC. Many companies tend to rely on ad hoc decision of their inventory managers for considering other criteria for ABC classification. These decisions are based on manager's expertise. Although sometime is very effective, this decisions may not always be consistent while considering all the criteria which may be relevant. AHP is also used but it is considered to be very subjective. So ANN rises as a solution with the development of technology. ANN is an artificial intelligence based technique, which is applicable to the classification process. ANN substitute the manager, they perceive relationships for both quantitative and qualitative inputs that provide intermediate steps towards reaching the decision maker's final judgement. Potential strengths: Capable of detecting nonlinear relationships and interactions, and patterns do not depend on various assumptions.[49]

AN ANN

Is a parallel, dynamic system of highly interconnected and interacting parts based on neurobiological models, it consists of individual highly connected nerve cells called neuron. Neurons receive information as a stimulus from the environment, and they pass from one neuron to another by exciting or inhibiting their neighbors.

If it is inhibited the information is not important and doesn´t pass on. It is like a filter for important information. Neurons are distributed in hierarchical layers. One of the most implemented is the multi-layer perceptron model (MLP). The number of layers and neurons determine the accuracy of the model.

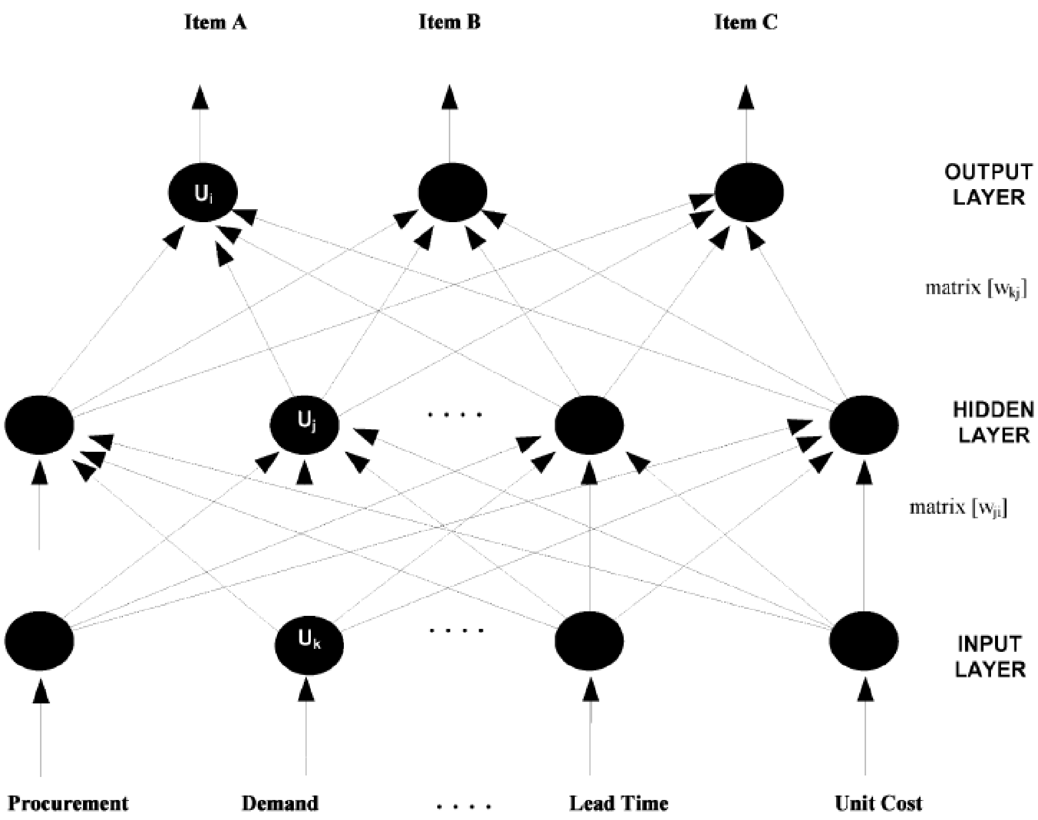


Figure 5 Framework of an ANN structure, Patrovi et al. [49]

Inputs are combined weighted and filtered through the layers. Large positive activates, large negative inhibits. The determination of critical components is generated by an iterative training process where cases with known results are presented to the network. There are two main:

1. Back Propagation algorithm based learning **(BP):** Its base is to load the input-output relations within MLP topologies. Trained about the past to generalize the future. First, weights are initialized, then during the feedforward every unit receives an input signal and send the signal to each of the hidden units. The error is estimated and weights are adjusted. The

mathematical basis for the BP algorithm is the optimization technique steepest gradient method. The BP may not provide the most efficient way to train neural networks, they typically achieve the best solution in the region of the starting point.

2. Genetic algorithm based learning **(GA)**. It is a search technique designed following the natural selection process in biological evolution, of how the genes of two parents combine in their children. Applied to problem solving, this method is very effective at finding optimal or near solutions to a wide variety of problems, it does not impose limitations of traditional methods. Its steps are initialization, reproduction,selection and convergence. This methodologies are an alternative to classic ABC. Eventhough many qualitative variables are hard to incorporate to this method, it has been prove that has better predictive accuracy than MDA. [61] [49]

Demand forecasting tools

In the previous section tools employed to classify spare parts are explained and, once the spare part is classified, there are different methods with diverse associated cost (resources and effort) and with diverse accuracy, which are extensively used in literature to forecast spares demand pattern and tendency.

1. **Single exponential smoothing**: **(SES)** This method is based on time series analysis, particularly adapt for low period forecast. In substance, the forecast of spare parts demand is obtained by applying a series of weights, decreasing in an exponential way, at the historical data. The forecast formula is:

   $F_{t+1} = \alpha X_t + (1 - \alpha) F_t$

   X_t Is the actual value of the demand at the instant t;

   F_{t+1} Is the forecast for instant t+1; α is the smoothing parameter.

   Generally the value varies between 0.1 and 0.4 on the basis of demand features (with unstable demand higher values for the parameter are used).

2. **Croston Method: (CR) -** Croston proposed a method (abbreviated as CR) that takes account of both demand size and inter-arrival time between demands. The method is now widely used in industry and it is incorporated in various best-selling forecasting software packages. [65]
   Croston's original method (CR) forecasts separately the time between consecutive transactions Pt and the magnitude of the individual transactions Zt. At the review period t, if no demand occurs in a review period then the estimates of the demand size and inter-arrival time at the end of time

t, Zt and Pt, respectively, remain unchanged. If demand occurs so that Xt > 0, then the estimates are updated by:

Z_t = α X_t + (1 –α) Z_{t-1}

P_t = α G_t + (1 – α) P_{t-1}

Xt actual value of the demand at the instant t; Gt actual value of the time between consecutive transactions at the instant t; α smoothing constant between zero and one. Hence, the forecast of demand per period at time t is given as: $F_{t+1} = \frac{Zt}{Pt}$

3. **Syntetos–Boylan Approximation- (SBA)** Syntetos and Boylan proposed a correction in Croston's Method. They showed in a study that their approximation was more accurate by changing the mathematical derivation of expected demand. In deeper researches they stated that there are demand categories that are better used with the CR method and there are others that go well with the SBA method.
   There are several variations applied at Croston's method after his introduction in 1972, and SBA is considered one the most performing by several authors.

   Syntetos and Boylan (2001, p.459-460) pointed out that Croston's original method is biased. They showed that in CR the expected value is not /p, but:

   $E\,(Ft) = \frac{\mu}{p} * (1 + \alpha \frac{1}{2-\alpha} * \frac{p-1}{p})$

   Where μ is the mean of historical demand; p is the mean of historical inter- demand intervals Pt.

   Based on the equation and ignoring the term (p-1)/p, Syntetos and Boylan proposed a new estimator given as:

   $Ft+1 = \left(1 - \frac{\alpha}{2}\right) * \frac{Zt}{Pt}$

   One can expect this new estimator to perform better as (p-1)/p gets closer to one, i.e., as the probability 1/p of positive demand in a period gets smaller. The effect is that Croston's original method has a smaller deviation if 1/p is large, which means that few demands are zero, and the Syntetos - Boylan modification has a smaller deviation if 1/p is small (many demands are zero).

4. **TSB (Teunter, Syntetos and Babai)**: TSB is a new method proposed in 2011, the method replace the demand interval by demand probability which is updated every period. The reason for this is the Croston's method only update demand when it occurs, however in real life there are plenty

of cases in which the result of forecast will be unsuitable for estimating the risk of obsolescence because of the outdated information.

In TSB method, the Dt represent the demand occurrence indicator for period t, so:

If D_t =0, then

Z'_t=Z'_{t-1};

D't=D't-1 +β (0-D't-1)

Otherwise

Z'_t= Z'_{t-1}+α (Z_t-Z'_{t-1});

D't=D't-1 +β (1-D't-1)

Y't=D't*Z'_t

Where**:**

Y't -Average demand per period;

Zt- Actual demand at period t;

Z't - Time between two positive demands;

D't – Estimate of the probability of demand occurrence at the end of period T.

5. **Moving Averages (MA) -** The moving average (MA) method is the mean of the previous n data sets. The formula for the moving average is:

   Ft = MA (n) = (Xt-1 + Xt-2 + ... + Xt-n)/ n

   As it transpires from the formula, this method is really simple and easy to compute, but it is applicable only in case of slow moving demand. In the other cases the demand gravitates with difficult around the average of last n periods.

6. **Two Step Forecast (2S):** [53] the two-step forecast (2S) is the only forecasting method that makes use of the additional information that is available. Instead of forecasting parts demand directly based on the part demand history, 2S starts at the component level. For each component type c, c = 1; .....; C, we update the number of repairs and the average demand per repair separately, using:

$$\dot{z}_{t+1}^{c} = (1-\alpha)\dot{z}_{t}^{c} * \alpha z_{t}^{c}$$

$$\bar{a}_{t+1}^{c} = \bar{a}_{t}^{c} \; if \; \dot{z}_{t}^{c} = 0$$

$$\bar{a}_{t+1}^{c} = (1-\beta)\bar{a}_{t}^{c} + \beta \frac{dt^{c}}{\dot{z}t^{c}} \; if \; \dot{z}_{t}^{c} > 0$$

Where 0 ≤ α; β ≤ 1. Note that we do not update the average demand per repair in months without repairs. The forecast of demand used only for components of type c is

$$x_{t+1}^{c} = a_{t+1}^{c} * z_{t+1}^{c}$$

By combining these forecasts over all (relevant) components, we obtain the final 2S forecast.

$$x_{t+1} = \sum_{c=1}^{C} x_{t+1}^{c}$$

In previous section Neural Network have been explained, but they are not only useful for assortment management as we saw, but also there are some method based in **Artificial Neural Networks or (NNA)**, as it is the one below.

7. **The back-propagation algorithm: (BPN)** Back-propagation algorithm applies a supervised learning. In this explanation, a network with one hidden layer is considered. The back-propagation algorithm provides an "approximation" to the trajectory in weight space computed by the method of steepest descent. The smaller we make the learning-rate parameter n the smaller the changes to the synaptic weights in the network will be from one iteration to the next, and the smoother will be the trajectory in weight space. This improvement, however, is attained at the cost of a slower rate of learning. If, on the other hand, we make the learning-rate parameter too large in order to speed up the rate of learning, the resulting large changes in the synaptic weights assume such a form that the network may become unstable (i.e., oscillatory).

Forecasting evaluation tools

A posterior issue that rises from the description of different methods is how we get to compare these methods in order to decide which one is the most accurate. There are measures that indicate and give us information that tries to orientate in the election of the methodology.

1. **Mean absolute percentage error (MAPE)**: expresses accuracy as a percentage.

$$MAPE = \frac{\sum_{t=1}^{n} \frac{|At - Ft|}{|At|}}{n}$$

It is a percentage error so one can compare the error of fitted time series that differ in level. At actual value. Ft forecast value.

Drawbacks in practical application:

- If there are zero values there will be a division by zero.
- When having a perfect fit, MAPE is zero. But regarding its upper level the MAPE has no restriction. A few number of series that have a very high MAPE might distort a comparison. Other methods avoid these problems.

2. **The root mean square deviation (RMSD) or root mean square error (RMSE)**: is a frequently-used measure of the differences between values predicted and the values actually observed.

$$RMSD = \frac{1}{N}\sum_{t=1}^{N}\sqrt{(Ft - At)^{\wedge}2}$$

3. **Mean Squared Error (MSE):** It is used as a measured of the average squared error, it is squared to get the absolute value of the error and add it. And by squaring it, more weight is given to bigger errors.

   The formula is:

   MSE= (1/N)*∑ (Fi−Ai) ^2

   Being the difference of the predicted values and the observed squared and averaged.

4. **A-MAPE: Adjusted Mean Absolute Percentage Error**: It is one of the most used in comparing spare parts demand forecasting methods. The formula is:

$$A - MAPE = \frac{\sum_{t=1}^{N} \frac{|At - Ft|}{N}}{\frac{\sum_{t=1}^{N} At}{N}}$$

   It avoids the drawbacks described in original MAPE therefore it uses is widely extended.

5. **The percentage best (PB):** the percentage best (PB), is the percentage of time periods one method performs better than the other methods under consideration. PB is particularly meaningful because all series and all data periods in each series generate results (Syntetos and Boylan, 2005, p.308). The mathematical expression for PB for method m is:

$$PB_m = \frac{\sum_{t=1}^{N} B_{m,t}}{N} * 100$$

   Wher Bm,t is 1 if for that period the error of the method is the lowest from the ones considered, otherwise it is 0. [22]

Others necessary resources for classifying spare parts with respect to demand forecasting

- **MTBF**: Mean Time between Failures. It is a reliability term used to provide the average time between two failures. This indicator is the inverse of the Failure Rate and it gives an idea of how reliable a product is. If the MTBF of the machines in an organization is known, it gives another indicator to estimate how many spare parts will be needed in a concrete period of time.
- **MTTR**: Mean Time to Repair. It is a basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device.
  It includes the time of detecting the avery, identifying it and solving the problem. It gives an idea of "how bad" it is that a determined part fails. If the MTTR is high, the spare part should be in stock, if not the production will stop for a long time with important losses associated.

Every estimation of the future demand is based on the historical Data Base (DB), if a system such as CMMS or ERP is implemented, all the information will be integrated in the system. Based on these information extrapolations are made with statistical tools.

For evaluating the characterization of spare parts demand, two parameters are recognized in international field:

- **ADI** - Average inter-demand interval: average interval between two spare parts demand. It is usually expressed in periods, where the period is the referential time interval which the business utilizes for the purchases;
- **CV** – Coefficient of variation: standard deviation of the demand divided by the average demand.

Preventive maintenance – Condition based replacement

In the spare parts demand forecasting field, many techniques have been developed in order to manage the replacement of the failed spare part. In particular, acknowledging that the forecasting of a concrete spare part requirement occurs when a failure occours. Therefore a huge importance of failure forecasting is assumed, and so of the machines condition monitoring.

In Figure 6 A general framework of replacement strategies is now offered in order to achive a broader view of the possibilities exploited by firms and research studies. Despite most of the techniques proposed have been extensively used, in this section the work will be focused on the method that represent a concrete failures, thus spare parts, forecasting tool: the condition-based management.

As already reported in the previous sections, in literature, two main categories of maintenance can be acknowledged: corrective and preventive. Corrective maintenance is the maintenance that occurs after a failure, as a whole, it represents all the actions and activities resulting from failure. Preventive maintenance is the maintenance that is performed before failure in order to retain equipment in specified condition by providing systematic inspections, detection, and prevention of incipient failure [67]. Usually such preventive maintenance schemes as block-replacement and age-replacement are time-based without considering the current health state of the product, and thus are inefficient and less valuable for a customer whose individual asset is of the utmost concern. The major role of degradation analysis is to investigate the evolution of the physical characteristics, or performance measures, of a product leading up to its failure [40].

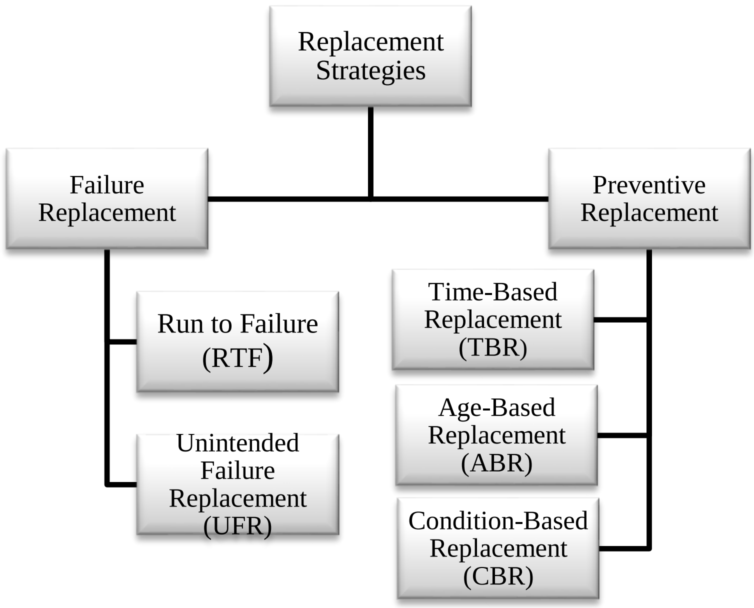


Figure 6 Replacement forecasting strategies: Condition-based management

In recent years, condition-based maintenance (CBM) has been becoming one of the most popular strategies of preventive maintenance, which aims at making maintenance decisions based on the evaluated health conditions of equipment. To establish an efficient CBM strategy, a measurement system must be available for monitoring the system condition at first. Second, one has to be able to make the optimal maintenance decision according to the known system condition, which is the problem of CBM modeling and optimization [68]. Although various monitoring techniques have been already developed (such as vibration monitoring, oil analysis, and thermography), research on CBM modeling and optimization is still at the beginning. To human beings, it often seems that machines fail suddenly, but in fact machines usually go through a measurable process of degradation before they fail. Today, that degradation is largely invisible to human users, even though a great deal of technology has been developed that could make such information visible. Many sophisticated sensors and computerized components can deliver data about the machine's status and performance. The problem is that little or no practical use is made of most of this data. Fault diagnosis provided by condition-based approach is triggered by a deviation recognition of equipment condition from the expected level. It is the process that detects abnormal problems, analyses the symptomatic information, identifies and locates the root causes of a failure, obtains the fault development trend, and predicts the remaining lifetime of the equipment. The intelligent systems used in condition-based fault diagnosis can be divided in the three categories listed below [15].

Rule-based diagnostic systems detect and identify incipient faults in accordance with the rules representing the relation of each possible fault with the actual monitored equipment condition.

Case-based diagnostic systems use historical records of maintenance cases to provide an interpretation for the actual monitored conditions of the equipment.

A model-based diagnostic system uses different mathematical, neural network, and logical methods to improve diagnostic reasoning based on the technical features of the equipment system. A model-based diagnostic system compares the real monitored condition with the model of the object in order to predict the fault tendency.

According to the literature, CBP utilizes a variety of techniques, whose main processes include the following:

- Site inspection.
- Visual review to determine surface conditions.
- Destructive testing to determine concealed conditions.
- Predictive maintenance (PdM) technologies.
- Continuous commissioning.
- Re-assessment cycles.
- Remote monitoring.

CBR is best suited to assets which present attributes such as: assets that are stochastic in their failure pattern (i.e. difficult to predict in a statistic model), assets with a wide dispersion pattern and assets with concealed conditions. The cost effectiveness of the CBM approach is related to the criticality of the monitored items, the reliability of the CBM techniques in providing valuable information, and the ease of interpretation of the results and their trends.

LORA: Given a product design and a repair network, a **LORA** determines for each component in the product (1) whether it should be discarded or repaired upon failure and (2) where to do that. Basten et al. (2009) in their paper propose a methodology to calculate LORA. The objective is to minimize total costs, fixed and variable costs. This methodology has to be adapted to each case, it needs to be flexible, there are commercial LORA-software to implement the analysis in the industry but too rigid to be implemented. [9]

LORA analysis characteristics: It should cover unsuccessful repairs, no-fault-found, finite resources capacity, the possibility of multiple failures mode in one component, and the option of outsource repairs. The method proposes an annual actualization.

The outcome of LORA is used to reconfigure the internal repair shop capabilities and will reveal that is economical to set up framework contracts for external procurement parts.

The economic order quantity (EOQ) is the optimal quantity to order to replenish inventory, based on a trade-off between inventories and ordering costs. The optimal quantity Q* to order (i.e., the order quantity that minimizes total cost). [27]

$$Q *= D\sqrt{\frac{2AD}{r * v}}$$

A= Cost of ordering.

D=Demand during the period T.

$r * v$ = Holding costs, value of the spare part times the internal rate r.

Continuous review systems:

- **The (s, Q) Policy:** Whenever the inventory position drops to the reorder point s or below, an order is placed for a fixed quantity Q. Values S and Q are settled depending on the Lead Time.

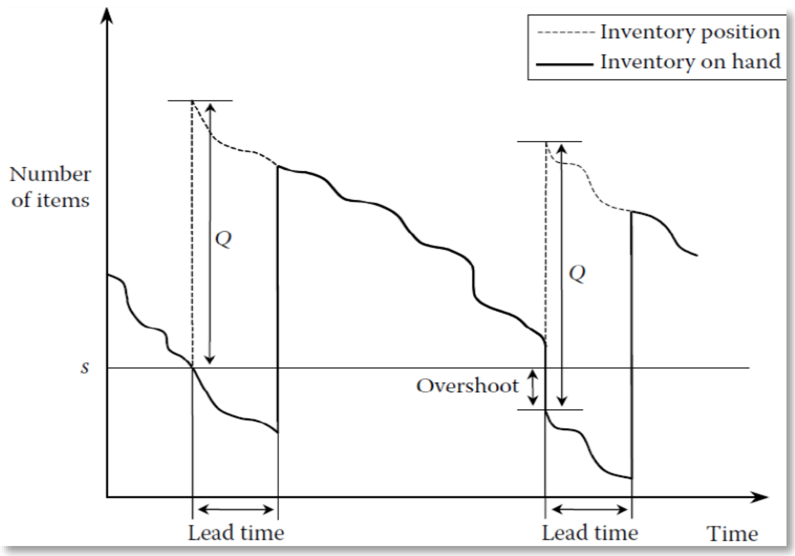


Figure 7 Static Stocking policies continuous review s, Q [24]

- **The (s, S) Policy:** Whenever the inventory position drops to a given level s, or below, an order is placed for a sufficient quantity to bring the inventory position up to a given level, S. [27]

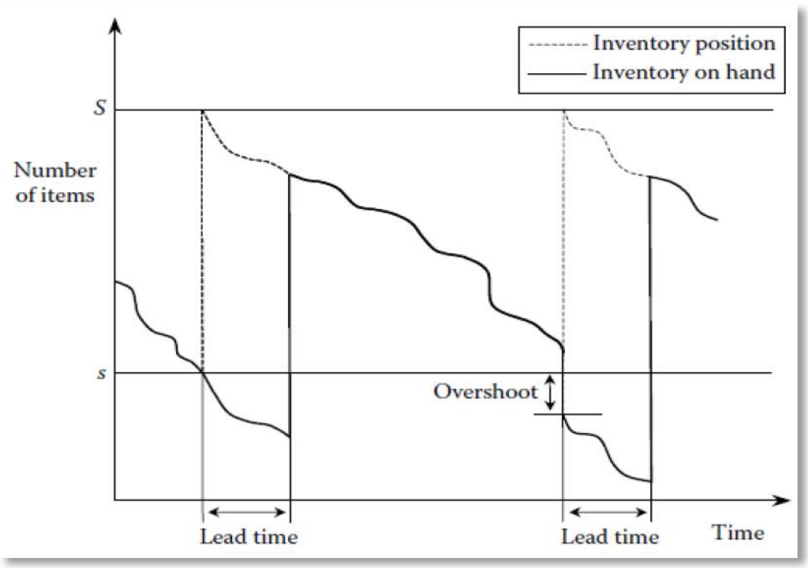


Figure 8 Static Stocking policies, continuous review s, S [24]

Uncertain situations are a major problem in the system of management and production. These situations can be caused by unexpected failures, unexpected repairs, etc. It would be convenient to analyze the effects of these uncertain situations on the calculation of optimal lot sizing in continuous review environment.

The (S-1, S) Policy: It is a special case of the previous **(s, S) policy,** where s= S-1, then any time a customer demand occurs, and order is made to return the inventory to the position S. It is used for low demand items where the set-up costs are low compared to holding costs. When demands are Poisson, results present similarities with conventional queuing systems and explicit results can be obtained for stochastic lead time case. [55]

Periodic review systems:

- **The (T, S) Policy:** Inventory position (items on hand plus items on order) is reviewed at regular instants spaced at time intervals of length T. At each review, an order is placed for a sufficient quantity to bring the inventory position up to a given level, S. [27]

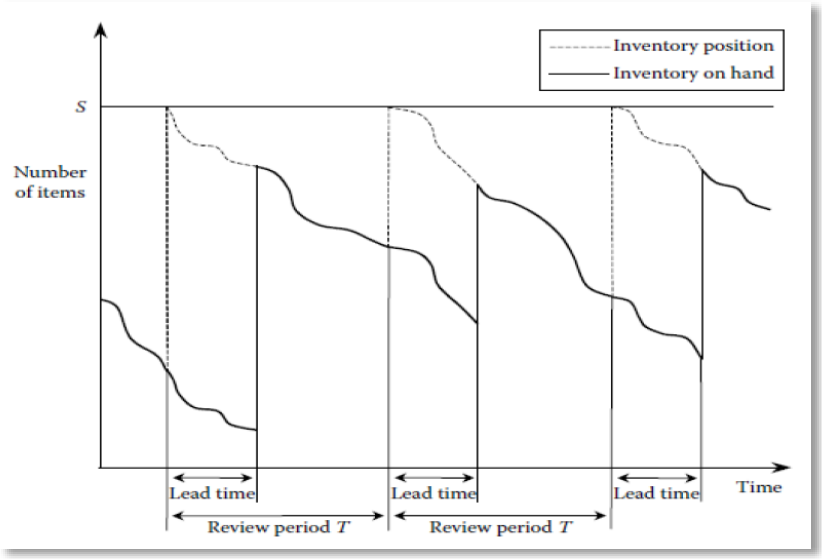


Figure 9 Static Stocking policies periodic review T, S

- **The (T, s, S) Policy:** Inventory position (items on hand plus items on order) is reviewed at regular instants spaced at time intervals of length T. At each review, if the inventory position is at level s or below, an order is placed for a sufficient quantity to bring the inventory position up to a given level S. If the inventory position is above s, no order is placed.[27]

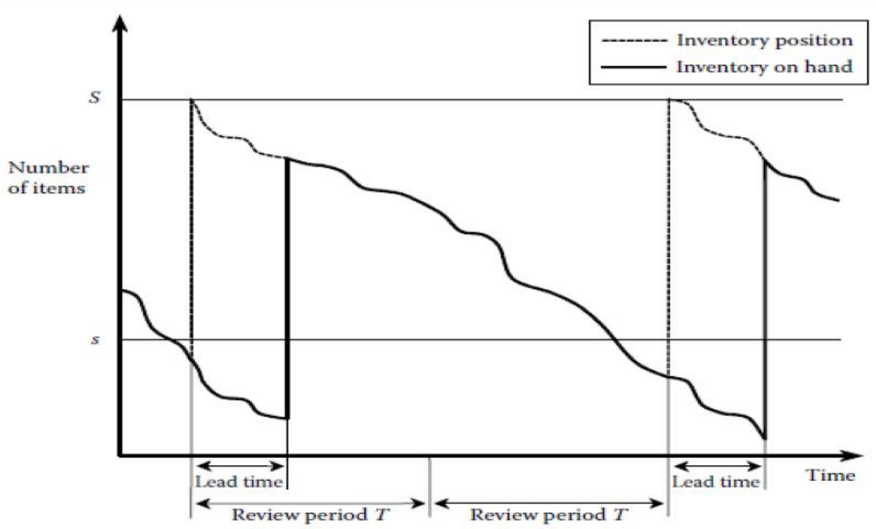


Figure 10 Static Stocking policies periodic review (T, s, S) [24]

Multi-echelon case with repair shop

Literature also provides several methods to manage the spare parts inventory control in a multi-echelon environment; assuming that the firm disposes of one repair shop and more than one stocking locations. Generally speaking, spare parts are stocked in locations named “bases”; then when a failure occurs, the failed part is removed, replaced with a new or fixed part. Thus, the removed defective part (in case that it is economically profitable) is sent to a repair facility known as “depot”. The function of the depot repairs the part (if possible), thus, keeps it in stock and eventually sent down to the bases to cover another part used in a repair. Through this classification, base level is considered the first inventory control echelon and depot level is considered another echelon: therefore the multi-echelon term.

A system with more than one echelon can, basically, be managed in two ways: the first is operating local optimizations in order to work on the system as a sum of the single stocking location, and the second is work on the system as a whole, exploiting and respecting positive features and constraints. Unlike the models used in the cases with a single location, in the inventory control referred to environments with various level it has been assumed as implicit the presence of a hierarchical relationships in the stocking location control.

The general assumption at the basis of every evaluation plan is to assess the value of the spare parts taken into account and establish if it is justified an analysis time and resources-consuming as the ones proposed below.

Avoiding the local optimization, already presented in previous section, mainly two typologies of managing are investigated: the METRIC-based (known as multi-echelon technique for recoverable item control) and the queue-based techniques. The basic differences between these two techniques deal with the assumptions and general complexity of the models as explained below.

METRIC-based models

This analysis is based on several critical assumptions, such as: one-for-one replenishment (S-1,S) policy, Poisson failure process, large working parts population and repair times independent of the number of parts in repair.

It is basically a mathematical model based on the supply system composed by the base and depot levels where the parts demand follows a Poisson distribution and a mean value calculated by a Bayesian procedure. When a unit fails at base level there is a probability r that it can be repaired at the base, a probability 1-r that it will be repaired at the depot. The advantages of the METRIC model are that an exchange curve of system availability is proposed versus investment value of spares parts rather than offering a unique value recognized as an optimum value. The second advantage is that system performance evaluation considers the system as a whole, with all the relationships and influences between the two echelons. [57]. **Muckstadt at al. (1973)** develop the analysis of the aircraft engines location issue. In order to accomplish the purpose a MOD-METRIC system has been developed: this system makes use of the average re-supply time for the end-product to establish the stock levels both for module and engines. In addition, the analysis is split into two levels: one corresponding to engine supply optimization and the other corresponding to module optimization. **Sherbrooke (1992)**. The purpose of the proposed paper is to find the best approximation possible of the expected backorders considering also lateral supply times; the study is based on low demand rate and even less lateral supply time. The idea is to use an interpolated factor to arrive at the lower and upper bounds (VARIMETRIC) is used. The demand at each base is assumed to be Poisson distributed. Other METRIC system-assumptions are also included. A simulation program is developed and run with various parameter values. The simulation gives accurate values for the case of depot-repairable only items but it does not apply as well to the base repairable items case. Since Sherbrooke considers the case of depot repair as particularly important (because the time to obtain the re-supply items from the depot can be long) he defends this case only. **Shtub and Simon (1994)** paper deals with a two-echelon inventory situation with not identical maintenance facilities where spares are expensive. In this paper the situation is the one of a two-echelon inventory system, there is a central warehouse which represents a special problem, where fill rate is to be maximized and a required priority exists among the facilities served by the warehouse. An algorithm is proposed and designed to assist management in allocating spare parts inventories and to recognize the consequences of a sequence of allocation decisions. By varying the simulation routine other scenarios may also be modeled.

QUEUE-based techniques

This method exploitation is justified by the fact that a multi-echelon system for repairable items can be viewed as a network of queues. Queuing networks models are being introduced to relax some assumptions that may be unrealistic in application (for example, infinite repair channels and infinite working item population, assumed by Metric). In literature, the analysis fall in to two types of queues: decomposition into individual queues and Markov chain representation of the entire system. The disadvantages of Markov chain models are that even for low critical problems the times for calculation is very high. As instance of a queue method modeling, **Gross et al. (1983)** developed a model of a two-echelon (two levels of repair, one level of supply) repairable-item provisioning system. It is desired to find the capacities of the base and depot repair facilities in order to dispose of a spares level which guarantees a specified system service level at minimum cost. For this purpose, closed queueing network theory is used to model the stochastic process, and an implicit enumeration algorithm is used to solve the optimization problem.

2.2. Assortment management literature overview

Table 1 summarizes the academic literature analyzed in spare parts classification field: it expresses how the assortment management issue for spare parts could be faced and implemented in real factory field. In the case studies researched, it has been decided to examine in depth the works accomplished in relatively recent years; this also to involve, in the assessments, the informative systems huge contribution for the spare parts classification issues.

Author(s)	**Year**	**Company**	**Methodology**				
			ABC	**NN**	**VED**	**FSN**	**Other**
Patrovi and Anandarajan [49]	2002	Pharmaceutical	**X**	**X**			
M. Braglia et al. [13]	2004	Tissue production and converting	**X**				AHP
Syntetos et al. [62]	2009	Electronic products	**X**				
Bacchetti et al. [6]	2010	White goods					Hierarchical multi-criteria
P. Joui et al. [37]	2011	Simulation					Multi-criteria
Molenaers et al. [41]	2012	Petrochemical			**X**		Multi-criteria
Vaisakh P. S. et al. [64]	2013	Chemical			**X**	**X**	
J. Chen & T.Chen [19]	2016	Simulation	**X**				Multi-criteria

Table 1 Overview of the case study contribution

In order to point out and check the benefits of the exploitation of a certain spare parts classification methodology in some companies, below has been depicted how these classifications affect spare parts management.

Patrovi & Anandarajan (2002): depict a case study of a large pharmaceutical company located in northeastern United States. The ANN (artificial neural network) model can be adopted as an interesting analytical tool in deciding whether classify a spare part in the A, B or C item category. The advantages of this method usage are related to two main aspects: first, ANNs can detect and extract nonlinear relationship and interactions among predictor variables; second, the patterns obtained and relative assessments of the precision of the ANN do not depend on the various assumption about the distribution of variables. Shortcomings of the exploitation of the tool must be recognized: first, variables, in number, which can be considered as an input are limited; second, the model doesn't have the potentiality and completeness to replace professional judgement. Furthermore, many new important qualitative variables may be difficult to incorporate into the models.

M. Braglia et al. (2004): The equipment analyzed concerns a plant working in tissue production and conversion. In particular, the plant is organized as follows: a continuous processing plant for paper production directly from pure cellulose, three converting lines for tissues production, one converting line for kitchen paper, and one converting line for toilet paper.

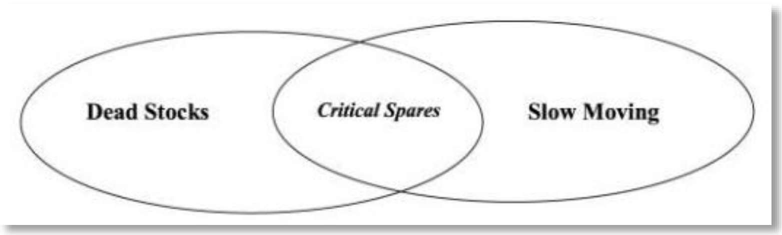


Figure 11 Sets for critical spares

The continuous production process works seven days a week. The converting department works six days a week, 24 hours a day. For what spares inventories concerns, potentially more than 10,000 articles must be managed. Thus, about 7,500 different components are stocked in the warehouse composing a value of more than two millions of dollars. The basic inventory policy adopted is based on the EOQ theory which makes it possible to obtain low risks of stock-out but with high levels of inventory. To reduce the dimension of the problem, a pre-analysis has been conducted to recognize the most "critical" spares. In particular, two ABC analyses have been based on slow moving and dead stock concepts. Slow moving items, means the spares category which have not been used for a pre-defined given period (five months). The so called dead stock, stands for spares characterized by a level of inventory which has never gone under a pre-determined level (dead stock) in a given interval of time (generally two years). The 1,600 spare components (20 per cent of the total) classified contemporarily in A-class in terms of slow moving and dead stock are defined as "critical" and subsequently analyzed with an approach named MASTA (multi-attribute spare tree analysis). Following JIT philosophy, 85 items are now managed, the single inventories of 52 items have been eliminated; and for 61 items the average stock levels have been considered too high and, as a consequence, reduced. It is interesting that, for some of these spares, the stock has been reduced to a single item. The monetary efforts reduction can be quantified in more than 100,000 dollars. This reduction is mainly due to the electrical components (65-70 per cent), followed by mechanical components of the tissue production lines.

Syntetos et al. (2009) present a case study of a European spare parts logistics operations of a big Japanese electronics manufacturer. The firm operates in to the European market in spare parts distribution; the spare parts classification was led by an ABC method divided on the basis of demand volume. The overall objective was to reduce logistics costs and increase considerably the hit-ratio (order fill rate) across Europe.

The proposed solution deals with the adoption of a Pareto evaluation, based on the demand value, but obtained as a combination of the spare parts cost and demand volume. Successively it has been considered appropriate to pursue detailed forecasting and inventory control methods. Before the project, the firm replenished spare parts using re-order points, supported by a 6-month moving average forecasting technique with judgmental adjustments.

In order to differentiate the approach according to parts classification, in the new solution different review periods and forecasting models were defined, as shown in Table 2.

Category	Review Period	Forecasting	Control processing
A	Week	Judgmental	Manual
B	Two weeks	System	Automatic
C	Month	Manually set	Automatic

Table 2 Forecasting & stock control for the spare parts classes discussed by Syntetos et al. (2009)

The new classification of spare parts allows the company to focus the managerial attention to the new A class SKUs (with a reduction of more than 900 items) accounting for almost 80% of demand value. As a result, is important to notice a decrease of the inventory costs whilst service levels targets were met.

Bacchetti et al. (2010) present a case in which the main European white goods manufacturers, (whose headquarters are in Italy) is analyzed from the parts classification point of view. Planning of parts was elaborated twice a month, exploiting the support of a software solution not integrated with the company ERP system. All the parts were managed in the same way (i.e. no classification modelling was in place). Items only differentiation is provided by a division brought by technology oriented differentiation and grouping together all the components with the same functionality. As a consequence, forecasting approaches were also non-differentiated. The new classification approach is composed by a multi-criteria structure which was developed taking in account of 6 factors explained below into details: sales cycle phase, response lead time to customers, number of orders, demand frequency, part criticality and part value.

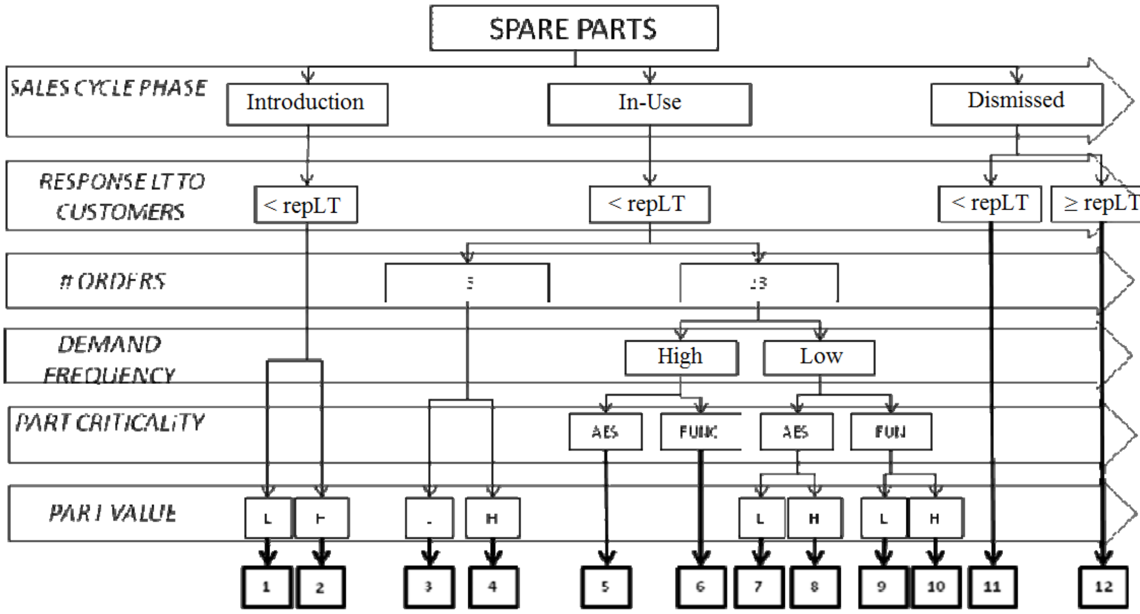


Figure 12 Steps for the spares classification, Bacchetti et al. 2010

1. Sales cycle phase. Sometimes evaluations on the demand pattern assessments are not possible or useful. When a new spare part is included in the assortment (spares for recently introduced products or new spares for existent products), historical information is obviously not available and this suggests the utilization of a forecasting approach that is not based upon a time series model but rather on causal techniques. Similarly, if the demand series consists only of zero, demand pattern analysis are not relevant.
2. Response lead time to customers. This criterion affects the decision of keeping or not in the inventory a particular spare part. That is to say, that the main component of delivery lead time (LT) is represented by the replenishment LT (lead time of receiving an order placed to the suppliers). Thus, is not necessary to keep inventories if the response LT is larger or equal to the replenishment LT.
3. Number of orders for some items can be very irregular and rare. Consequently, it is possible that some spare parts are demanded only once or twice in a period of several years. In these cases, only a reactive approach is possible a time series forecasting method may not be used.
4. Demand frequency. Literature showed by means of experimentation on the system employed by a software manufacturer that the ADI criterion is a very robust one for differentiating between alternative demand patterns. The researchers demonstrated, empirically, the insensitivity of the ADI cut-off value, for demand classification purposes, in the approximate range 1.18–1.8.

5. Part criticality**.** The functionality of a spare part determines its criticality and this affects the service levels offered to customers. In particular, the company makes a distinction between aesthetic and functional parts (more critical), and asks for different service levels and safety stocks for the two categories.
6. Part value. The cost of an SKU influences the overall inventory holding cost. The unit part value is used in order to dimension the parameters of order-up-to (OUT) level policies: for high value parts the OUT level is lower than that set for low value parts.

P. Jouni et al. (2011): In the case study presented by the authors, spare parts were categorized into three group; this considering the difficulty of implementation and usability of the categorization, the number of factors that will be used in the framework should be carefully selected. In order to accomplish the categorization desired by the authors, three important aspects have been highlighted and analyzed in depth: these are the supply category, demand category and price of the spare parts. For what supply category concerned a precise selection allows to emphasize three possibilities: key parts, industry specific parts and commercial parts.

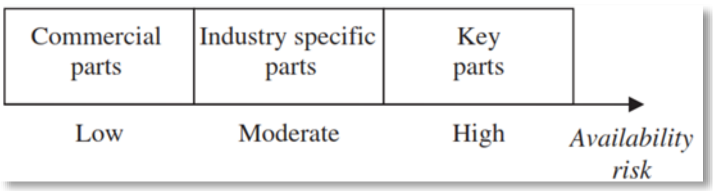


Figure 13 Part categorization, supply risk field

- Key parts are characterized by a low number of possible suppliers and are in most cases parts made only after the order. Being custom made, they follow MTO production planning also in the supplier's manufacturing process, for this reason, lead times are longs and key part suppliers request customers demand information in order to be able to plan their production. The demand forecasting is essential as in some cases the production quantities cannot be changed easily in a short period of time and there is a great risk of unavailability.
- Industry specific parts present similar key parts feature but are easier to manufacture and, for this reason, there are more vendors available and less availability risk in the supply. They are still usually manufactured according to company specific drawings, but are more generic in nature (such as machined mechanical parts) and the supplier lead-time is considerably shorter.
- Commercial parts are common bulk materials such as light bulbs, screws and bolts and widely used across all industries. Several sources are available for commercial materials, reducing also the possibility of variances in the lead-times as these kinds of parts are usually also stocked at suppliers' warehouses.

After the evaluations on how supply risk can affect spare parts availability and the resulting criticality, other two factors are placed at the basis of this categorization method: demand category and spare parts price. From the demand point of view five groups have been recognized according to demand variability and general value.

In Figure 14, the percentages of the cells represent the distribution of the categorized spare parts in the firm's assortment.

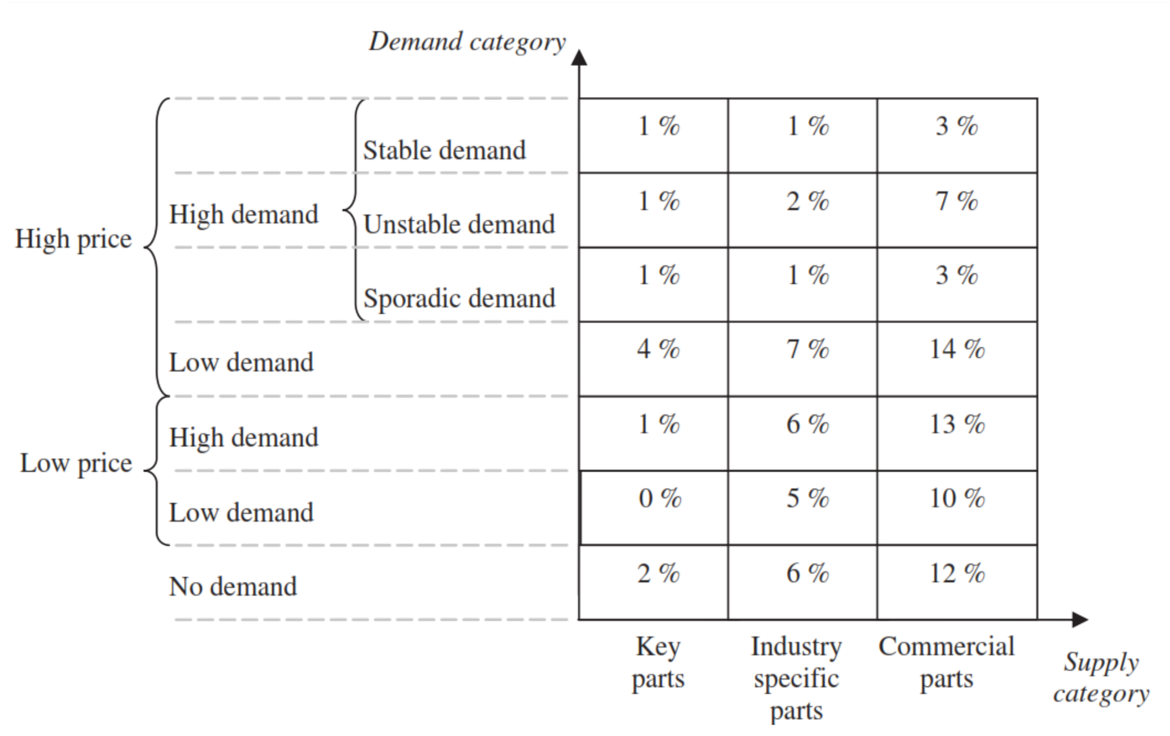


Figure 14 Categorisation matrix, link between demand, supply risk and price

Molenaers et al. (2011) executed a research work based on the study of an international petrochemical company located in Belgium. Likely every firm of the field, the one token in to account is strongly dependent from the availability of its assets and technical facilities (such as pumps, compressors, heat exchangers and so on); for this reason, at the basis of the policy adoption it is necessary the continuity of the production flow. Taking this into account, it is known that minimum downtime possible is assured also, and mainly, by spare parts availabilities. At the moment of the study, the firm dealt with more than 100 thousand SKU's in stock whose monetary value could be estimated of about 100 million euros. An overall ABC analysis showed that 98% of the total demand value was represented by merely 20% of the total article assortment, comprising 46 percent of the total stock value. It was highlighted that the organization disposed of an extensive and highly valuable spare parts assortment, which for a distinct proportion, 54%, could be classified as non-moving for four years. The criterion exploited to accomplish the most suitable spare criticality analysis are reported as follow:

- equipment criticality;
- probability of item failure;
- replenishment time;
- number of potential suppliers;
- Availability of technical specifications and maintenance type.

Vaisakh P. S. et al. (2013): the company that the authors analyze works in the chemical industry, in which firm managers have to deal with almost 40,000 inventory items including raw materials, spare parts and work in process inventory. These inventories need a proper inventory control system for minimizing the cost. It is found that there is a great gap from the optimal inventory management pursued by the company. The inventory costs represent the 39.42% of the total annual cost. According to industry standard values, it is acknowledged that the inventory costs of a continuous chemical process industry should be in between 25 – 30%. A combined FSN and VED has been exploited in the authors' work. To find out the non-moving items in store department FSN analysis is used while VED analysis is performed to classify non-moving items on the basis of their criticality. Acknowledging that the higher is the permanence of the item in the inventory, the slower the movement of the material would be. Accordingly, spare parts are classified in to three classes according to the FSN classification, via fast moving (F), slow moving (S) and non-moving (N) items based on their consumption and average stay in the inventory for a specified period. Combined FSN-VED analysis reveals that there are lot of items under non-moving – desirable (ND) category. Under ND category, 26 items, should be discarded from the store in order to reduce spare parts holding cost. This will not affect the production process, since it is less critical. Space availability in store department will be higher. On the basis of this analysis and results, suggestions can be given in order to improve the inventory management: such as a better co-ordination among purchase, production, marketing and finance department that will help in enhance efficiency in inventory management of spare parts. According to these considerations it is clear that the company can avoid to keep unnecessary spare parts in the store.

Antosz and Ratnayake (2016): within the process of the spare parts management authors agree on recognizing that it is vital to answer the following questions: how important is the particular part for ensuring the process of production continuity; how frequent are its failures; how much time do we need to exchange it; how high is the cost of its purchase; should it be stored; what is the time of its delivery; how many potential suppliers provide this part. That is why, in the proposed model the classification criteria are determined in two basic areas. The first is the machine maintenance process, the other is the logistics process. Within the machine maintenance area the following criteria were proposed:

- machine category (A B C D);
- spare part exchange time, in hours (<2, 2-8, >8);

- complexity of the exchange process (easy, medium, difficult);
- failure type (accidental, chronical);
- failure frequency, in years (<8, 8-16, >16);
- Employee's qualifications needed for exchanging a part (low, medium, and outsourcing).

J. Chen & T.Chen (2016): in their case study analysis, a classification has been offered in order to outline a method useful when warranty and others technical spare data are available. Based on authors' practice, this paper presents the following modelling steps for spare parts classification. The flow chart of the modelling steps is shown in Figure 15. The classification process moves from precise and particular assessments, whose value gathering work allows the authors to develop a multi-criteria method. This method builds its basis on the features listed below.

1. Reliability: in the after-sales center database of enterprise S, the warranty information may include number of the facility, production date, sale date, failure date, work hours and other claims information.
2. Supply characteristics: generally speaking, both spare parts replenishment lead time and supplier scarcity reflects the difficulty in obtaining spare parts. Considering that there are more uncertain factors if the lead time is longer, and the possibility of shortage will be greater. Scarcity factor is divided into three categories, respectively: not scarce, general scarcity, very scarce, with 1, 2, and 3 to represent.
3. Part cost: statistics show that although small the number of high-priced spare parts, the cost of spare parts is very high. This feature can be at the basis of the model because the general purpose is to control firm's outgoing.

4. Criticality: if the criticality is higher, once the failure occurs, it will directly affect the whole operation. We should increase its attention which has the higher criticality. The criticality of spare part is divided into three categories, which are common parts, important parts, and key parts, with 1, 2, and 3 to represent.

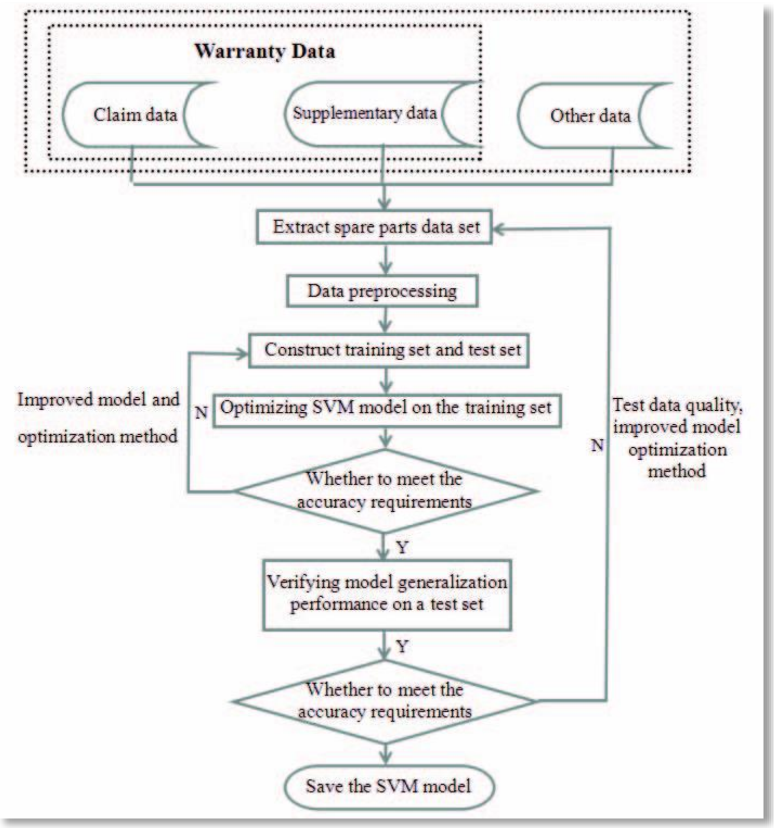


Figure 15 Spare parts classification process

The elaboration of the assessment is provided by (SVM) support vector machine based on machine learning method which is introduced for ABC classification of spare parts with small sample size. SVM states for a machine learning algorithm which is based on the statistical learning theory created by the author. SVM allows advantages such as: global optimization, short training time, good generalization performance, complexity of the algorithm and the dimension of feature space for limited samples for classification. It is suitable for the classification of spare parts. SVM has obtained good results in classification problems by its excellent nonlinear and generalization performance.

2.3. Demand forecasting literature overview

In order to manage and guarantee an optimal inventory and production flow control, an effective demand forecasting method plays a central role. Effectively, the spare parts management, in industries processes, acquires a crucial and strategic function. Features typical of the spare parts demand are their particular demand pattern; some of the traditional forecasting techniques may not be still efficient as for the common production parts. The spares demand pattern is difficult to modeling cause of the intervals in which the demand value is equal to zero and periods with demand are characterized by large variation levels. Below, a literature review is presented: real case studies analysis is offered and reported in order to accomplish a view on the forecasting techniques that authors proposed and applied to the firms they examined.

Authors	**Year**	**Company**	**Methodology**												
			CR	**SES**	**NNA**	**BPN**	**SBA**	**SY**	**TSB**	**ZF**	**NF**	**2S**	**ES**	**MA**	**GM**
T. R. Willemain et al. [69]	1994	Electrical equipment Jet engine Veterinary health Consumer food items	**X**	**X**											
M. R. Amin-Naseri & B. R. Tabar [44]	2008	Petrochemical	**X**		**X**		**X**								
F.L.Chen et al. [19]	2009	Semiconductor				**X**								**X**	**X**
W. Romeijnders et al. [54]	2012	Aircraft components					**X**		**X**	**X**	**X**	**X**	**X**	**X**	
ºM. Z. Babai et al. [5]	2014	Aircraft & automotive	**X**	**X**			**X**	**X**	**X**			**X**			
R. Hemeimat et al. [30]	2016	Paper mill	**X**				**X**		**X**				**X**	**X**	

Table 3 literature overview of the forecasting methods

Willemain et al. (1994) propose a case study in some different companies' fields, such as: electrical, aircraft, veterinary and food. The forecasting methods exploited are placed among the most classical and more frequently adopted methods, these are: the single exponential smoothing (SES) and an alternative of the Croston's method. The analysis portrayed moves from three statistical aspects of the industrial data: the intervals between shipments, the sizes of the shipments and the relationship between intervals and sizes. They compare these two methods, using artificial data created to violate Croston's assumptions and real-world data from industrial sources. Data kind that own the most troublesome for both Croston's method and exponential smoothing had a highly-skewed distribution of demand size and positive autocorrelation of intervals between demands. Datasets the study dealt with presented differences in several aspects, especially depending on the field in which the companies work. Mean intervals show how consumer food product owns the least intermittent demand pattern, since, in most cases, more than a single time period elapsed between shipments; on the other hand, the aircraft firm, with a smallest gap between shipments of more than 250 days. Regarding the forecasting methods results, on average, Croston's method is more accurate for all four companies' data. Effectively, Croston's method is superior in forecasting the artificial data series, generally reducing MAPE by 10 to 20 points. Since the actual forecasting method adopted from the companies is the SES, the probability of improvement is high for all four companies._However, in this study as the Table 4 depicts, Croston's method proved more accurate than exponential smoothing.

Type of product data	**# Data Series**	**Absolute reduction in MAPE**			**Percentage of Series with reduced MAPE**
		Best case	**Average**	**Worst case**	
Electrical equipment	4	24%	14%	7%	100%
Jet engine tools (daily)	16	7%	1%	-3%	88%
Jet engine tools (weekly)	16	24%	7%	0%	94%
Veterinary health	6	27%	10%	1%	100%
Consumer food	6	7%	3%	-1%	83%

Table 4 Data series exploited and MAPE reduction

Because Croston's method involves fairly simple calculations appropriate to forecasting grate numbers of low-volume items, production planners and inventory managers facing intermittent demand would benefit from switching to Croston's method.

Naseri and Tabar (2008): in their study, recurrent neural network has been exploited for lumpy demand forecasting of spare parts. In order to assess the performances of the proposed_model, the

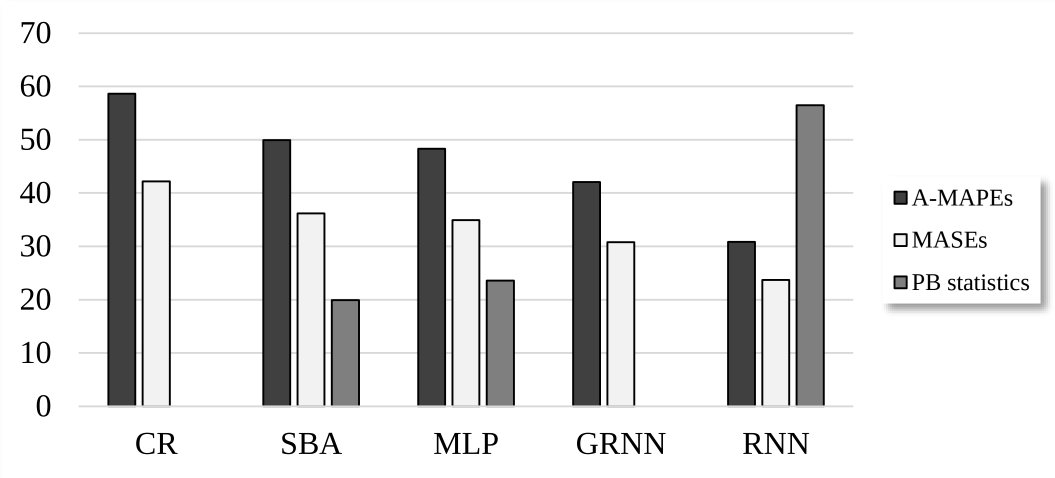


Figure 16 Accuracy indicators by Nasery and Tabar [43]

development is composed by comparing their forecasts to those obtained by using also two of the most used methods, such as the Croston's method and Syntetos & Boylan. The studies deal with 30 types of spare parts demand in Arak Petrochemical Company which has been elaborated. The data were handled for 67 monthly periods from 2001 to 2006. The data series were divided into two sets; namely training and test sets. Starting from 67 observations per month, 55 observations have been used for training the networks, and five methods tested using the last 12 observations. As can be seen in the Figure 16 a simple average of 30 A-MAPEs for RNN is 30.85. While this measure for method GRNN is 42.08, for MLP is 48.31, for SBA is 49.95 and for CR is 58.64, which clearly proves the superiority of our proposed RNN method.

Chen F.L., Chen Y.C., (2009): the case study deals with the forecasting techniques developed and tested in order to reach the most suitable prediction model. This investigation has the purpose to elect a technically appropriate tool, pursued through the comparison of the predicted demand and actual demand of critical spare parts in a semiconductor factory. The company analyzed is one of the leading semiconductor factories in Taiwan. The techniques exploited are listed below:

- MA: stays for moving average, considering the length of data, the author use 2 to 18 periods of data to derive the forecasted value of last ten terms of BGA sockets (one of the critical spare parts) requirement, and compare the difference with the actual requirement.
- GP: This investigation utilizes 4 to 6 entry of GM (1, 1) (grey method) to predict the consumption of BGA socket. The reason is that, according to the 28 months of data length, the GM (1, 1) needs

at least four data sets to predict future situation, and the more entries of GM (1, 1) may not indicate better prediction performance.

- BPN (back propagation model): the analysis carries also back–propagation network application to forecast the value of BGA sockets in last ten terms. At the training and testing process of BPN the first 18 data sets are used, and the last 10 data sets are used for testing process.

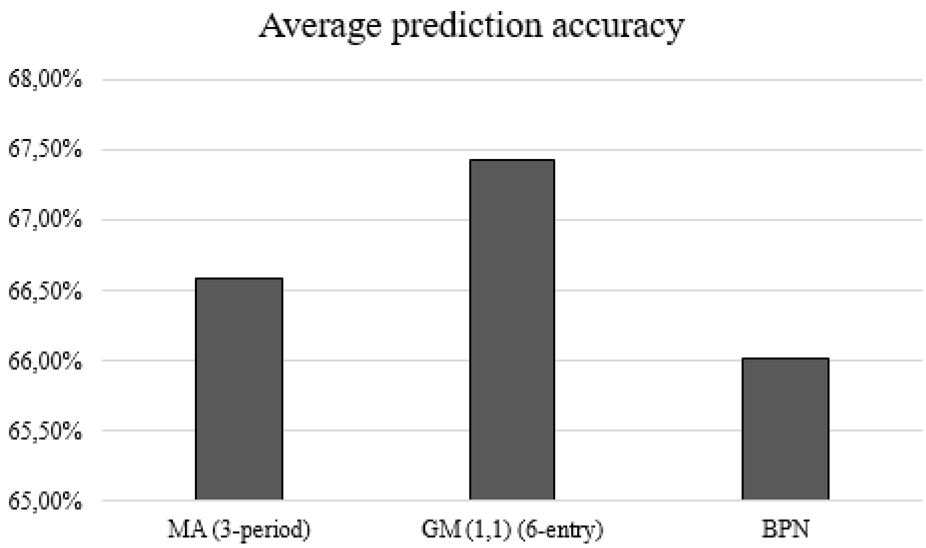
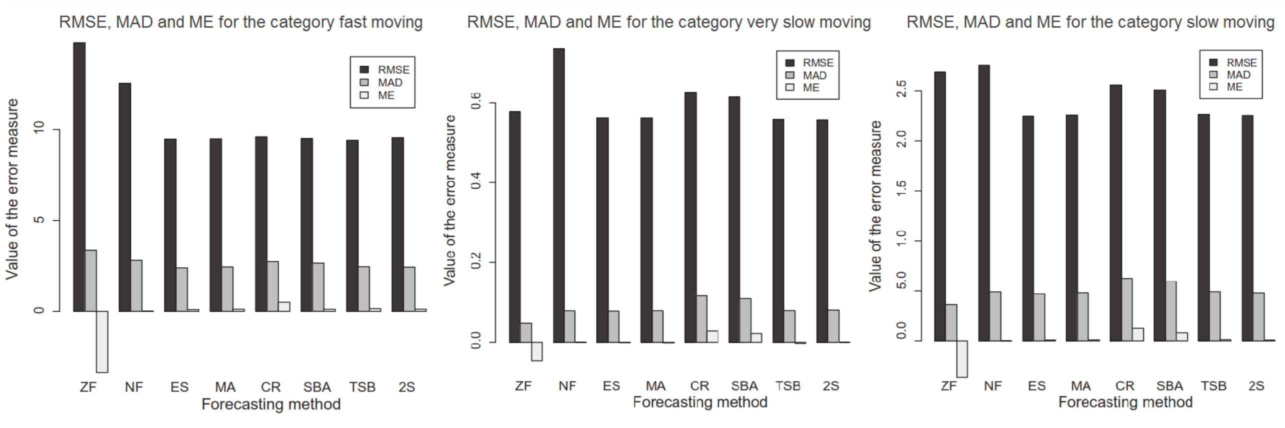


Figure 17 Comparison between the three forecasting methods elected by Chen F.L., Chen Y.C., (2009)

According to Figure 17, the GM(1,1) (6-entry) shows an higher average accuracy (67.42%) than BPN and MA, the order from high to low average prediction accuracy of prediction methods is GM(1,1) (6-entry), MA (3-period), BPN. It is clearly highlighted how neural network, when the data sets are few, data variation is large and the value of some influential factors is unknown at the prediction timing of current term, the GM(1,1) might have better prediction performance than BPN and MA. In this analysis, all the defects of NNs appear clearly. In fact, although majority of the scientific authors consider neural networks as the best performing forecasting methods from the, they don't well perform when data sets are few: a large training set is needed in order to take advantage of their peculiarities. In other cases, also traditional methods (as Moving Average) perform better.

W. Romeijnders et al. (2012): in this paper, the authors propose a method that, chase the most suitable demand forecasting technique on the basis of the spare part repaired. This two-step forecasting method updates separately the number of repairs for each type of component and the average number of parts needed per repair. The method proposed finds the empirical and comparative evaluation throughout the usage of a data set examination for a service provider in the aviation industry. The results obtained in this study show that the two-step method is one of the most accurate methods, even with a considerable better performance than the Croston's method. The data set contains information on over 100,000 repairs at Fokker Services during the period of ten years and three months. For each repair are recorded: the date of issue, the type of component that is repaired, and the spare parts used. Spare parts categorization starts with the number of months with positive demand during the initialization period. The three categories are recognized in: very-slow moving (1–5 months with positive demand), slow moving (6–20 months), and fast moving (21–84 months). Further categories could be chosen by considering the demand size lumpiness as well, but it has been determined that demand 'speed' data has



the most significant effect on the comparative results in the study. The two-step forecast (2S) is the only forecasting method that makes use of the additional information that is available. Instead of forecasting parts demand directly based on the part demand history, 2S starts at the component level. In order to accomplish the correct assessments, the techniques adopted are: NF, MA, ES, CR, SBA, TSB and 2S.

Figure 18 Analysis of the forecasting techniques accuracy by Romeijnders et al. [53]

The results are similar across the categories slow moving and very slow moving. The most important conclusion is that, for these categories, 2S is one of the best methods, and that it performs considerably better than the well-known Croston method but does not outperform all benchmark methods. Methods ES, MA and TSB perform as well as 2S.

Badai et al. (2014): The empirical investigation selected in this paper deal with two spare part datasets which consist of the individual monthly demand histories of 5000 SKUs over 7 years from the royal air force and another which consists of the individual demand histories of 3000 SKUs covering 24 consecutive months from the automotive industry. Explore the empirical performance of forecasting methods used in intermittent demand context, paying particular attention to the effects and implications of the smoothing employed for updating purposes. The dataset consists of items with a very high lumpiness degree. To develop an assessment on which techniques performs better are analyzed the following methods: SES, SY, SBA, Croston, TSB, Naïve and Zero.

Table 4
Minimum (across SKUs) MSE results—dataset 1.

Estimator	α	β	ME	MSE	MASE
SES	0.05		−0.066	74.970	0.891
SY	0.1	0.05	0.099	75.144	0.892
SBA	0.1	0.1	−0.107	74.923	0.883
Croston	0.1	0.05	0.116	75.137	0.893
TSB	0.1	0.05	−0.064	75.033	0.889
Naïve			0.054	136	1.127
Zero			−4.422	146.219	1.229

Table 5
Minimum (across SKUs) MSE results—dataset 2.

Estimator	α	β	ME	MSE	MASE
SES	0.05		−0.118	233.804	1.510
SY	0.15	0.3	0.190	231.267	1.424
SBA	0.15	0.3	0.156	230.961	1.413
Croston	0.15	0.2	0.414	232.906	1.492
TSB	0.15	0.02	−0.178	232.202	1.402
Naïve			0.001	449.615	1.642
Zero			−1.344	238.172	0.872

Table 5 Assessments on forecasting techniques exploited by Badai et al. [5]

Measures like mean error (ME), the mean square error (MSE) and the mean absolute scale error (MASE) has been adopted in order to assess the performance of the forecasting methods accuracy

The two datasets analyzed lead to different results: in fact, those for dataset 1 (with relatively fast moving SKUs) are most in line with expectations and simulation findings. Considering all SKUs of that dataset, Croston has the largest positive bias, SBA a smaller negative bias, and TSB and SY have even smaller biases. The different Croston-type methods show very similar MASE, MSE and therefore also inventory performances. For SKUs from dataset 1 with a negative trend in demand, TSB does show a superior inventory performance, although the other methods do not lag far behind. The results for dataset 2 paint a very different picture. Croston is still the most biased, but has the best inventory performance. Even for only SKUs with decreasing demand from that dataset, Croston outperforms TSB and all other methods. This could relate to a high degree of non-stationarity of that dataset, rendering theoretical results based on the assumption of stationary demand less indicative.

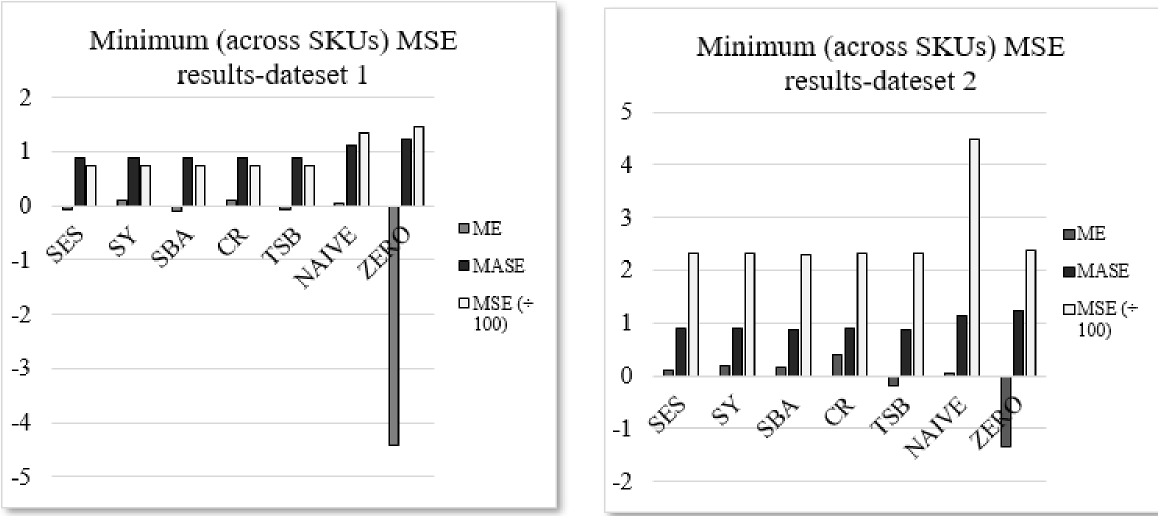
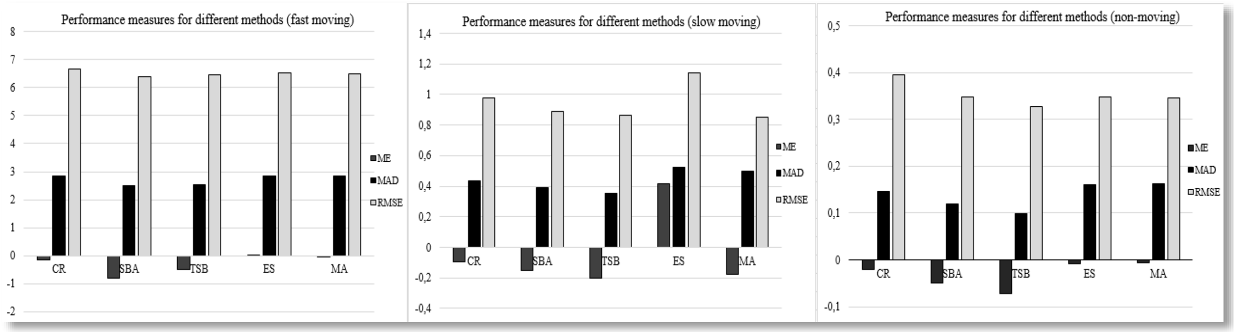


Figure 19 Evaluation on the forecasting methods accuracy by Hemeimat et al. [30], from left to right (a),(b),(c)

Hemeimat et al. (2016), the authors, in an investigation made on a paper mill apply evaluate five different forecasting methods through three accuracy indicators in order to elect the most suited tool.

Figure 19 (a) shows the performance measures obtained for the five forecasting methods for the fast moving items. The results show that the reliance on RMSE instead of MAD has small impact on the comparison between methods. The SBA method gives the lowest RMSE with value equals to 6.385. However, it gives high bias through ME value of −0.815. The TSB method gives the second lowest RMSE value with a value equals to 6.460. TSB gives −0.508 ME value which is better than SBAs' ME value. However, it is considered a low ME value compared to the remaining three methods. MA and ES methods show close error measures values. Lastly, the CR method shows the poorest RMSE performance with a value equal to 6.661.

Figure 19 (b) shows the results obtained from the techniques evaluation of the five forecasting methods for the slow-moving items. The TSB method leads to the lowest RMSE with a value equal to 0.867. It also leads to lowest ME with a value equals to −0.201. The SBA method, not so far from TSB, gives the second lowest RMSE value with a value equals to 0.889. SBA leads ME equal to −0.150. Lastly, the ES method shows the higher RMSEvalue



With a value equal to 1.139 and ME value equal to 0.010. Figure 19 (c) shows the performance obtained by the accuracy tools exploited for the five forecasting methods for the nonmoving items. The TSB method gives the lowest RMSE with value equals to 0.328. Also it gives the lowest ME value of −0.073. The MA method gives the second lowest RMSE with a value equals to 0.345. In addition, MA has the best bias performance with ME value equals to −0.006. Lastly, the CR method shows the poorest RMSE performance with a value equals to 0.396.

In recent years, condition-based maintenance (CBM) has been becoming one of the most popular strategies of preventive maintenance, which aims at making maintenance decisions based on the evaluated health conditions of equipment. Below are proposed some case studies in order to contextualize the CBM methodology in the demand forecasting field.

H. Qiu et al. (2007).

Bearing failure is one of the foremost causes of breakdowns in rotating machinery and such failure can be catastrophic, resulting in costly downtime.

To prevent unexpected bearing failure, vibration analysis has been used extensively for various bearing condition monitoring techniques. Driving by the desire of improved machine uptime and near-zero breakdown productivity, more and more attention has been put onto predictive maintenance, which necessitates advanced tools in prognostics. Prognostics is using predictive maintenance practices and tools to analyze the trends of machine performance against known engineering limits for the purpose of detecting, analyzing and correcting problem before failure occurs. Four double row bearings were installed on one shaft. A high-sensitivity accelerometer was installed on each bearing housing. Four thermocouples were attached to the outer race of each bearing to record bearing temperature for monitoring the lubrication purposes. Several sets of tests ending with various failure modes were carried out. The time domain feature shows that most of the bearing fatigue time is consumed during the period of material accumulative damage, while the period of crack propagation and development is relatively short. A prognostic approach that can detect the defect at the early stage is demanded so that enough buffer time is available for maintenance and logistical scheduling [52].

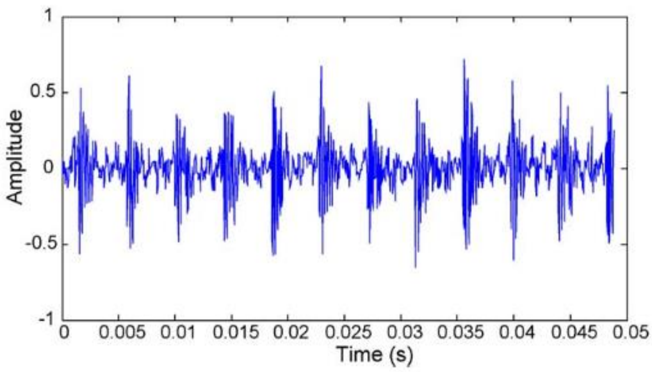


Figure 20. The vibration signal waveform of a faulty bearing

In Figure 20 presents the vibration waveform collected from the bearing number 4 at the last stage of the bearing test. The signal exhibits strong impulse periodicity because of the impacts generated by a mature outer race defect.

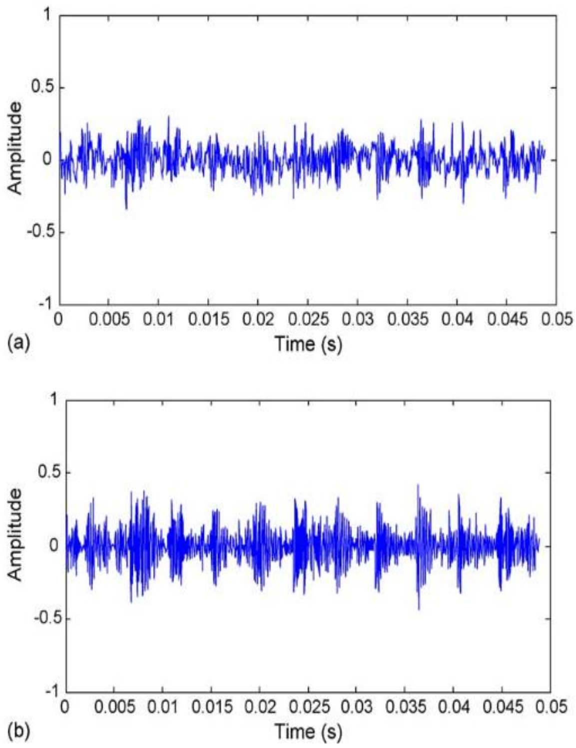


Figure 21. The vibration waveform with early stage defect: (a) raw signal (b) de-noised signal using the wavelet filter

However, when examining the historical data and observing the vibration signal three days before the bearing failed, there is no sign of periodic impulse as show in Figure 21 (a). The periodic impulse feature is totally masked by the noise. Applying the designed filter to the noisy raw signal, the de-noised signal results as filtered and analyzable, providing as shown in Figure 21 (b). The periodic impulse feature is, therefore, revealed, which is strong evidence of bearing outer race degradation. The wavelet filter-based de-noising method successfully enhanced the signal feature and provided potent evidence for prognostic decision-making.

S. Ignat (2013)

Presents a case study in which Bagger pumps represent an important critical aspect for continuous and nominal output operating cauldrons. A system composed by three Bagger pumps is analyzed and the CBS methodology has been applied in order to reach the most effective maintenance policy. In this case degradation assessments bring important values: degradation modeling is a critical and challenging aspect of the implementation of a CBM program. In fact, it is known that, degradation model measurements traverse upward or downward toward a failure threshold, and the system is considered failed at the time when the measurement crosses a predetermined failure threshold. The failure mechanisms for the system must be understood so that an appropriate degradation model can be developed. After an FMEA criticality analysis of the equipment, a Markov chain model with five states has been developed. At the basis of the model there is the presence and evaluation of lots of technical data, the data mainly employed for the Markov chain are: MTBF (λ) and MTTR (μ). After the development of the model assessments are obtained with the indicator Forced Outage Rate (FOR) equivalent to $\lambda/(\lambda + \mu)$. [34]

H. Qiu, et al.

In this paper, are analysed the predicted probabilities of equipment failures over time with assessments on cost effectiveness of many maintenance schedules. With the purpose to have the possibility to assess these maintenance strategies first, a brief description is offered:

- Corrective maintenance strategy, called "strategy A", utilizes FIFO behavior so that the maintenance is performed whenever there is a machine failure and there is a maintenance person available.
- Scheduled maintenance strategy, called "strategy B" in which maintenance is performed in regular time intervals.
- CBM, called "strategy C" in which maintenance crews possess information about the current condition of the equipment.
- Predictive maintenance strategy, called "strategy B", which use the current and predicted equipment conditions and take into account both production benefits and maintenance expenses.

In 22 our different combinations represent the four cases developed; these cases are assessed to evaluate the effects of different components in the cost function. In figure are exposed the benefits of the strategies in the different environments, it is clear that the performances of the csb-based models, although more complicated, bring to higher monetary benefits [67]

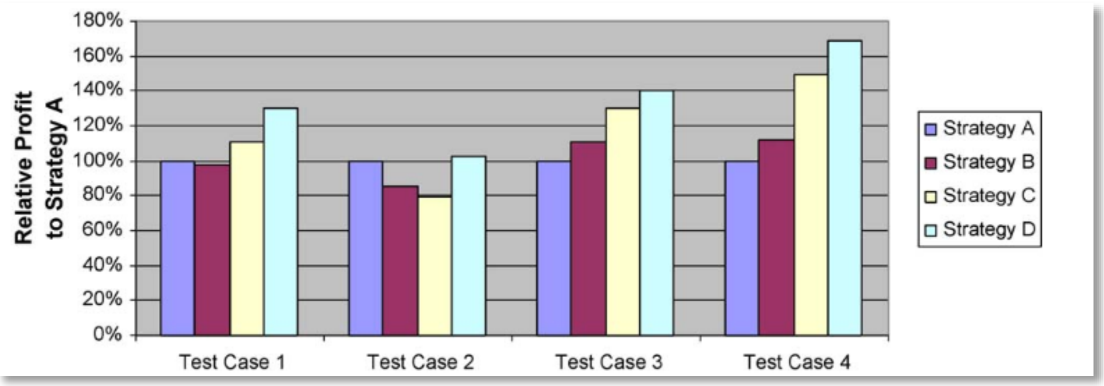


Figure 22 Relative profit chart between maintenance strategies for the four test cases

2.4. Supply management literature overview

The manager should ensure the availability of spare parts during the production given a service level, which means long time availability. There is no law in the legislation that regulates the time a supplier of an eventual machine has to keep producing spare parts and this fact could be the reason for the lack of availability. If the manufacturer has decided not to support the product or that the support will only last for a finite period of time. The part may also be outsourced, and that source could eventually dry up. Supply management features and relative tools have been researched and the results have been provided in most of the assessments by the theoretical study. Practical evidences have been found in the decision on the logistic level in which to address the reparation of a spare L.O.R.A. (level of repair analysis examined by [9] [23] [42]), through the METRIC-based approaches ([59] [60] [44] [58] [30] explained in section) and, in a general view, through the terms present in spare parts supply contracts: parameters as the price, lead times, penalties and others features. [1] [2] [47]

2.5. Inventory control literature overview

The general function of spare parts inventories is to assist the maintenance staff in keeping equipment in operating condition. Therefore, the policies that govern the spare parts inventories are different from those that govern other types of inventory such as, thinking of a manufacturing plant, the raw material, work-in-process and finished goods inventories. In fact, spare parts are characterized by low demand with stochastic and frequent irregular patterns.

Below, a literature overview is presented with the aim of expose how spare parts inventory issue has been managed and solved by authors throughout the years and inventory control methods exploitation.

Author(s)	**Year**	**Company**	**Replenishment policy**			
			(S-1, S)	(s, Q)	(s, S)	**Other**
J. Ashayeri et al. [5]	1996	Computer service parts				EOQ
K. Cobbaert et al. [19]	1996	Wire-drawing mills		**X**		EOQ
R. Botter et al. [10]	2000	Electronic components	**X**			(R, s, Q)
K. P. Aronis et al. [3]	2004	Circuit packs	**X**			
M. Braglia et al. [13]	2004	Tissue production and converting	**X**			EOQ
P.L. Chang et al. [18]	2005	Semi-conductor				(r, r, Q)
E. Porras et al. [49]	2007	Oil rafinery	**X**		**X**	(s, nQ)
M. Bevilacqua et al. [10]	2008	Food production	**X**			(s, nQ)
Syntetos et al. [63]	2010	Industrial Valves		**X**		
Nenes et al. [46]	2010	Distributor of castors and wheels				(R, S)

Table 6 inventory control literature overview

The study reported how is similar, through firms of different fields, the decision on inventory methodology adoption. In fact, has been noticed a huge presence, among others methods, of the (S-1, S) model adoption which clearly allows the firms to manage very expensive stock, in terms of price value and critical components availability. Where permitted by the products features also the economic order quantity is a method adopted in the case studies analyzed; this method usage is particularly worthwhile in fields in which spare parts considered have not a quite great value and the risk of obsolescence is low. Shown below descriptions of the case studies investigated from the authors.

J. Ashayeri et al. (1996): the authors offer a contribution in the spares replenishment field throughout a study of an Italian computers and computer service parts manufacturer. The company's stock which the authors study saws over 10.000 different components, on average, almost 50% of the components have a positive inventory status at any time. There are 2.300 different types of repairable module of which 1.600 types are frequently demanded. There are two types of repairable modules, those generated by the customers and those with a service contract; 90% of the repairable modules demand is constituted by the latter ones.

K. Cobbaert et al. (1996): the study offered in the paper rises in connection with an inventory audit made in 1993 at an engineering firm specialised in the fabrication of machinery for wire-drawing mills. More in the deep of the analysis, it is presented a distribution center which deals with more than 30.000 parts for machines. From this center, the items are distributed, on request, to wire fabricating subsidiaries, scattered all around the Western World. After accomplishing an ABC-analysis of the inventory, it is clear that a great number of slow moving items were stored, and that these constituted a large portion of the huge monetary value of the stock. It appeared that most of the slow moving items were obsolete spare parts: they could not be used anymore. The main cause for these large residues seemed to be the following. The distribution center was under the obligation to provide at any subsidiary, at short notice, a series of fast moving spare parts. As a result, large inventories of these items were kept. However, after some time and without much warning some wire-drawing machines were modified or machines were entirely taken out of production, thus making sets of parts redundant. Such changes happened rapidly, in a very short time span, and usually all machines of the same type were involved. In this paper a few simple inventory models for fast moving items subject to "sudden death" obsolescence are developed. Contrary to the models developed in the literature, which demand unrealistic assumptions and rely on dynamic programming. The proposed techniques are practicable and immediately useful for inventory management. First, the EOQ dealing with an invariable obsolescence risk was reconsidered. This model was then changed to incorporate a varying risk. Also the standard (S, Q) model was modified and the impact of lead time was analyzed. When the obsolescence cost is not extremely large compared to the other cost parameters, all resulting formulas and techniques appear to be simple and implementable. However, since the obsolescence risk changes over time, regular updating of the formula coefficients becomes unavoidable. To deal with this complication, items should be clustered in homogeneous groups. Each group is such that its items follow the same risk pattern. When the danger for obsolescence is real, management should take it into account. This is illustrated by a small numerical example.

R. Botter et al. (2000): EDIAP is a large multinational company; it develops, manufactures, sells, supports and services electronic devices to be used in industry. In order to support the installed base throughout the product lifecycle, EDIAP has a multi- echelon distribution and repair structure to supply customers with service parts. It operates in a market characterized by growing importance of after sales activities and severe competition. In each country, management is responsible for service performance and related costs. Stocks for service parts are kept at a recommended (order-up-to) level, called target stock level (TSL). When customer demand appears, the stock level will drop below the TSL and automatically an order is generate. Prices of service parts are high, and customers demand usually one piece at a time of a certain item. Hence the ordering procedure follows the (S-1, S) rule. At European level, inventory control follows the (RsQ) policy, that is to say, stock levels are reviewed weekly (R), and a quantity of service parts (Q) is ordered whenever the stock level has fallen below the reorder point (s). In total, there are about 50,000 active part numbers. Conventional inventory theory is not applicable here, as demand frequency is far too low. Sophisticated mathematical models, with complex distribution functions to approximate low demand levels, have to be rejected also. The reason for this rejection is simple: management finds them too difficult to implement and too hard to maintain.

Three dimensions described can be depicted in a framework. Along each axis two general classes are defined. This choice is arbitrary: it is up to management to decide upon the number of classes for each of the dimensions. We suggest taking no more than two. Then the number of different segments becomes eight, which is manageable. Each segment represents a particular group of service parts, each with its own approach. The segments are shown in Figure 23:

1. Low price, short response time, high usage. These cheap, fast moving items have to be stocked in large quantities in local warehouses, i.e. close to the market.
2. Low price, short response time, low usage. These cheap, slow moving items also have to be stocked close to the market, but in lower quantities.
3. Price, long response time, high usage. For these items inventory costs and transport costs should be investigated, in order to determine whether or not local stocking is better than central stocking. Local stocking of fast moving parts could decrease transport costs, as larger quantities can be shipped by cheaper means of transport.
4. Low price, long response time, low usage. These service parts are only to be stocked centrally, at the ESC.
5. High price, short response time, high usage. These parts require firm management, as stocking is expensive. Owing to the short response time, parts primarily have to be stocked in local warehouses. The quantities should be as low as possible, and depend on the desired customer service level.

6. High price, short response time, low usage. Again firm management is needed. It may be worthwhile to consider a fast means of transport, even if it is expensive (e.g. taxi). In this case stocking centrally in the countries becomes possible, thus reducing inventory costs.
7. High price, long response time, high usage. For these parts a trade-off has to be made to choose between central stocking in the countries and at the ESC.
8. High price, long response time, low usage. Owing to the long response time these items can be stocked centrally at the ESC and shipped by regular means of transport when needed.

In this way an integrated stocking strategy is obtained for all segments.

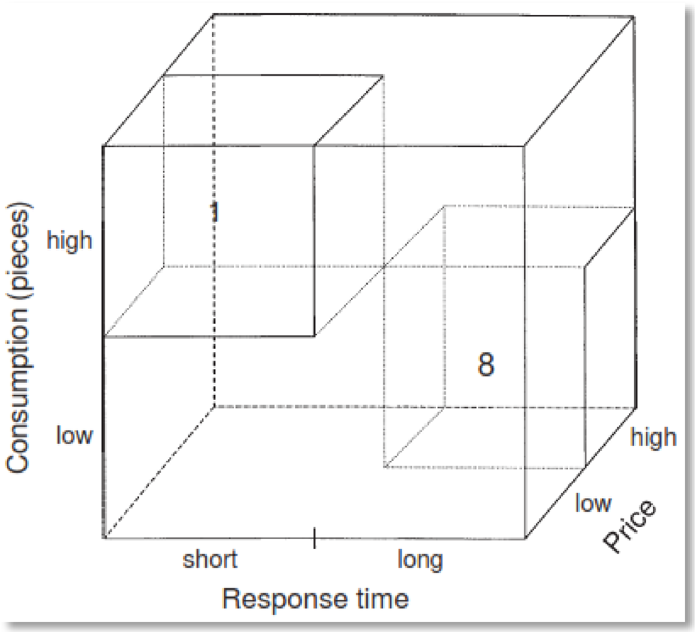


Figure 23 Example of framework depiction for consumption, R. Botter et al. (2000)

K.P. Aronis et al. (2004): The Company, the authors take into account, designs, develops and manufactures communication systems. One class of its products is circuit packs with specialized software downloaded in them. These circuit packs are parts of electronic equipment, installed in telephone switching systems at large communication firms. It is clear that continuous operation of these systems is essential for customers. When such a system ceases to operate because of a failure in a circuit pack, it has to be immediately restored by replacing the failed circuit pack with a readily available spare part. Thus, the demand for spare parts originates by the random failures of the installed circuit packs. The proposed method is not much more complicated than the one currently in use by the company manufacturing and providing the spare parts. Using the same form of inventory control policy, i.e., the (S-1, S) system, the Bayesian method results as functional tool to have lower total stock for the same level of service.

M. Braglia et al. (2004): The equipment analysed concerns a plant working in tissue production and converting also presented in the spares classification methods phase. The IMP matrix represents a good support to plan the inventory management policies since it makes it possible to identify the strategy in function of the criticality class of the item. Paper also shows the IPM matrix developed in our case study following the ideas and suggestions of company maintenance experts. As one can see, in terms of inventory, each equipment spare is assigned to one of four possible strategies:

	Spare part classification			
Inventory policy	A	B	C	D
No stock	X	X		
Single item inventory	X	X		
Just-in-time policy		X	X	
Multi item inventory				X

Figure 24 Inventory management policy matrix

1. no stock: under a MASTA program, the unavailability of a spare represents a conscious decision reached after that the department involved has made assessments on what facility function would be affected by the absence of the spare in case of failure on the cost or problems tolerable to have an immediate availability of the item;
2. Single item inventory: this is, certainly, the most basic approach. Considerations concerning the risk of unavailability for the plant, the capacity to prevent failure time with appropriate maintenance policies, inventory problem and supply characteristics lead toward the stock of a single unit of the spare part;
3. Just-in-time policy: this represents the most desirable approach. This is mainly possible due to the high level of integration between customer and supplier which makes it possible to obtain quick and reliable supplying in cases of failure. Despite the potential critical consequences for the plant of an unavailability of the item, considerations about the easiness and velocity of supplying, the good “control” of failure phenomenon with appropriate maintenance policies and the problems of storage (i.e. cost, space, etc.) lead toward the absence of inventory;
4. Multi item inventory: this expensive strategy is mainly due to the high critical impact of an unavailability of the spare on the performances, in terms of cost and quality, and safety of the plant. Difficulties in spare provisioning do not allow a just-in-time strategy of supplying to be used;

P.L. Chang et al. (2005): This paper is motivated by a case study developed for manage the inventory control of spare parts at a semiconductor equipment manufacturer in Taiwan. The company manufactures many different types of integrated circuits (ICs). The production is guaranteed through the usage of a typology of equipment which involves a spare parts inventory of more than 2000 different types of items with a value of over US$15 million dollars. In spare parts inventory systems the situation may occur that identical parts can be installed in different equipment, with different importance for the production process. Hence, some of the demand may have very high penalty costs in case of a stock-out. In this paper it is discussed a model that enables the authors to handle different classes of demand. The aim of this article is to develop an inventory model with two demand classes using a (r, Q) policy. In the model proposed, only two parameters are included where Q is the order quantity, r is the critical level and is chosen to be equal to the reorder level.

The assumptions:

- demand classification is defined recognizing two spares classes: critical and non-critical demand;
- the proposed method is based on the stochastic continuously reviewed constant reorder quantity policy (r, Q);
- all outstanding backorders can be satisfied in every replenishment and the stock level after a replenishment order arrives results higher than r;
- the lead time of replenishment is constant;
- critical or non-critical demand over the lead time is high enough so that the normal distribution can be used to describe the demand patterns of spare parts;
- Inventory demand shortages are back-ordered.

E. Porras et al. (2007): the company under study is a petrochemical complex located in the Netherlands. At the moment of the study (2000), there were 130 thousand materials catalogued, of which kept in stock at the site 43 thousand. From the total of 43 thousand materials stock, 14,383 were spare parts, the 80% of the total stock value which is around 27 million euros. Using factors as criticality, demand and price, the authors include each item in a combined class defined the three features defined above. This classification allows the authors to optimize the system per class rather than for individual items and it is practically made in expert judgement with no quantitative methods. In the model proposed, the authors adopted an (s, nQ), (S-1, S) and (s, S) inventory policies for the system, with the re-order point "s" evaluated using various demand lead time distribution such as Willemain's bootstrap method, empirical distribution, Poisson and normal distribution. Thus, the lot size "Q" will be evaluated according to the economic order quantity (EOQ) using average annual demand. From the models implementation results, it is evident that for the aggregated values across all classes considered in the system, all the models outperformed the current system under the ex-post approach, allowing to record a lower total cost and higher fill rates, with overall circle service level (CSL) within 5 ± 1% of the current CSL. For the different models under the ex-post approach, authors make the following observations: the normal (distribution) model achieved the best overall performance among the models, achieving the highest total savings, although for demand class 1 typology the empirical and

Model	Parameters
Current policy (C)	min–max (s, S)
Poisson based model (P)	$(S-1, S)$
Normal based model (N)	(s_N, nQ)
Empirical based model (E)	(s_E, nQ)
Willemain based model (W)	(s_W, nQ)

Figure 25 Inventory models considered

Willemain models performed very similar with respect to the normal. For this spares class the Poisson model performed the worst of all models. Total savings for the normal model can be assessed of 8.4% over a total current cost of 15.5 million euros for the 5-year period, and with overall fill rate of 92.6% despite a current fill rate of 89.2%. The cycle service level achieved by this model was 85.1%, slightly lower than the one of the current system. The empirical model outperformed Willemain's model in terms of total savings (1.05 vs. 0.96 million euros), both achieving overall fill rates above 90% and similar overall cycle service levels. To explain the difference in performance of these models, we found that the Willemain model evaluates slightly higher re-order points to achieve the same service level as the ones of the empirical model. The reason of this is ascribable to the reason that the Willemain method produces a larger range of different lead time demand values, whereas the empirical method uses the exact values observed in the data set to construct the LTD distribution.

M. Bevilacqua et al. (2008): This paper concerns a maintenance spare parts on an important Italian pasta producer. The process included in the pasta production can be listed as follows: wheat selection, first transformation of cereals, winnowing of wheat, conditioning, milling, dosage, mixing and braking, modelling, dehydration, cooling, storage and packaging. In 2006, the company did not adopt and perform any sort of preventive maintenance policy for the spare parts of the productive plants. The maintenance management policy consisted only on a corrective one with the most part of spare items purchased only in presence of a failure. Maintenance Manager decisions on spare parts order policy was based only on his own personal experience, leading the department even to critical situations, such as: the risk of long plants stop in case of critical components stock out, a supplier lead time high uncertainty, the inconvenience due to possible hurried repairs and renewals, in order to avoid plant stop. Authors' aim is to compare various policies with real demand data from the case to see which one is best under what circumstances. Authors also evaluate the performance of the system using Normal, Gamma and Poisson distribution based models.

In the Poisson distribution usage adopted to estimate the Lead Time Demand (LTD), "Q" is equal to 1. This model is often referred to as (S - 1, S) model, with s = S – 1. As average demand is generally low in this case, the EOQ calculation also yields a value of 1.

In the case of the Normal distribution an (s, nQ) inventory policy has been adopted for the system, with the re-order point "s" evaluated using the LTD distribution according to the modelling methods described above. Thus, when overshooting of the re-order point "s" cannot be overcome by the lot size "Q", an alternative lot size equal to nQ is ordered, such that the inventory

	Normal model		Poisson model		Gamma model	
Utilization class	Inventory level	Inventory value [€]	Inventory level	Inventory value [€]	Inventory level	Inventory value [€]
A	927	23170	825	21320	870	21715

Figure 26 Stock value corresponding to the distribution model and demand class

position is brought above s, where n is an integer value. In the case of Gamma Distribution the inventory management policy used was *(s, n Q)* type. According with these results all items with an average value lower than 6 will be managed using the Poisson model, while for the other items Gamma and Normal models will be tested.

Nenes at al. (2010) present a case of a small Greek distributor of casters and wheels with a range of about 3,000 components, bought from 28 different suppliers. The authors develop and apply an easy-to use inventory control system for lumpy demand items. The authors move from the observation that, even if researchers may propose sophisticated methods to forecast or manage demand, in real contexts the methods utilized are limited to the implementation of a few basic and generic tools, such as traditional forecasting techniques or the computation of the economic order quantity. The inventory control system is based on a periodic review order-up-to level (S) inventory policy (R, S), the review period R depending on the supplier characteristics. The authors implement a decision support system based on the following steps:

1. Selection of data input for each SKU (review period, lead time, target fill rate, demand history);
2. check for sufficiency of demand data: simple policies are proposed for SKUs with insufficient demand data;
3. demand analysis: checking the goodness-of-fit of the Gamma and Poisson distributions (the former for faster-moving items and the latter for the slower-moving ones);
4. search for demand data outliers;
5. Computation of base stock levels for each SKU policy and other characteristics (expected demand, coefficient of variation, average stock-on-hand).

The proposed decision support system is integrated within the company's information system. The main effects of the project acknowledged by the company managers are the identification of obsolete SKUs, the reduction of inventories, for a given service level and the reduction of urgent orders to suppliers and transportation costs.

Syntetos et al. (2010) address the case of a wholesaler of industrial valves. The company sells more than 2,000 SKUs which are primarily stored in the warehouse ready for dispatch. The company's supply base is quite vast, given the wide range of items available in its catalogue. The planning system prior to the project was based on manual stock control, with a periodic re-order point type system. This procedure was not formalized and relied on the skills of one single person. For instance, the order quantity corresponded to the average demand over a number of weeks – the number not being readily available; similarly, the re-order points were arbitrarily specified, with new SKUs not even having a suggested re-order point. The new implemented solution described in the paper did include demand classification but only for the purpose of demonstrating to management the distribution of SKUs with regards to their contribution to profit as well as the tremendous opportunities that existed for scrapping a large number of obsolete SKUs. Since a considerable proportion of SKUs showed intermittent demand, the Syntetos-Boylan Approximation (Syntetos and Boylan, 2005) was used for demand forecasting; this was in conjunction with a periodic reorder point (s) order quantity (Q) (s, Q) policy that matched, conceptually, what was previously in place, but obviously through a rigorous and much more formal application. The application of the new methodology (for a target service level of 95%) led to expected inventory-related cost savings of about 40%. That beneficial performance was accompanied by the introduction of an aggressive write-off strategy for obsolete SKUs that was perceived of equal importance by the management of the company to the very new procedures.

3 DEVELOPMENT

3.1 IDEF representation methodology

In this paper it has been decided to exploit a particular tool to represent the flow charts: IDEF. IDEF acronym stands for Integrated DEFintition: it is a method designed to model the decisions, actions, and activities of an organization or system. This methodology's peculiarity is that the process flows are representable in a multi-echelon structure. Starting from a broad process vision, according to the flow chart detail degree, this method allows to conduct the analysis deeply through the steps that compose the process. The two primary modeling components are: functions (represented on a diagram by boxes), and data and objects that interrelate those functions (represented by arrows). Starting from the very first level of aggregation, in which only one box is presented (IDEFØ), it is possible to appreciate its composition: the boxes that compose IDEFØ (Idef 1 level). In the detail is even possible to go more in the deep with the analysis, exploding the Idef1 level, comprehending its composition through the lower level Idef2, and so on according to the process detail.

Therefore, IDEF methodology exposes the process levels and compositions but also the interdependence between the sub-processes. Besides, one of the most important contribution of this method exploitation is the opportunity of both realizing the structure of a process and observing the Input, Output, Resources and Constrains involved in a particular process.

The "box and arrow" graphics of an IDEFØ diagram show the function as a box and the interfaces to or from the function as arrows entering or leaving the box. The basic syntax for an IDEFØ model is shown in the figure. IDEFØ is useful in establishing the scope of an analysis, especially for a functional analysis. As an analysis tool, IDEFØ assists the modeler in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong.

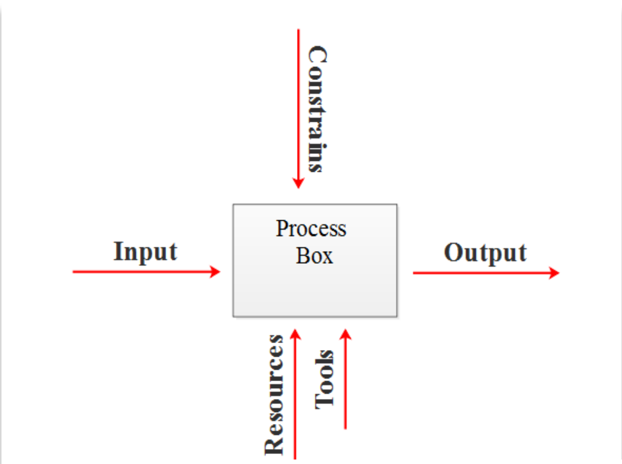


Figure 27 Idef0 representation conceptualization

Thus, IDEFØ models are often created as one of the first tasks of a system development effort. Input: information that the process need in order to elaborate an output. It can be composed by whether information or materials that have been originated by a sub-process within the whole process or from an external source.

- **Input:** the information needed to deal with the elaboration process, available whether from the external environment or from the internal facilities or from both the sources (i.e. parts list or parts forecasting demand);
- **Constrains:** Boundaries, as in every business field, there are features of the system that must be respected, whose limitations involve the exploitation of the optimal resource utilization method (as instance: engineering information and business restrictions);
- **Resources & tools:** instruments through which the input can be modified and managed, according to the constraints procured from scarcity of resources, in order to obtain the output;
- **Output:** final result, what the process reached after the input managing through the process constrains and the resources availability and administration.

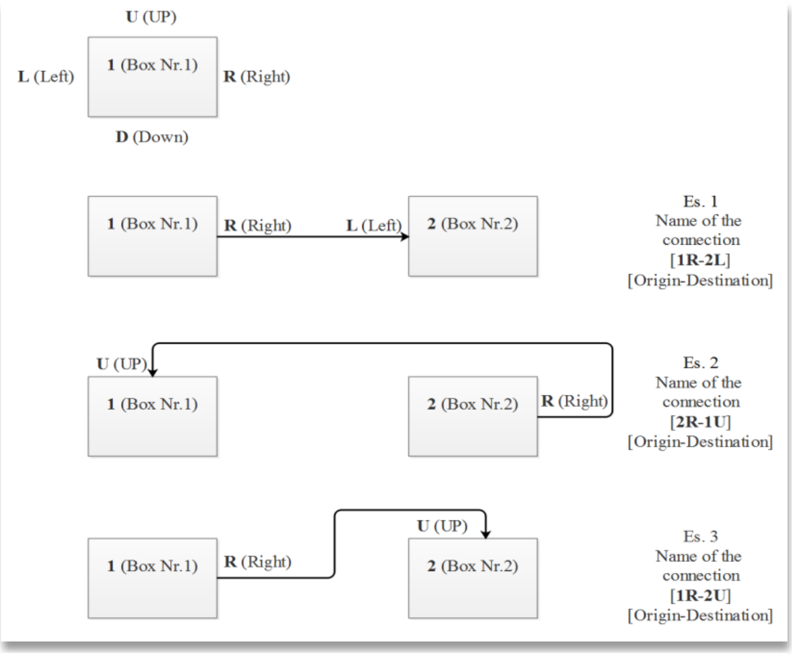


Figure 28 Idef0 boxes connections aknowledgement

In order to allow a clear and, as much as possible, easy interpretation of the connections that characterize the framework, a reading methodology is developed. As it is shown in the figure below, each arrow is named accounting their box and the side of the boxes from which they start and arrive. The boxes are identified by a number which characterized the position whether in the whole framework or in the exact process step. Besides, the boxes are also identified by a letter; the letter is useful in order to express the cause-effect connection through the boxes. According to IDEFØ rules, the position at which the arrow attaches to a box conveys the specific role of the interface.

3.2 Justification of the framework design (Three levels Idef0, Idef1, Idef2)

In order to understand framework's development, it is important to exemplify the hierarchical contribution of the IDEF0 tool to the process scheme. Through the usage of this method, there is the possibility to express clearly, with different detail levels, the value that each decisional phase provides to the whole framework. Acknowledging that with IDEF0 tool the deeper the analysis goes, the lower the aggregation level will be and so the wider the process aggregation level will result.

The detail level selection is a consequence of the information aggregation level that the work has the aim to provide. Beginning from what the literature proposes, it is clear that there's the availability of every sort of high specificity and customized solution; for this reason, there is the need to express the theme of the spare parts decisional issue support. In this work, has been selected IDEF2 as the maximum level of specificity: this because on a hand it is positively assessed the feature provided by an easily readable level, in fact, this characteristic assures the reader an ease usage and consultation of the framework; on the other hand, after having explained the model at the level zero and level one, has been considered important to go deeper in the analysis to explore which are the elements that plays a role of mayor importance. These boxes thus, affect the upper levels with all the proper features like resources, constrains and logical loops. The motivation has to be researched also in the concrete purpose of the work, that is to offer a framework developed on a tactical-strategical level focusing the attention on the information flow that this aggregation level can pursue; following this approach the result is that non-further level after the second would be worthwhile for the analysis, of particular value for this work.

Thus, it has been decided to develop three level of representation: level 1, 2 and 3. The behavior of the representation is reported in Figure 29.

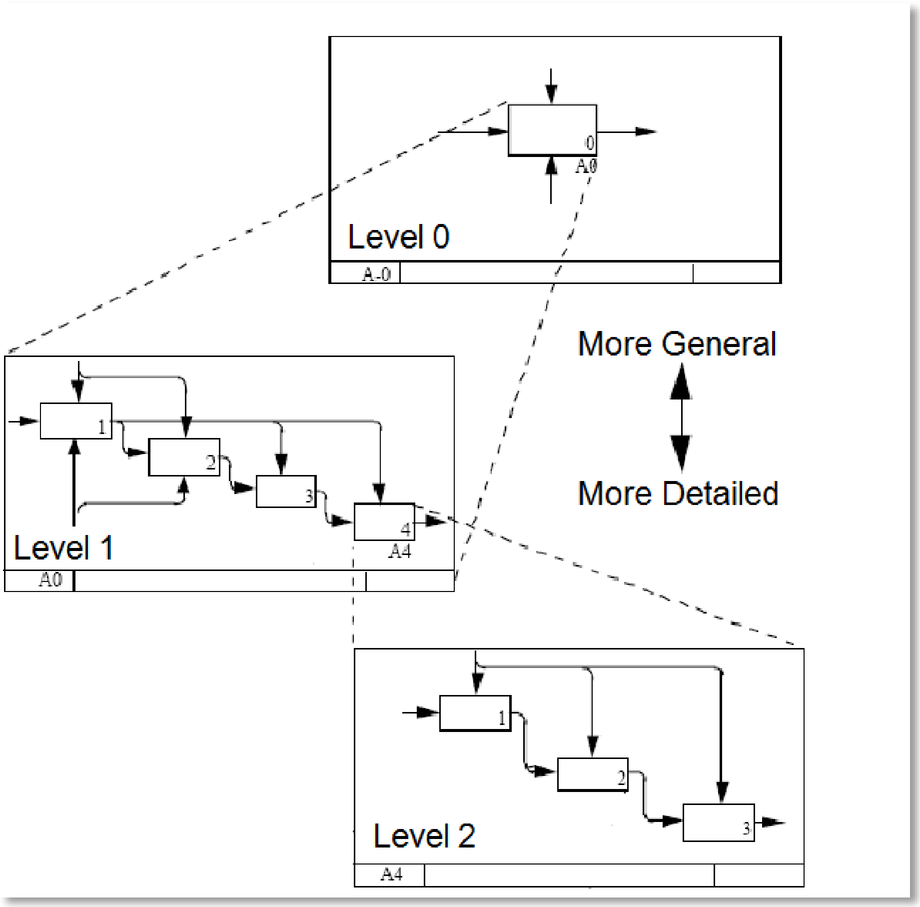


Figure 29 General Idef0 as instance, representation with number of level used in the framework proposed

3.3 Justification of the election of the four main processes

As already said in the previous section, the study is developed around the election and the analysis of four key decisional steps: assortment management, demand forecasting, supply management and inventory control. Each step presents its own peculiarity and information flow; generally speaking, there are many features that make the single decision step unique, but also resources or dependences that make quite similar one step to the others. In their paper Driessen et Al. [23] establish Parts return forecasting as a first level step when approaching spare parts management, however, it has been considered not to be at the same level of importance of the previous four, it has been considered a step in Demand forecasting, because at the end, parts return comes as a source of supply, a demand rate would be satisfied due to this internal flow of parts.

3.3.1 Assortment management

The assortment management phase deals with the decision to collect or not technical spare parts features in a data storage. According to Dreissen et al. (2010), in terms of time phases, are typically distinguished two options when to include a part in the assortment: before or after the first need for the part.

Considering the case in which a part is included in the assortment, then there is a possibility that the part is never needed during its lifecycle. Taking this possibility into account, time spent on collecting information, signing contracts with potential suppliers on unit price and the agreements on times such as lead or repair times with the consequent database updating of the part, has not been worthwhile, but at the opposite assumes the result of an unnecessary operational costs. In the opposite adverse situation, there is the possibility that a part is not included in the assortment while its data may be worthwhile in order to manage a machine failure situation: in this case there may be a time consuming phase to gather part details and lose, in this way, production time, leading to a situation in which machines must be stopped.

Assortment management contribution consists also in the criticality analysis inclusion. In fact, after the decision to collect or not technical details of the spare part, the decision immediately downstream focuses on the selection, if necessary, of a classification technique whose features have been reported in previous sections.

Below, in Figure 30, a framework is proposed in order to clarify which are the information flow that characterize this decision phase.

Input information includes all the features that are proper of suppliers detailed technical studies on the part provided. These sorts of analysis are developed by production supplier departments in phase of testing and materials examinations. Information in input need to be elaborated in order to accomplish a complete record dataset that, once processed, will allow the final spare parts classification. [16]

Resources needed for the assortment management are represented basically by two tools: is universally recognized the huge contribution conferred by the informatics systems (such as ERP and CMMS), as already said, through these elements the availability of the information needed is guaranteed; important resources can be detected in the classification methods (such as qualitative and quantitative classifications tools) [16] [23].

The source of the constraints is represented by various aspects: in fact, acknowledging the purpose of the decisional phase and considering the resources availabilities and their operation mode some limitations must be faced. Firms departments involved in this restriction issues are basically the engineering and business one: on a hand, in order to produce the classification and the assessments on spares, competences must deal with tools usage and time availability are readily detectable [66] .

The output of the box, respecting the limitations and exploiting the resources to develop the information in input are so represented by classified and prioritized parts [49][13][62][46][37].

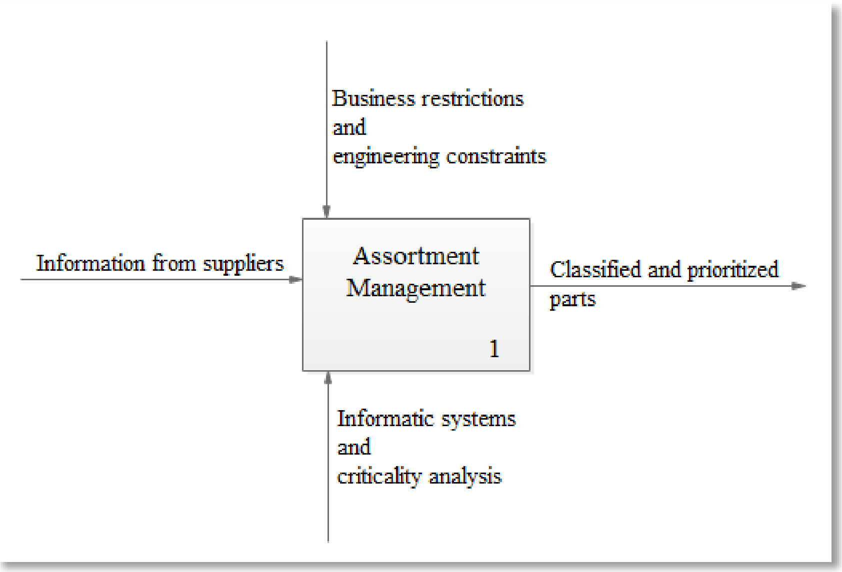


Figure 30 Assortment management box with input/output/resources/constraints

3.3.2 Demand Forecasting

Demand forecasting is the decisional phase in which the definition of the typology and quantity of spare parts is provided. Through the demand forecasting analysis is possible, collaborating with involved departments, to develop an assessment on which parts need to be owned and in which quantity.

This phase contribution is represented by the building and the estimation of forecasts, this process is developed in order to obtain a decisional support when information on the spare part flow is required.

In Figure 31 the demand forecasting general framework is proposed.

The resources needed in this process must permit to manage all the information available in order to obtain the forecasts and the consequent assessments. Many tools have been found and classified for their completeness and usage possibilities, such tools may be recognized as the historical datasets on the basis of which methods like CR, 2S or queue techniques can be exploited [69][44][54].

The output of the process is the result of tools usage, developed also departing from what databases make available. Taking into account this, value is given by the possibility to know the demand tendency and its amount (in terms of quantity). The result is then worthwhile for assessments that will be done in the following sections [69][19][54][6].

The constraints that have to be faced are related to the properly conducted usage of the tools. In particular, the engineering department have to be able to manage information derived by the historical data base analysis, spend time and assess the real necessity to implement such a sort of techniques to gain data referred to future demand [23][69].

Input is given by the planning activities: such as operational and monitoring planning. The operational planning: which presents detailed information to direct people to perform their tasks required in the day-to-day. It gives the information about what operations, when, how much and who in order to achieve the objectives. The monitoring planning: Monitoring is the systematic process of collecting, analyzing and using information to track a program's progress toward reaching its objectives and to guide management decisions.

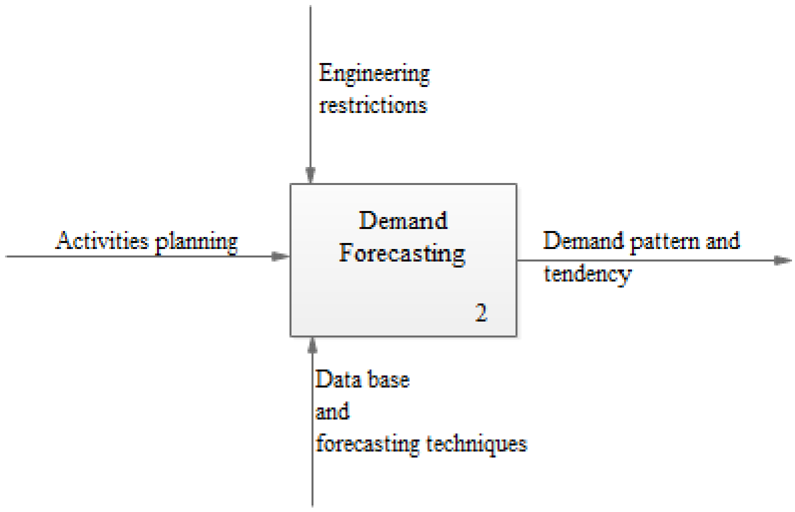


Figure 31 Demand forecasting box with input/output/resources/constraints

3.3.3 Supply management

Logistic of spare parts, thus the supply management, involves the process of ensuring one or multiple supply sources of ready-for-use LRU's, as well as SRU's, in a determined moment with specific characteristics such as lead time and procurement contracts. In order to obtain a sound supply channel, it is important to recognize the features that affect the process more and may be worthwhile in the decisional phase. According to the firm structure many supply methods are available, such as: internal repair shop, external repair shops, external suppliers or re-use of parts. Many features need to be established, such as details of the contracts like the lead times, in fact agreements are made on planned lead times.

In Figure 32 is presented the framework of the supply management decisional phase: aspects that affect the process are explained below.

Information in input basically deal with the nature of the contracts seen in other supply events, this may concern the evaluation already done in past or consideration accomplished through the analysis and assessments of the supply possibilities. In addition with information derived from the whole logistic process, resources will be exploited to move forward the input development.

The constraints are, in this case, given by the supply nature of spare parts suppliers, in fact the peculiarities of the spare parts, such as the specificity of the items, force the logistic process to manage difficulties in arranging spares stocks. The resources have to guarantee a profitable and sound assessments to build a sound logistic structure [16][23][39].

The resources are represented by tools that allow the management to exploit the decision on how to assess the quality and riskiness of the supply channel. One of the most important decision, after having collected technical spares data, is the decision on managing the spares availability internally (make) or exploiting the outsourcing (buy). Other important decision is to choose among the ones available the most profitable collaboration through the suppliers.

Contracts and specific agreements for the items required are the final outputs of the process. Acknowledging specific links between items and contracts it is possible to organize following phases of the process, such as the management of the stocks and locations.

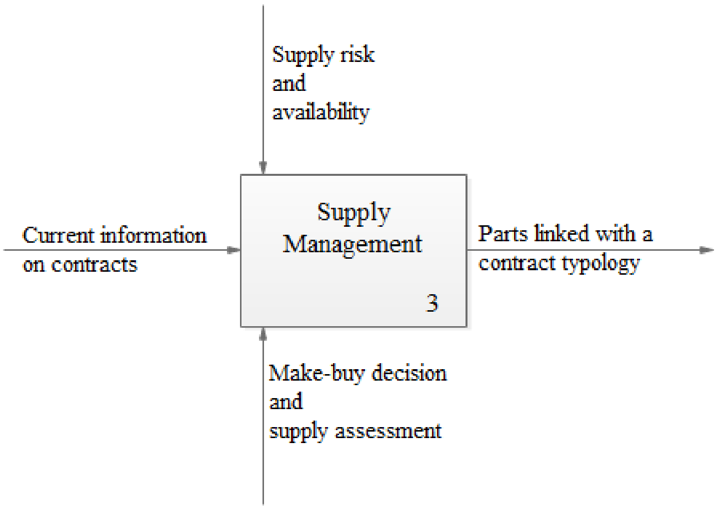


Figure 32 Supply management box with input/output/resources/constraints

3.3.4 Inventory control

The spare part inventory control phase deals with the choice on what, where and in which quantity stock. The process is composed by some decisional steps where a spare part has to go through a classification analysis in order to find suitable necessities in terms of location and quantity; then replenishment policies must be evaluated and selected on the basis of the criticality, in terms of value, price and rate of the relative machine/s failure of the spare part.

In Figure 33 a schematization of the inventory control phase is proposed and information that are involved in the phase explained below.

In input the decisional phase saws information elaborated by upstream phases such as the features of contracts and the spares demand forecasts. The contracts represent the list of agreements that the have been stipulated with internal or external suppliers, while the other input is the concrete evaluation on the basis of the forecasts results, of the demand tendency and pattern [1][2][14].

Input will be elaborated and developed by the resources available, these resources deal with the possibility to select the proper and most suitable replenishment policy also through the features of the firm but, in particular, of the spare under analysis. Replenishment policies (i.e. (s, S), (S-1, S) or (EOQ)) usage is been studied and reported in the literature review, where details on the company and the consequent choices are been presented [5][10][19]. Other resources deal with the evaluation of the stock location and the values considering the presence of a repair shop, methods such as METRIC and Queue techniques have been selected as potential exploitable methods [39].

Constraints are necessarily represented by the business and the engineering department restrictions. In order to exploit the resources, there is the need for specific competencies in the replenishment policies field and also the technical tools availability that make accessible the possibility to join the decision on the previous cited policies to location strategies.

The general output of the inventory control phase is obviously the combination of the previous influences and it is represented by the final decision on the stocks location and on the replenishment policies related to the different spares typology [5][10][19][39][46].

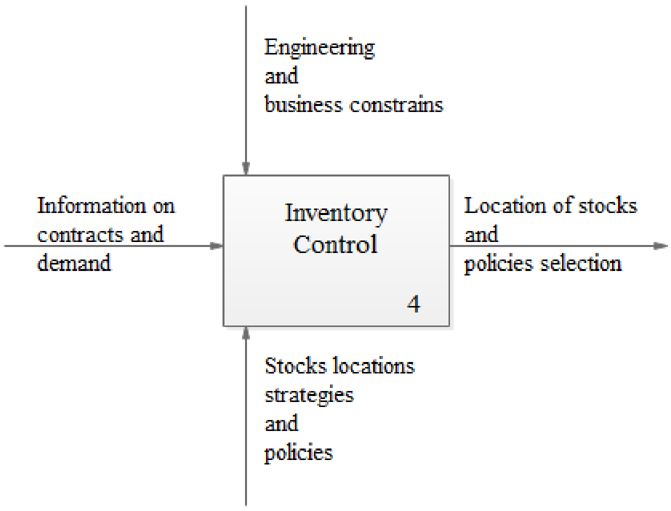


Figure 33 Inventory control box with input/output/resources/constraints

3.4 First level of the framework

Many scientific publications have been written in order to reach the most suitable spare parts managing process. The purpose of this work is to offer a framework trough which have broad and clear vision of the main steps to follow when managing the spare parts issues. With a simple representation of the processes, first the main steps will be presented and then, will be assumed a more technical and quantitative behavior in order to analyze more deeply each phase of the process.

In the following sections the general framework composition is presented: despite a great number of the studies provide descriptions of the maintenance decision phases [15] [23], a broader and generic view of the process has been built. The phases taken into account at the first aggregation level are basically four, listed below:

1. Assortment management;
2. Demand forecasting;
3. Supply management;
4. Inventory control.

As it has already been highlighted in the previous sections, it is clear that in a complete and branched decisional process a representation made through a linear flux would lack of the grate number of mutual and unilateral influences that maintenance decisional issues bring with them. For this reason, the conspicuous number of arrows that compose the framework do not follow just a vertical top-to-bottom direction, but also is evident how the decisional phases downstream affect the ones upstream in many different ways; as instance, not only input-output interdependence through the boxes but a big contribution is made by the meaning of resources and constrains.

3.4.1 Assortment management within the whole process

In this section, relationships between the assortment management phase and the others (demand forecasting, supply management and inventory control) are explained and discussed. Arrows, named with the methodology presented in **¡Error! No se encuentra el origen de la referencia.**, indicate the information flux that flows from the assortment management box toward the others and vice-versa.

Information flux toward the assortment management

Acknowledging the assortment management purpose [23], in order to understand the mode of operation, the fluxes toward the box are divided into informations from outside and from inside the firm.

As already exposed, information that come from outside assume a huge value from the moment that they represent the frist step in the direction of the assortment management development [Out-1L]. These sorts of information guarantee a basis from which begin the spare part classification process. Thus, suppliers are involved in this decisional phase assuring to the firm an important contribution, this is constitued by the datasheet that report spare parts features (i.e. MTBF, MTTR, price and others specifc values). These datasheet, on one hand, increase the competences of the firm in the technical features knowledge and, on the other hand, allow the firm to not spend further time in this data acquisition. Information that come from the suppliers may be already enough in order to accomplish a classification process, in fact, in literature these are enough to proceed with a spare part assortment management [49], [64], [62].

Information from inside the process are mainly represented by the contribution provided by the demand forecasting phase [2R-1L]. This phase is often involved in the assortment management process thank to the spares demand tendency: this allows to develop and enhance the characterisation of the component adding an important element in the analysis. In literature many case studies which include the classification of spare parts through the demand features contribution are offered [7], [15], [6]. Spares demand tendency is a feature that allows the assortment management through both monocriteria, [62], [41], [19], [1], and multicriteria classification methods .

Tools and resources available in order to manage the spare parts assortment are differentes depending on the exact phase in exam [Out-1D]. In particular, in the very first technical information gathering phase, sound elements can help process development: the informatic systems. Thank to this tool technical information obtained in past, which concerns the exact component or similars (through which is possible to execute an analysis for spares similarity), allows to increase the assortment technical features collection [1], [7]. In the assortment management mature development phase others tools represent the resources exploitable (i.e. ABC, AHP, VED, FSN and others) as seen numerosus times in literature [15], [23].

As seen with inputs, also assortment management constraints are composed by two main fluxes: internal and external. The information external flow [Out-1U] represents part of the limitations that this phase has to face: standards represent all the technical values that this face must respect, engineering information represent the spares features that in many cases lack and have to be gathered by the firm. The internal flux is brought by the supply management phase [3R-1U], in fact this decisional step causes obstacles to overcome such as the spares information on criticality.

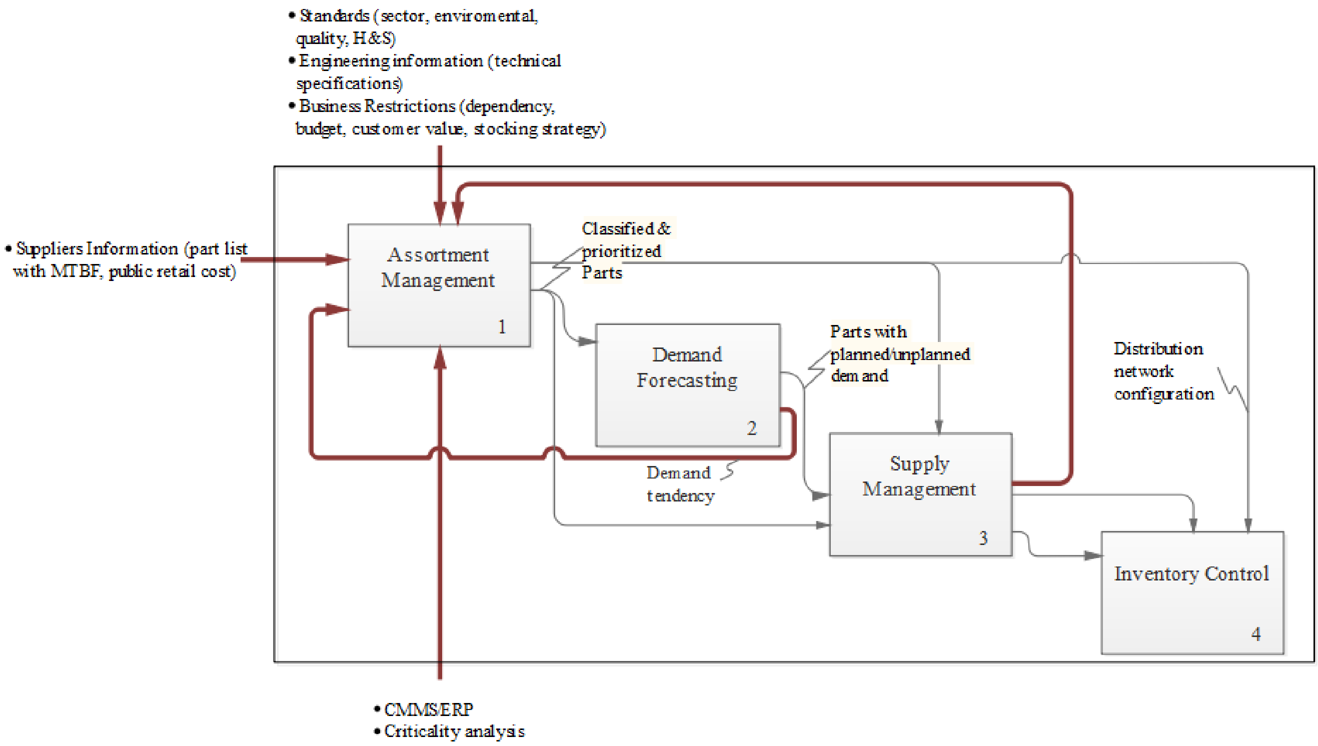


Figure 34 Information flux toward assortment management, highlighted in red

Information flux from the assortment management

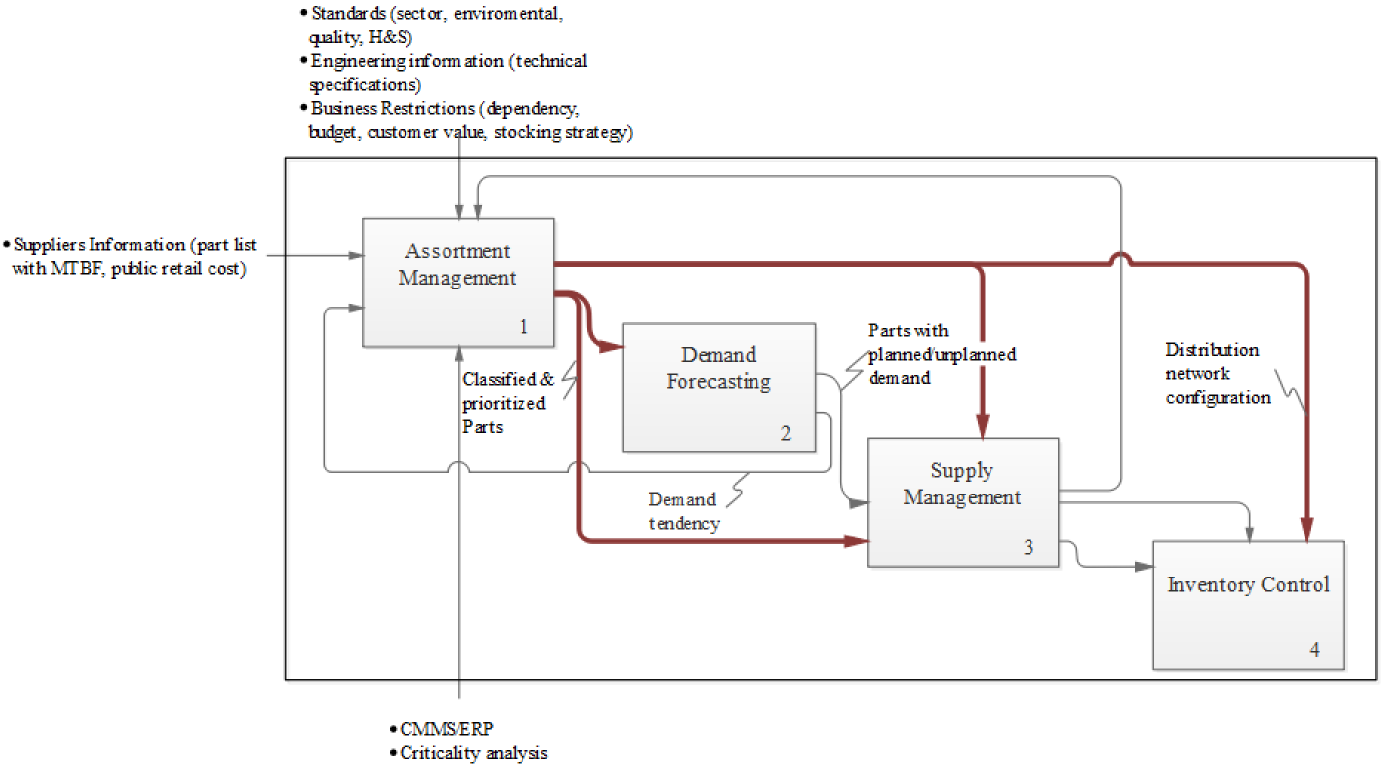
Now it is defined how the elaborations provided by the assortment management process generate value in the whole like an input or like a constraint in the other phases.

Most evident result of this phase is the generation, at first, of a decision on the inclusion or not inclusion of a part within the assortment, with the consequent study of the technical features; second, the production of spread sheet which should indicate the priority level of a part with a precise location within a classification.

These information are exploited as input in the demand forecasting step [1R-2L]. The demand forecasting has the purpose the identification of the part typology requested and the proper quantity. Taking these considerations into account, parts classification is used by the phases within the process linked to the demand of the returned parts (parts fixed by the repair shop) and also linked to the classification of spares strictly from their demand pattern point of view.

Parts classification represents an input for the supply management as well [1R-3L]: the suppliers' definitions from their availability and characteristics point of view need parts technical information to exploit them in this definition process [67], [6].

It is important to highlight also that assortment management phase is also a constraint for two of the three downstream processes. For the supply management phase [1R-3U] there is the necessity to face



the classification provided by the assortment management phase as a constraint, in fact, limitations derived from the need to manage in differ ways parts with a certain level of criticality [23], [15]. The limitation is also for the inventory control: the replenishment policies are strictly linked to the features of the spare parts [1R-4U]. Parts with a determined degree of necessity and priority must be considered differently from others typology [36], [4], [20].

Figure 35 Information flux from assortment management, highlighted in red

3.4.2 Demand forecasting within the whole process

In this section, relationships between the demand forecasting phase and the others (assortment management, supply management and inventory control) are explained and discussed. Arrows, named with the methodology presented in **¡Error! No se encuentra el origen de la referencia.**, indicate the information flux that flows from the demand forecasting box toward the others and vice-versa.

Information flux toward the demand forecasting

Demand forecasting phase can count on information that come, at first, from the upstream assortment management phase: as explained in the previous section, this input is composed by the parts classification, elaborated both from the part return forecasting phase and from the phase related to the part demand classification [1R-2L], [7] [23]. From the outside, information deals with the monitoring and operational planning [Out-2L], that is to say all the activities that involve the scheduling activities of the tasks.

Resources [Out-2D] include tools needed to develop the input in order to accomplish the purpose of the phase: projections of the spares demand. The most used and exploited techniques are represented by the historical data base, which provides many technical information which can be used in the most part of the general demand forecasting phases. For what the return forecasting phase concerns tools as queue theory can be retained useful and worthwhile especially in the capacity dimensioning [67][44][19][54][30].

Constraints are represented by all the technical information gathering issues: these may be recognized in the general costs proper of these activities [Out-2U]. From the supply management phase can be individuated the limitation procured on the eventual presence of a repair shop, in fact the presence or less of a repair department involve the demand forecasting phase to respect this restriction [3R-2U]. In particular, restrictions are recognized in lead times, availability and costs of the related department.

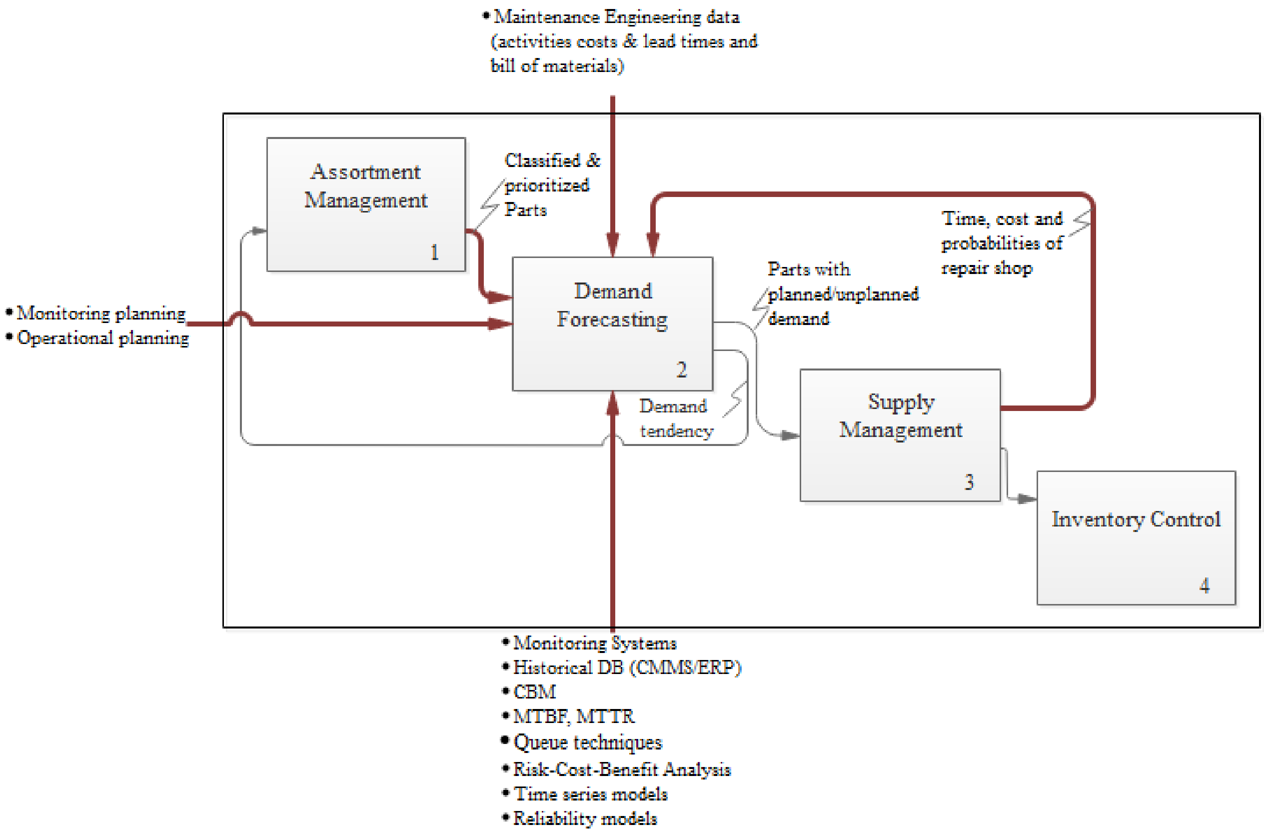


Figure 36 Information flux toward demand forecasting, highlighted in red

Information flux from the demand forecasting

Acknowledging that the aim of the demand forecasting phase is the one of providing numerical relevant reports serving phases downstream but also the assortment management phase as affirmed before, the meaning of the fluxes is explained below.

Connection between demand forecasting and the assortment management allows to obtain information on the parts demand tendency [2R-1L] [15], [7]. This categorization is, on one hand, a support for the processes related to the selection of the spares classification criterion but also enhances the degree of the assortment management. Demand forecasting is also the input of the supply management phase [2R-3L]. The connection meaning is clear, in order to manage a supply relationship, the demand forecast pattern provides important contracts basis, involving particular suggestions on the necessity or not of an internal repair department or the decision of an outsourcing suppling.

In Figure 37 the representation of the demand forecasting output information.

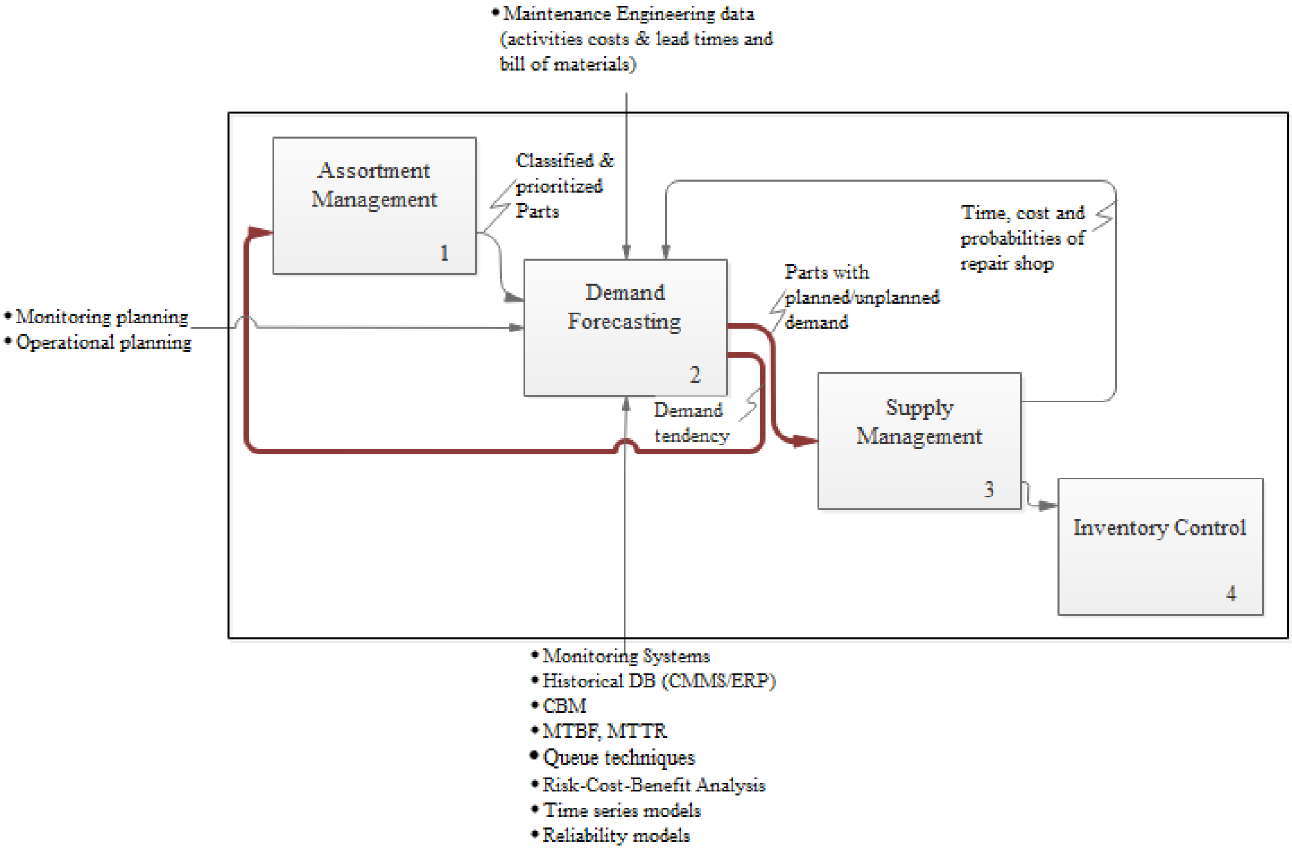


Figure 37 Information flux from demand forecasting, highlighted in red

3.4.3 Supply management within the whole process

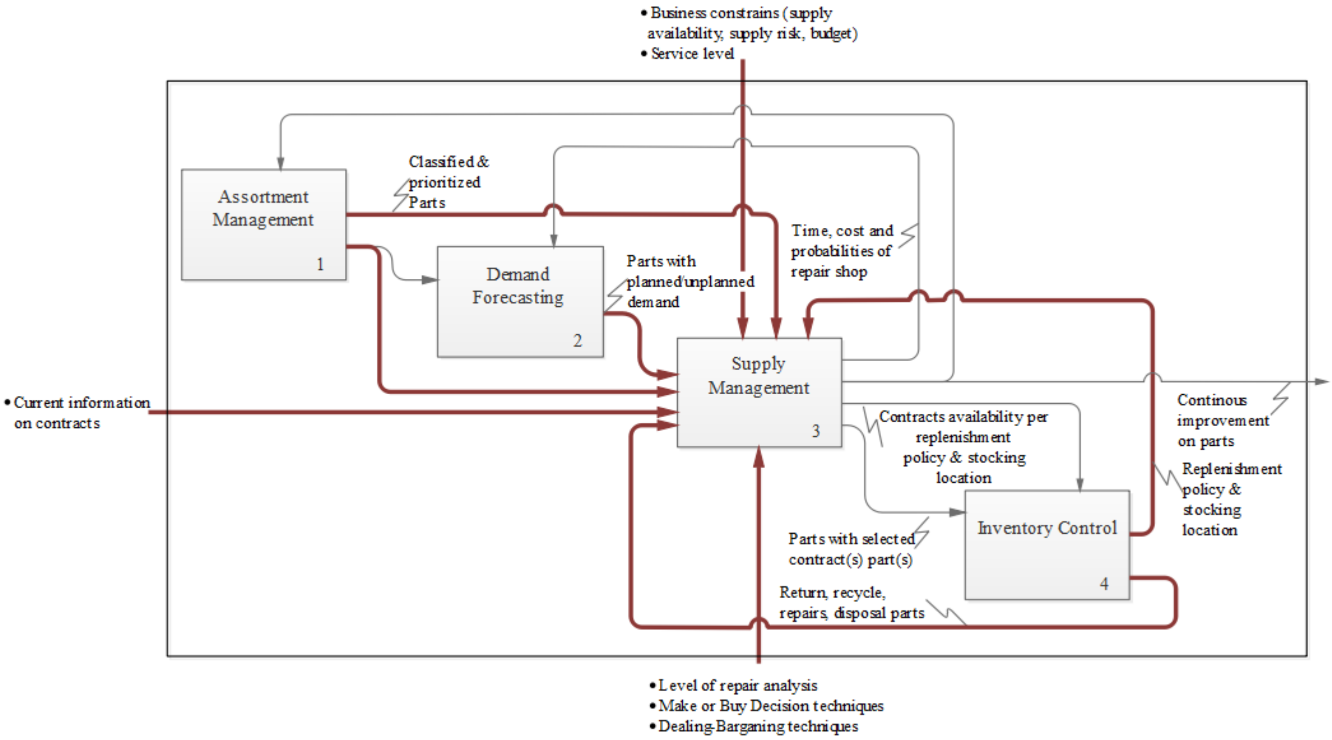
In this section, relationships between the supply management phase and the others (assortment management, demand forecasting and inventory control) are explained and discussed. Arrows, named with the methodology presented in **¡Error! No se encuentra el origen de la referencia.**, indicate the information flux that flows from the supply management box toward the others and vice-versa.

Information flux toward the supply management

The first input that supply management phase can count on is represented by the current information on contracts, this input produces value within this decisional phase because provide important information in the supplier selection process: historical data on contracts and other available information are an efficient departure point for the analysis. It is possible that this input allows the phase development providing through similarities of contracts already signed in past or simply provides general information on the actual condition of things in the suppliers potential partnership field [Out-3L]. Others inputs can be found in the technical data, gathered also in the upstream phases: assortment management and demand forecasting. As already underlined, the assortment management phase provides an important contribution given by the transfer, to the supply management department, of all the data collected through analysis of data basis but also through the adoption of quantitative and qualitative tools (i.e. ABC, FSN, VED etc.) [1R-3L] [13][41]. Also the demand forecasting phase provides data as an input: the supply management phase need exact spare typology and quantity, also elements with a precise maintenance policy [2R-3L]. Also the inventory control phase represents an input: it allows to process information on components nature and related policies and all the information connected with the repaired parts [4R-3L].

Inventory control represent also a limitation respecting the fact that the huge relationship existent between the two phases is transferred also like a constraint: nature of the spares join to maintenance policies that can be planned and choose represent a flux that must be managed and respected [4R-3U], [1R-3U]. Further limitations are represented from the outside by possible suppliers, in fact in spare parts field supply risk is high because there is the possibility that their availability is not guaranteed and also by the managing of supply parameters; many contracts for the supply of spare parts indicate the critical factors which can be recognized, as instance, in price, standards, delivery time and its bureaucratic system of the countries in which the companies operate [Out-3U] [1] [2] [34] [47] [14].

Resources are represented by tools as the level of repair analysis (a method through which decide whether to repair or not a failed part), make or buy decisions (which imply the choice of develop the process internally, in the internal production or spares repair) and dealing techniques referred to the



parameters selection [Out-3D].

Figure 38 Information flux toward supply management, highlighted in red

Information flux from the supply management

In the previous section, it has been acknowledged that the supply management phase has provided the typology and number of supply channels. Recognizing that these channels could be whether internal or external, the final choice represents a limitation for the demand forecasting phase depending, this process, also by the presence or less of an internal department dedicated to the spares reparation [3R-2U]. [3R-2U] the final result is to have contracts that allows to enhance the spares quality supply or parts with better performance into the system [3R-Out]. Acknowledging that supply management deals also with the suppliers location, the influence of this feature is been recognized as a constraint for the inventory control phase in which there is the decision making on supply policies and acquisitions lead times [3R-4U]. Is also an input for the inventory control phase, in fact, it represents the information to process through the resources available [3R- 4L].

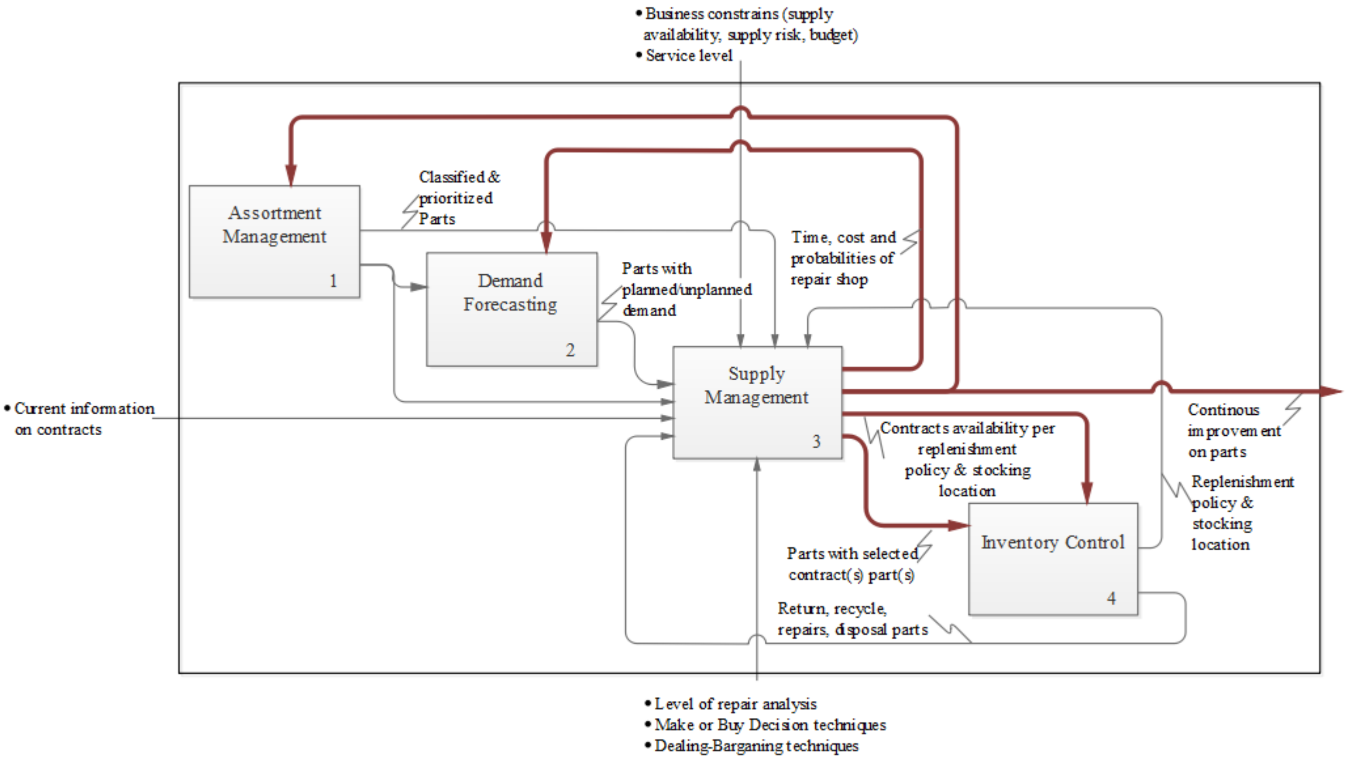


Figure 39 Information flux from supply management, highlighted in red

3.4.4 Inventory control within the whole process

In this section, relationships between the inventory control phase and the others (assortment management, demand forecasting and supply management) are explained and discussed. Arrows, named with the methodology presented in **¡Error! No se encuentra el origen de la referencia.**, indicate the information flux that flows from the inventory control box toward the others and vice-versa.

Information flux toward the inventory control

Inventory control stage aim is the decision making for stock location and for replenishment policies of the different spare parts. Information flux in input is represented by the contribution given by supply management; in fact, the information in input are constituted by agreements token in contracts [3R-4L].

Supply management represents also a constraint due to the intense relationship between these phases in the modalities expressed in the previous section [3R-4U]. As already explained inventory control has to face the limitation from inside the process while the outside constraints deal with all the stocking issues such as availability, locations and lead times [Out-4U].

Constraint is also given by the assortment management, which causes a limitation on the basis of the selection of spares to keep in stock and in technical databases that this phase is responsible for the providing and to analyzing [1R-4U].

Resources are given by policies and their parameters selection, based on models' results. [Out-4D].

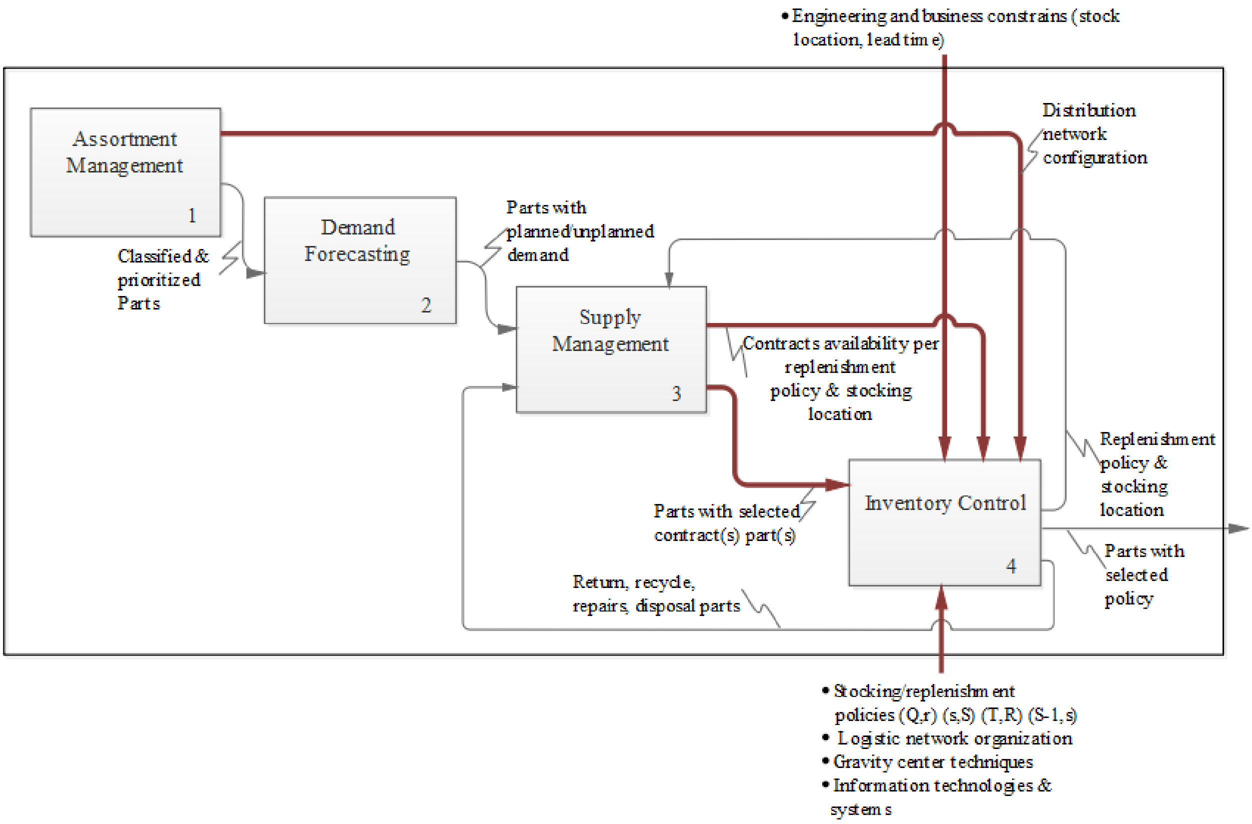


Figure 40 Information flux toward inventory control, highlighted in red

Information flux from the inventory control

The process's output is, at first, represented as a connection between the part and the consequent choice of the policy, selected on the basis of the spares features but also considering the supply typology selected with the resulting assessments [4R-Out].

It is at the same time both constraint and input of the supply management phase: an input because the policies that the firm can adopt are developed on information from the supply choices [4R-3L]; a constraint because the inventory control department possesses the control of the stocks and, for this reason, the phase upstream is limited: the choice of the supply source must take into account the facilities already owned [4R-3U].

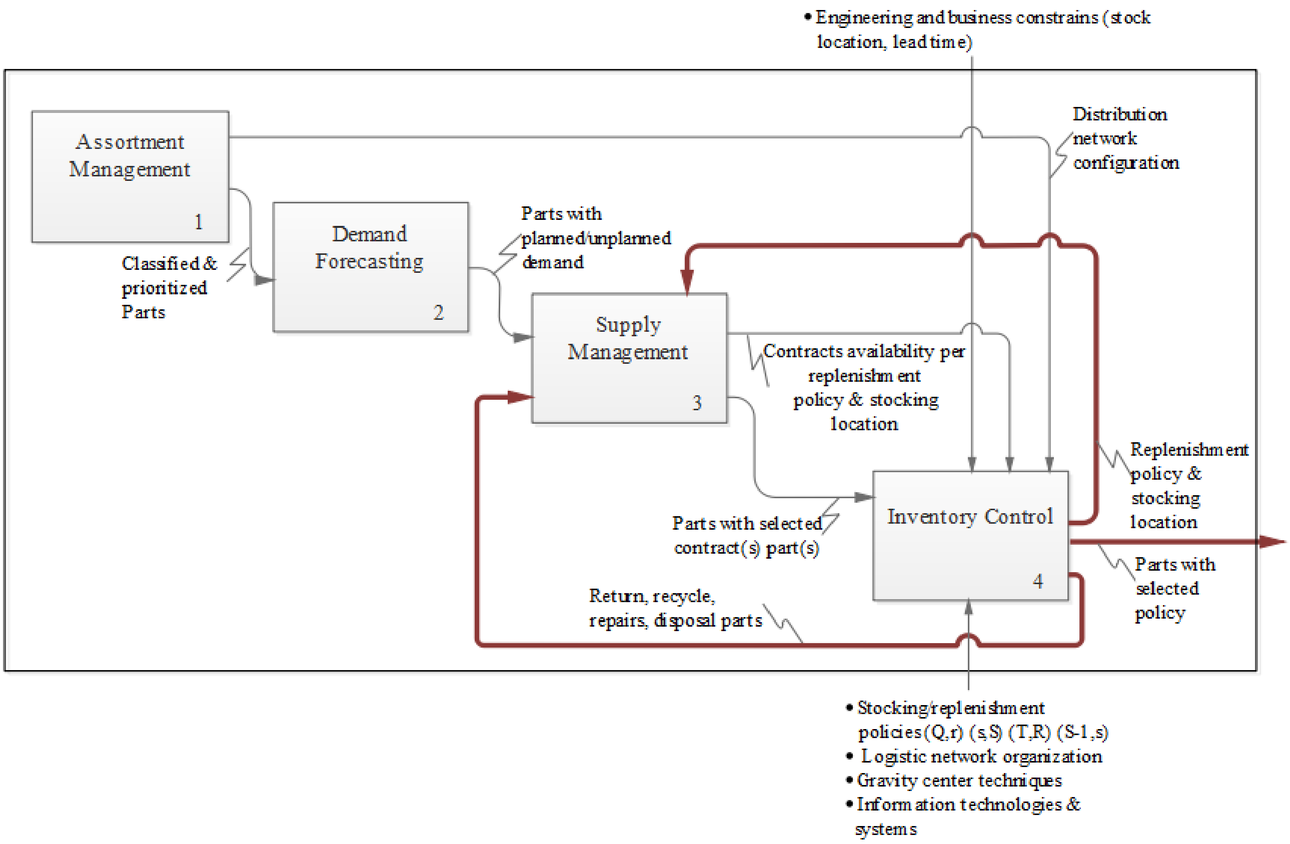


Figure 41 Information flux from inventory control, highlighted in red

3.5 Level 2 of the framework

This subchapter dives deeper into the details of each of the steps selected on the first level, presenting the actions involved and linking them within each step and to the whole process. It is the last zoom in that will provide an insight to the decision making process.

3.5.1 Assortment management level 2

Include or not the technical features of a part in the information database is, actually, the first issue on which elaborate a decision. Time spent on collecting information, signing contracts with potential suppliers on unit price and (contractual) lead and/or repair times and adding the part to the database has been done without any use, which results in unnecessary operational costs. It is therefore absolutely necessary to manage inventories efficiently in order to avoid unnecessary investments; reducing the inventories level to a considerable level without any adverse effects on production and sales, by using inventory planning and control techniques. Again, the reduction in "excessive" inventories carries a favorable impact on profitability. For many asset-intensive industrial plants, classification of the total spare parts assortment into relevant categories is a crucial task in order to control the wide and highly varied assortment. Spare parts differ strongly in terms of stock-out effects, item value and demand pattern. [62]

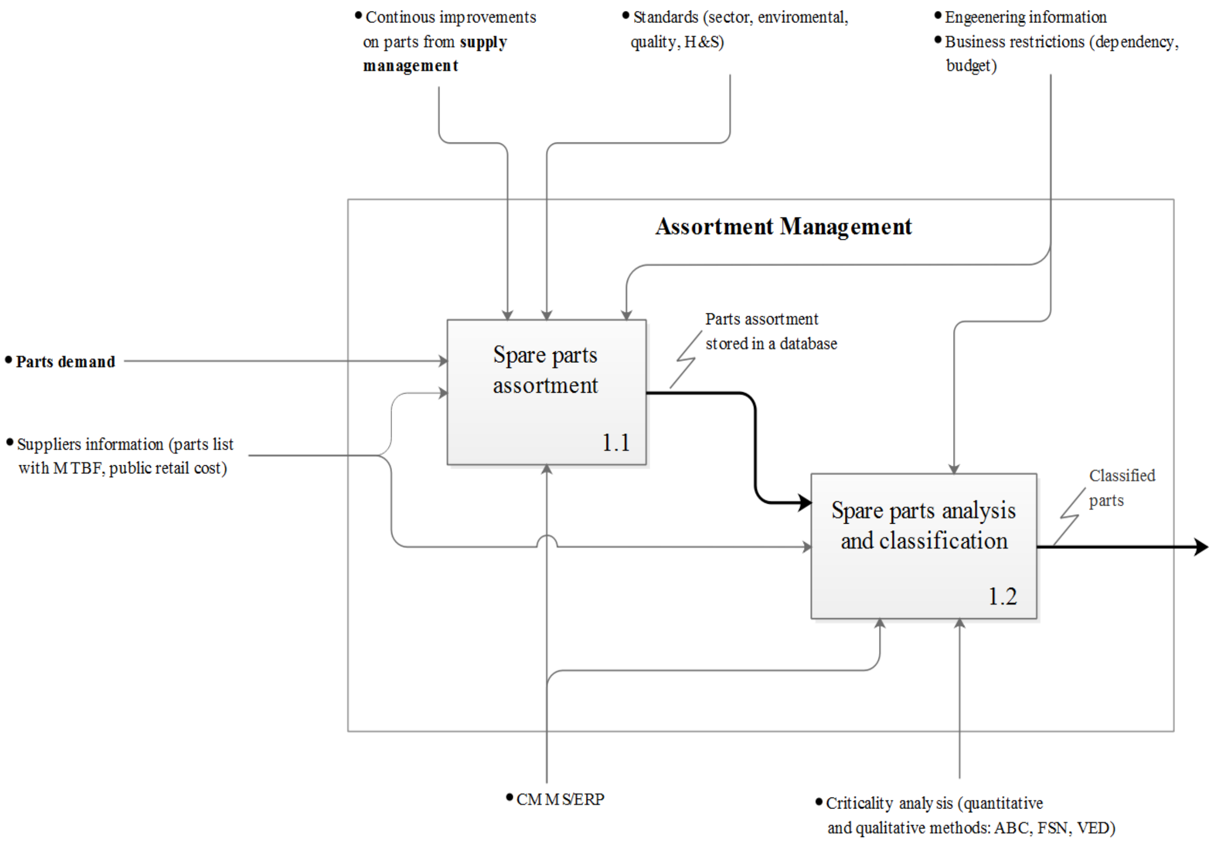


Figure 42 Assortment Management framework, second level

This first block can be divided in two steps, firstly the decision that was mentioned about including the part in the assortment, and then the posterior classification and analysis of each spare part included.

Connections spare parts assortment 1.1

To help in the decision of the block 1, the first input is the demand of the spare part, it receives also the information about the supplier. Depending on the information the decision is taken. Tools provided in this step consist on CMMS and ERP implementations as an efficient way for managing the information of the spare parts. Boundaries that have to be respected would be the standards, a continuously updated supply management improvements **[Out-1.1U]** and finally restrictions related to engineering and business strategy, as it could be the effect in the budget of the failure of one of the pieces. **[Out-1.1U]**.

As it can be seen in **[1.1R-1.2L]** the output of this block provides a flux of information of spare parts included in the assortment with all the needed information ready to be analyzed and classified.

Connections spare parts analysis and classification 1.2

As an input 1.2 receives information provided as the output of the previous step, characterized by **[1.1R-1.2L].** In addition qualitative and quantitative methods and criticality are provided as tools. **[Out-1.2D].** this methodology provides the classification of each of the spare parts in the assortment. Again, this information is limited by the restrictions imposed by engineering information and business strategy.

The output of the process consist on the information flux of the parts included in the assortment perfectly classified and analyzed, in continuous revision and improvement in order to update the information. **[2R-Out].** It includes all the information of the parts and it is the first step than permits the organization a control of the assets.

In case a part is included in the assortment, it is possible that the part is never needed and never used during its lifecycle. Then time has been waste, time spent in collecting information, signing contracts with suppliers, lead and repair times and adding the part to the data base result in unnecessary operational costs.

However, if it is decided not to include the part in the assortment there two possible problems or adverse consequences.

First, the part fail and the supplier is still available, then the lead time is higher because of data collection and negotiation.

Second, when the part is needed and the supplier is no longer available. In that case the part has no option but to be custom made. With this purpose specialized technical information concerning the form, fit and function is needed. This might seem obvious but, if the part is not included in the assortment the information is not available.

A balance should be found between to opposite forces, the cost of including the part in the assortment and the expected cost of extra-downtime. On the one hand, it has to protect the organization against stock-outs of raw materials, work-in-progress inventories and finished goods. On the other hand, inventory costs must be held to the lowest possible level. There are different methods that find this balance regarding diverse criteria. For example, based on the probability that the parts will be needed in the future.

Sometimes we see organizations that have thousands of types of materials and spare parts. This fact easily generates difficulties in following the track of this resources and therefore effectively managing materials. To keep an organization from misallocating its material management resources, planning and control systems are essential, and need to be implemented.

3.5.1.1 Spare parts Assortment

In the spare parts assortment management, there are two main resources is needed to highlight: CMMS and ERP, both provide substantial help to manage all the information necessary for assortment management. Those resources need to be integrated within an organization to optimize their potential use. Integration of CMMS with an ERP, shares cost data related to maintaining assets, and reduces the need for redundant data entry. In spare parts, within two or three clicks of a mouse, the user scans the part into a WO and the CMMS automatically adjusts inventory.

3.5.1.2 Spare parts analysis and classification

To practically define criticality, meaning with criticality the need to include a part in the assortment two types of classification methods are applicable: ‘quantitative methods’, implying the adoption of drivers based on a numerical value, some examples are ABC or FSN, and ‘qualitative methods’, assigning criticality levels based on a quite subjective judgment or on scoring methods.

3.5.2 Demand forecasting level 2

After deciding whether or not to separate demand streams, the demand process needs to be characterized on behalf of the following three purposes: to determine the number of parts to stock, to determine the repair shop capacity and to provide the necessary input for updating and characterizing supply contracts. [23]

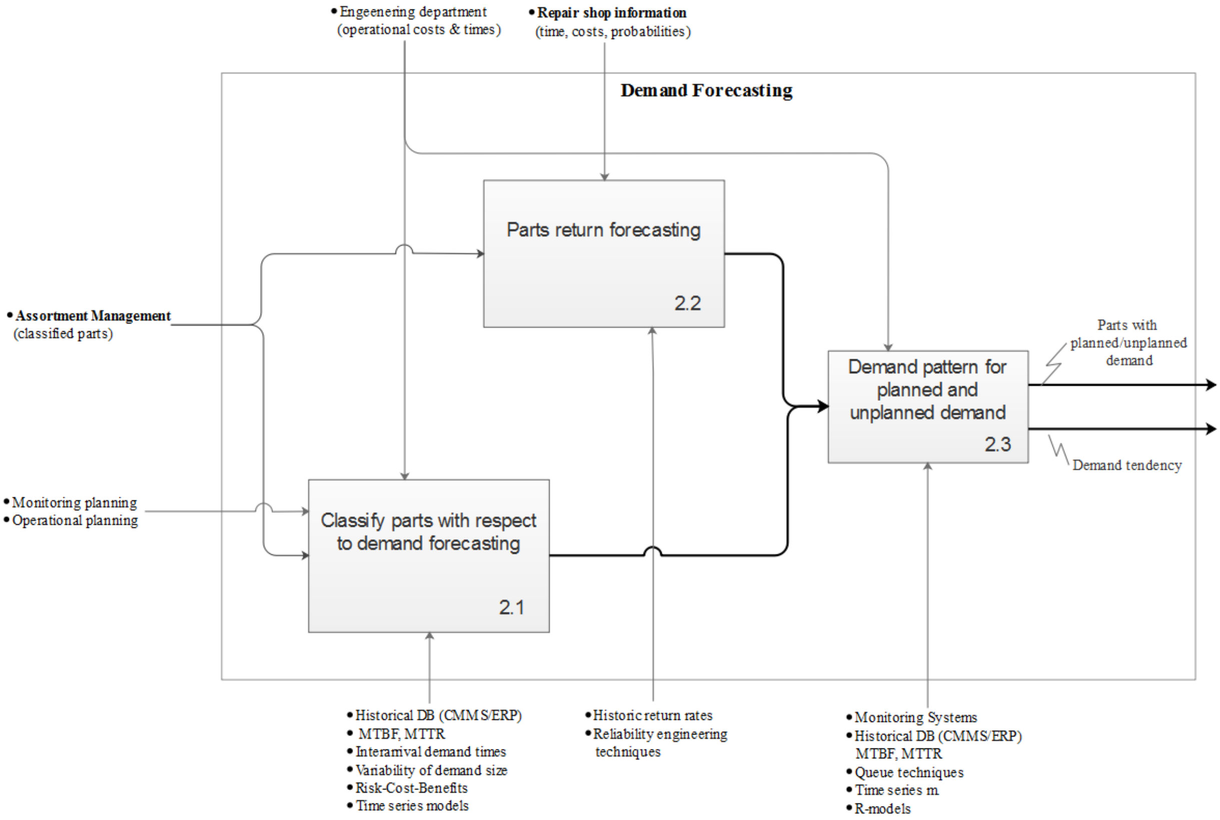


Figure 43 Demand Forecasting framework, second level

Demand forecasting are the techniques used by enterprises to estimate the future consumer demand or in the case of spare parts, internal demand (parts are needed inside the enterprise) to minimize inventory and avoid stock-outs. Spare parts demand is very particular. In the majority of the cases, it takes place with irregular time intervals and reduced numbers but quantities vary a lot. This is the reason why forecasting demand for spare parts is a quite important and complicated step.

This step is subdivided into three secondary blocks, firstly parts are classified depending on the type of demand and their importance. Concerning spare parts, parts return forecasting has to be included as a step because depending the internal repair shop parameters a demand rate would be satisfied due to this internal flow of parts. Joining these two steps together finally the demand pattern and the tendency provides the output of this block.

Connections classify parts with respect to demand forecasting 2.1

To classify parts for demand forecasting the operational planning and monitoring planning are used, joined to the output of the assortment management **[Out-2.1L].** As tools information from the data based is proportionated, data such as MTBF, MTTR. Operational costs are also received to decide resources allocation.

The process output provides the necessary classification to establish the demand pattern. **[2.1R-2.3L].** Parts divided by their type of demand and the amount of resources that should be detonated to its prediction.

Connections demand pattern for planned and unplanned demand 2.2

The information received by this step consist mainly in the information received by the previous step and information from the internal repair shop. The parameters of the internal repair shop determine the demand. **[Out-2.2D]** Historic return rates and reliability are also tools in this step.

The output provides the probability of return of a repairable, and the return rate that satisfies partially the demand. Parts are divided in consumable or repairable, there is a probability of failure and associated costs that would determine the process. **[2.2R-2.3L].**

Connections demand pattern for planned and unplanned demand 2.3

[2.1R-2.3L], [2.2R-2.3L] the classification and the information from return parts forecasting work as inputs for establishing the demand pattern. As tools time series and queuing techniques and as constraints the information from the engineering department.

The output of the process are the spare parts with unplanned demand and the demand tendency to predict future behavior, constantly reviewed and up to date. **[2.3R-Out]** Unplanned demand and deterministic demand are treated differently.

3.5.2.1 Classify parts with respect to demand forecasting

There are parts for which future demand information will be studied and parts which information will not be used. But this is not the only classification for spare parts concerning its demand forecast. Using information on future demand usually decreases the overall forecast error but, on the other hand, it increases difficulty, the effort and therefore the cost.

The decision to use future information depends on: (i) the price of a spare part, (ii) the ratio between planned and unplanned demand of the spare part.

Depending on this ADI and CV spare parts can be classified in four types:

1. **Slow moving** (or smooth): this items have a behavior which is similar to that of the traditional articles, at low rotation, of a productive system;

2. **Strictly intermittent**: they are characterized by extremely sporadic demand (therefore a lot of a period with no demand) with a not accentuated variability in the quantity of the single demand;
3. **Erratic:** the fundamental characteristic is the great variability of the requested quantity, but the demand is approximately constant as distribution in the time;
4. **Lumpy**: it is the most difficult to control category, because it is characterized by a lot of intervals with zero-demand and a great variability in the quantity.

Ghobbar et al. (2003) suggest some "cut values" which allow a more detailed characterization of the intermittent standard of spare parts demand.

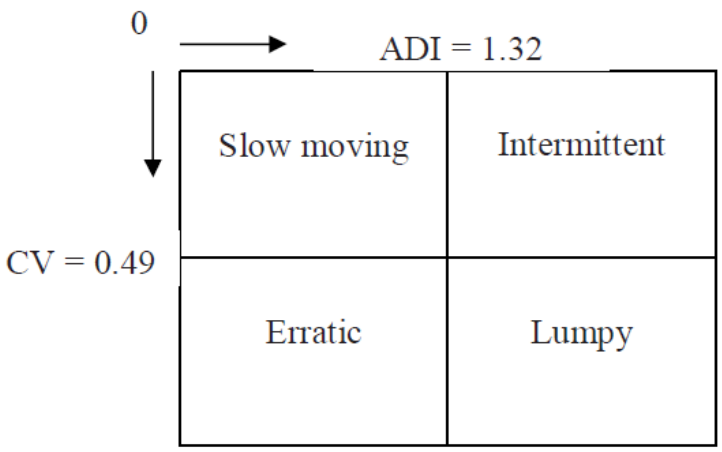


Figure 44 Spare classification based on the demand pattern

Spare parts can also be classified in terms of cost and criticality. The cost relates to purchase and maintenance cost and can be classified as low, moderate or high. Criticality is based on the risk (and cost) of not completing the process or assigned equipment function. Also criticality can be classified as low, moderate or high.

The figure below is an example of cost criticality/loss matrix proposed by (Ben-Daya et al. 2000).

Cost\Criticality	Low	Moderate	High
Low	LL	LM	LH
Moderate	ML	MM	MH
High	HL	HM	HH

Table 7 Matrix of cost/criticality combinations

3.5.2.2 Parts return forecasting

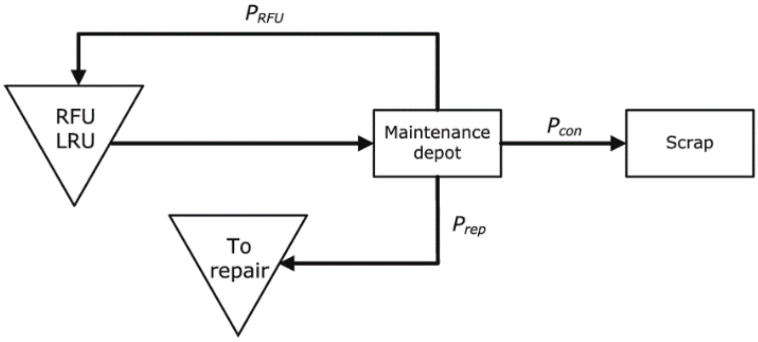


Figure 45 material flow with a repair facility

If the cause of the system breakdown is unknown, sometimes all the parts that may have failed are requested. Then after the actual cause is founded, the other requested parts return ready-for-use to the original stocking point within an agreed hand in time. Then with the part that caused the problem there are two options: The part needs to repair, the part is beyond repair and needs to be scrapped. The MLO needs to keep track of the return rate, and the hand in time for planning and control.

If we take the case of consumables, as we can see in the figure, the part can either be returned ready-for-use or not returned at all. A part is request is a part demand? If the part is handed in afterwards our level of inventory grows unnecessarily, so the solution is to delay the registration of the part demand until the hand in time has elapsed. Obviously, this system is only effective if the hand in time is small compared to the procurement lead time.

The case of repairables is different, there is the option that the part is sent to repair. There is a probability of prfu that is the probability of a requested part to return as a ready for use, a probability of being sent to repair of prep and the probability of a part being condemned is pcon.

We can see that these return rates have to be forecast, normally they are forecasted based on the historical return rates, corrected for special accidents. This is often enough, but concerning expensive parts with low demand rates need more care and control. Techniques from reliability engineering can be used for these special return rates. The cost associated to these techniques are high and can only be used with expensive parts.

3.5.2.3 Demand pattern for planned and unplanned demand

The previous steps collect information extracted from the databased incorporated in the ERP or CMMS system. Different methodologies have been implemented to classify the parts, to decide how deeply we should study the demand forecasting of a piece in concrete and this classification united to information provided by the engineering department such as operational cost or criticality, it is then time to give a pattern for the demand of the spare parts, taking into account the part return policy and its estimations. The output of the demand forecasting is an estimation and a pattern for each type of part, of the number of parts that will be needed, this information will provide feedback to the previous step Assortment Management and it will be part of the input of next steps as Inventory control for which it becomes essential. Depending on the pattern of our demand the policy of inventory control varies as it will be discussed below.

3.5.3 Supply management level 2

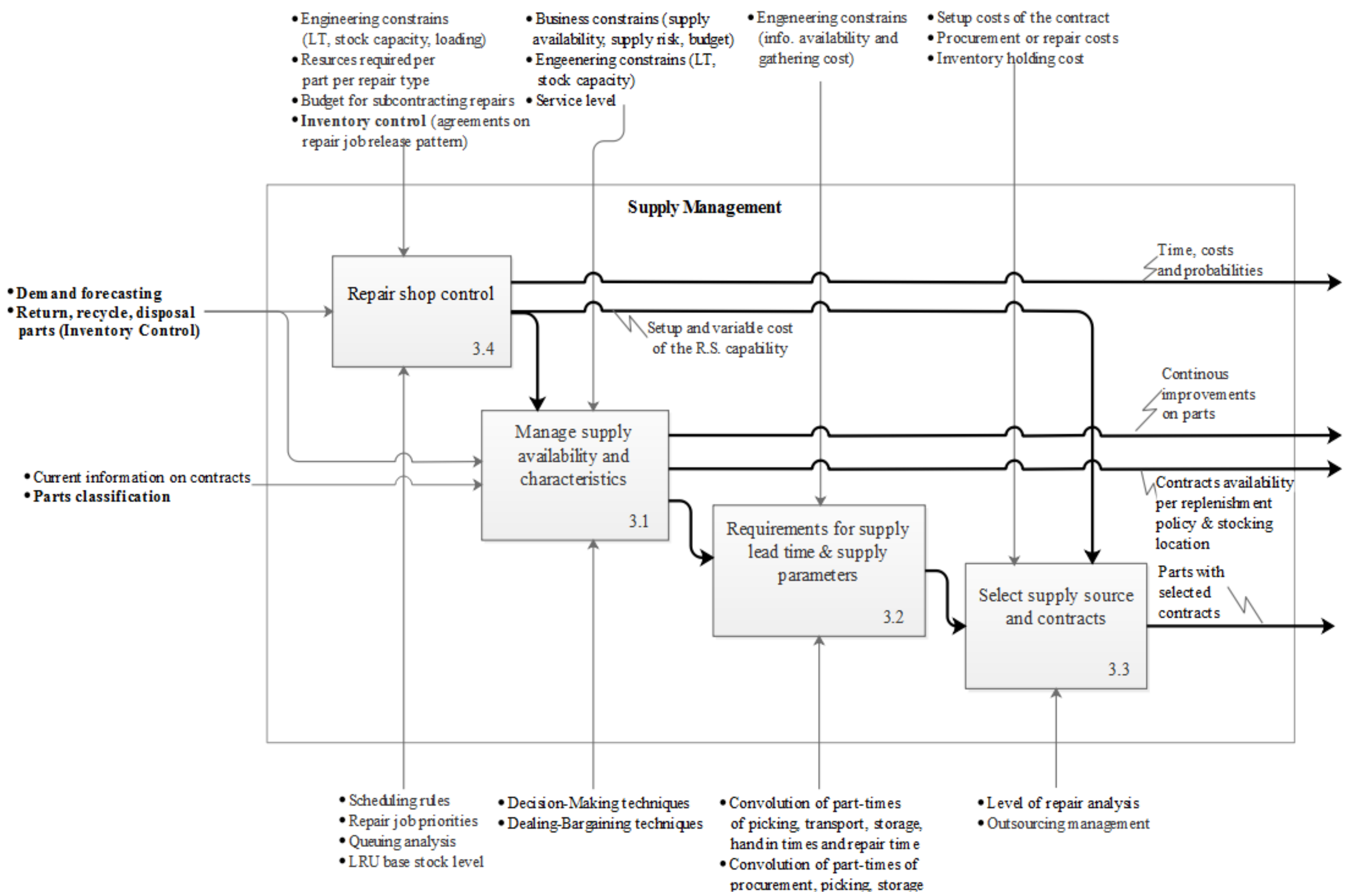


Figure 46 Supply Management framework, second level

Goals of the Spare Parts Business

The spare parts logistic offers to the manufacturer huge possibilities for increasing the business key results. The adoption of the most suitable way to have access to the spare parts may allow to the farms great advantages both on the economic and on the supply chain efficiency side. Below is proposed a deeper analysis on how to manage this aspect.

Logistics of spare parts (supply management) involves the process of ensuring one or multiple supply sources of ready-for-use LRU's, as well as SRU's, in a determined moment with specific characteristics such as lead time and procurement contracts.

Connections manage supply availability and characteristics 3.1

To manage supply characteristics firstly, are needed information provided by the internal repair shop, then information concerning contracts with suppliers is added. [Out-3.1L]. It is a constraint because contracts determine the supply management for the contract period. The service level required and the information about the parts that come from the assortment are also provided to this step.

The output of this step are the characteristics of suppliers desired in order to determine the parameters of the supply. [3.1R-3.2L]. How many suppliers, can the internal repair shop meet a determined demand rate or is it better choice the outsourcing?

Connections requirements for supply lead time & supply parameters 3.2

[3.1R-3.2L], engineering constraint and information regarding procurement lead time of each spare part, to decide the required service level of the supplier. It receives convolution of times (picking, transport storage etc.) [Out-3.2D] as tools and the engineering limitations [Out-3.2U] as a constraint. Any changes in the type of supplier will mean important changes in the parameters.

The output of this process consists of the accumulated information about the supply of each spare part that enables the manager to decide the most convenient supplier and signing the contract. [3.2R-3.3L].

Connections select supply source and contracts 3.3

To select the supplier and the contract, information about the outsourcing and the service level are received as input. The setup of the contract and the setup time are constraint to this process that needs to make sure the availability of every critical spare part. Inventory holding costs are also required to determine the best ordering policy. [Out-3.3U][Out-3.3U].

The output are the parts with each contract that correspond to the main overall output of the process. The selected supplier and the parameters for each part, arrival rate, costs or supplier availability, in case that the supplier could disappear and alternatives need to be find. [3.3R-Out].

Connections repair shop control 3.4

To define the parameters of the repair shop, information provided by parts demand forecasting is vital [Out-3.4L], then repairing priorities are added, as well as demand forecasting for the parts. The constraint, in this case, are the level of inventory available for repairable, budget and engineering boundaries**.** [Out-3.4U].

The repair shop is considered to be a supply option for spare parts, the flow of information that provides nourishes the whole supply chain process. As we can see in [3.4R-3.1U], [3.4R-3.3U], it works as a constraint when selecting a supply source and managing supply characteristics. As well, information of the repair shop will be used by inventory control afterwards because it determines the level of stock.

3.5.3.1 Manage supply availability and characteristics

The manager should ensure the availability of spare parts during the production given a service level, which means long time availability. There is no law in the legislation that regulates the time a supplier of an eventual machine has to keep producing spare parts and this fact could be the reason for the lack of availability. If the manufacturer has decided not to support the product or that the support will only last for a finite period of time. The part may also be outsourced, and that source could eventually dry up.

At this point, the decision to take comes as follows, how many suppliers are we going to choose? What type of suppliers are there and why should one be chosen above the others? These two questions depend on the product, and they are answered always taking into account the need for availability of the part and that the decision need to be based on the information of each part of the assortment, as it was mentioned previously, supply characteristic was a criterion in which the decision to include a part in the assortment was based, so again this information is taken into account. Spare parts replenishment lead time and supplier scarcity are influenced by the difficulty of obtaining a determined spare part. If there are many uncertain factors on the table the lead time will grow.

Each part has one or more supply sources, and as we said the problems comes when the actual supply source is known to disappear within a certain time period, or even worse there is no supply source at all. Then an alternative need to be searched, another supplier, or if possible, transforming a consumable into a repairable in order to make our internal repair shop the supplier. The spare part to watch are the critical ones, high personalization and elevated cost.

Firstly, the decision of treating a part as a consumable or a repairable is faced, this decision is evaluated by a **LORA** (level-of-repair-analysis). And will have its consequences when selecting the type of supplier. [9][23][42]

There are several types of supply sources:

- **internal repair shop**: it is considered as a supply source, it provides ready-to-use spare parts, according to the capacity of the internal repair shop as it will be explained below;
- **external repair shop**: if the capacity of the internal repair shop is limited and the cost of repairing the spare parts is limited, it is possible to establish a cooperative relationship with an external repair shop that is prepared to satisfy the desired supply parameters;

- **External suppliers**: it can be chosen because the internal repair shop does not meet the demanded amount of spare parts or because it is decided not to focus internally in repairing the part, mainly because of economic reasons. Then a cooperative relationship is established with the supplier. The amount of suppliers for each part varies. Due to the fact that the manager needs to rely on the supplier, the advantage of choosing one unique supplier is that there is an emphasis on developing long-term cooperative relationship, based on mutual trust, beneficial for both sides. It benefits from discounts associated to large volume orders and from the personalization of the service that reduces inefficiencies associated to mutual knowledge. Establishing a standard of quality becomes easier and variability is reduced. On the other side, the decision of choosing only one supplier implies a risk: Production becomes depends on the supplier, if any difficulty makes the supplier fail his commitment then production would be severely affected, whereas if multiple sourcing was chosen a problem with one of the suppliers would be solved with an increased production of the others (with the consequent over-cost) and the damage would be controlled. Normally it is recommended to establish relationships for critical components only.
  Another alternative is to establish and unique supplier for a high percentage of the total need but having another minor supplier as a back-up;
- **Re-use of parts**: For example parts that are known to become available in a short period of time caused by phased out of end-of-life systems, maybe used by other companies. [23]

3.5.3.2 Control supply lead time and supply parameters

Once we have seen the potential suppliers and their characteristic, having collected information about the product and the characteristics of different suppliers, it is about time to establish the parameters that will be evaluated to measure the "level of service" or the "convenience" of a supplier.

There is no option but to highlight three parameters at first level when approaching this decision, they are all of paramount importance:

- **Supply lead time**: it consists of: repair or supplier lead time, procurement time, picking, transport and storage time of parts and, in case of repairables, hand in times of failed repairables. For all these components of the supply lead time, agreements are made on planned lead times;
- **Costs**: it determines how much the company is going to spend and therefore it influences benefits;
- **Quality**: it establishes de level of service. "Quality is the goodness of a product" (Shewart, 1931). The higher the level (or the amount) of characteristics supplied, the higher the product's quality. It can be measured by the number of defects.

Quality is basic for production, it can be controlled by inspection. Choosing multiple sourcing over single sourcing normally leads to more inspections, lower quality level, because establishing a long term relationship with a continuum flow of information between the parts, could reduce ineffectiveness and rise the service level. As firms increasingly emphasize cooperative relationships with critical suppliers, executives of buyer firms are using supplier evaluations to ensure that their performance objectives are met. [51]

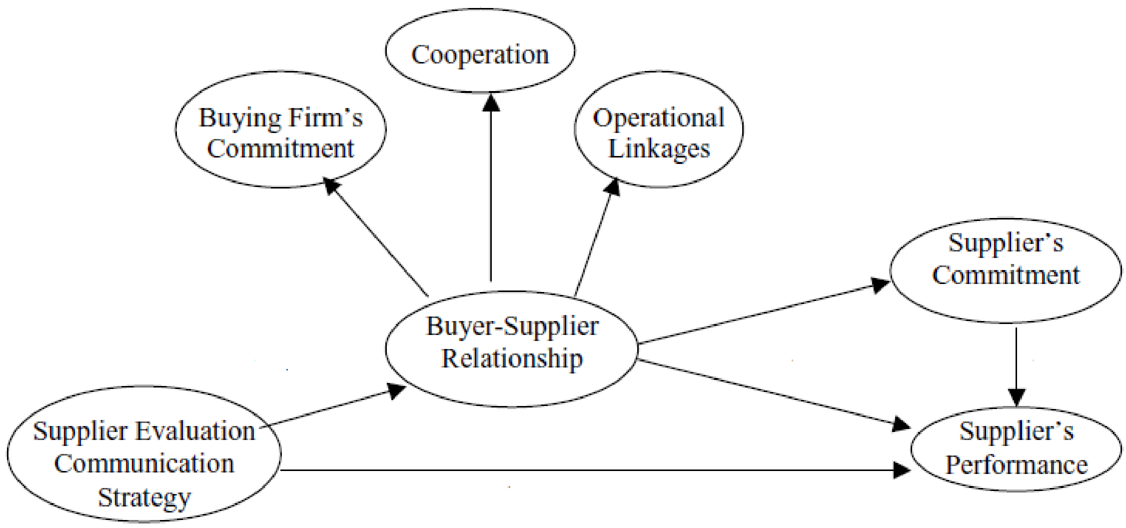


Figure 47 Supplier evaluations: the communication

Some quality theories establish that establishing a long term relationship with the supplier, could make unnecessary the inspections. However, this presents a utopic situation of mutual trust that allows the company to trust the supplier's inspections.

Depending on the type of spare part, a balance need to be made, changing priorities between the parameters presented before.

Other parameters to take into consideration are:

- **Flexibility**. If the demand of a spare part is very variable, the company needs suppliers that can increase or decrease their production in order to meet variable needs;
- **Ordering policy**. How much spare parts need to be ordered at the same time. It can influence the level of stock;
- **Volume discounts**. It is related to the ordering policy. The more you order the lower the cost;
- **The economic situation of the supplier**. A stable economic situation of the supplier means lower risk of lacking availability.

3.5.3.3 Repair Shop Control

Concerning the different types of supplier, the internal repair shop appears as a potential one, based on the fact that it provides a flow of spare parts as any other supplier. It has been included in the model as a part of supply management, receiving information about the assortment, and all the engineering constraint, (as the mechanical characteristic of parts and repairing processes and cost), it becomes a source of variable capacity. That takes the manager to the next step, deciding the capacity desired for the repair shop that minimize total cost always taking into account the necessity of availability of the spare parts, regarding if there are alternative suppliers (outsourcing) or not.

The amount of resources associated to a repair shop determines the waiting time, when a spare parts enter the repair shop the main time the sojourn time consists mostly of waiting time for resources such as specialists, tools and SRU's to become available.

The level of stock of spare parts and tools has to be set as a managerial decision. Most of the jobs need to be finished within the planned lead time to make the repair shop effective.

The resource capacity dimensioning decisions are based on the estimated repair workload, the repair workload variability (extracted from demand forecasting and parts returns forecasting) and the estimated repair time and variability (extracted from engineering constraints), when all resources are available. In making this decision, congestion effects need to be incorporated explicitly.

Sometimes, however, tools require a high investment that need to be justified with its use, that have been predicted during the parts return forecasting, provided with the information of the assortment management.

Since the costs of internal repair are the result of the resources required for repair, the dimensioning decision and the offered repair load can be combined to estimate the repair lead time and the cost of performing an internal repair. This information is used by supply management, it needs to be updated, to periodically reconsider the buy or repair decision and, in case of repair, the decision of where to repair the part.

To sum up, the repair shop the following variables need to be established based on the capacity desired: The number of specialist hired, the number of shifts, the level of SRU to stock, and the tools required. In addition, repair jobs need to be scheduled, leading to due-dates, the resources associated to the repair shop are the constraint and a consequence of the dimension of the repair shop.

Deciding "acceptable" times for repairing each parts, the MLO and specialist from the repair shop have to work together to come to a solution acceptable for both that will imply a stock level of SRU. The stocking level of SRU will be part of the next section, inventory control.

Line replaceable Units if they fail, are sent to the Failed LRU's stock, from this stock failed LRU that are economically repairable are sent to the repair shop to be repaired. The repair process consists of three phases:

- inspection and disassembly;
- repair and assembly;
- Testing and quality control.

After the inspection phase, it is known which parts need to be removed from the LRU and replaced afterwards. Parts removed at the repair shop are called Shop Replaceable Units. SRU's can be either repairable or consumable and so there are multiple levels of repair. The exact requirements are known after the inspection phase (capacity and resources). Each repair job consists of multiple repair steps. A repair man is required during each step of the repair job, and each repair step requires a certain skill. Repair shop can subcontract some jobs, and have the possibility to conduct emergency repairs, but in case specialized skills and capacities are required, this may result in extra set up or changeover times. The boundaries of a repairable inventory system are determined by its repair limitations: a limited set of capacities is only able to conduct repairs for a limited set of repairable parts. Therefore is important focusing on the critical parts that will add more value to the process or which repair would save more money for the company.[70]

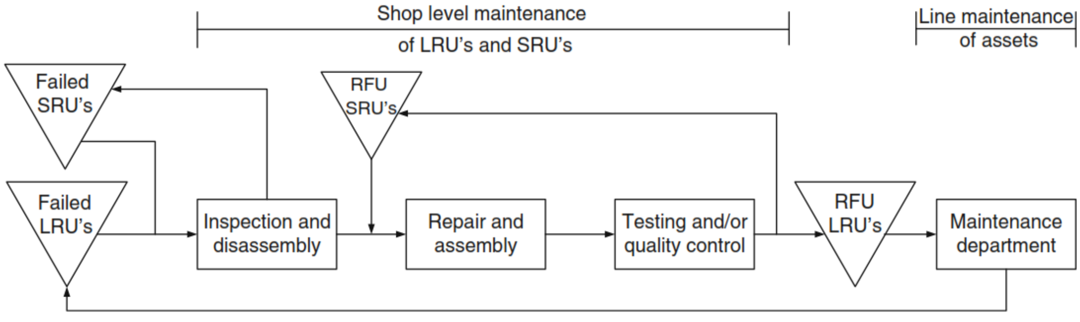


Figure 48 Repair shop process representation

3.5.3.4 Select supply source and contracts

The MLO needs to make sure that spare parts can be replenished at any given time. For this purpose, the MLO needs to set up contracts with one or multiple supply sources in a cost efficient way.

External supplier relationships are based on contracts, with expiration dates, that always need to be updated time before the contract expires, to ensure the supply and avoid a break during the time needed to update the contract.

When choosing a supplier all the information before is taken into consideration, and it is added the cost of signing the contract. The contract establish the lead time, the cost, the level of service, the penalization for not achieving the previous parameters and the responsibility in case of failure of the spare part. Each contract is valid for a period of time at the end of which all the terms are updated and renegotiated.

Supply Options

In the previous step a classification of the supplier was made, now another classification s presented that depends on the phase:

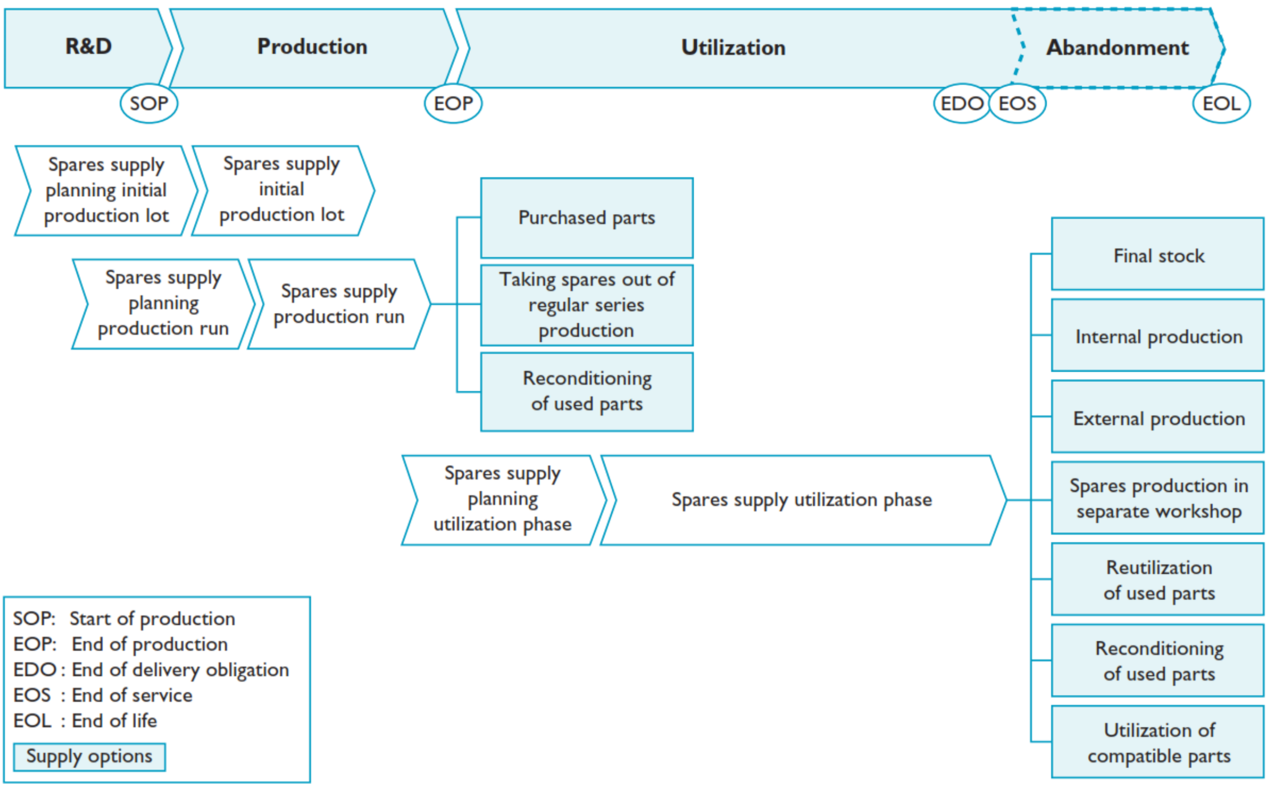


Figure 49 Supply options framework

Spare parts supply for primary product customers during the whole product life cycle can be achieved with different supply options. The three phases of the spares supply planning and implementation in the product life cycle model, with the possible supply alternatives. The life cycle-specific selection and, if applicable, combination of different supply alternatives, amount to a supply strategy. A combined or successive application of different supply alternatives is possible. The deliberate selection of only one supply option can likewise be a supply strategy. In the image below the different types of supply options are illustrated depending on the phase of the process.

Supply in the Production Phase

The selling date of the first primary product defines the beginning of the spares supply period. This first phase is characterized by uncertainty and forecast difficulties because of the absence of experience on the required amount of spares parts over time. The spare parts demanded after early failures can be taken out of the regular series production. Hence, there is no sales risk and there is no need for storage capacity for spares. The spare parts supply during the series production phase is uncomplicated. Experience has been accumulated on the spare parts demand in the past, and spares can be picked out of the regular series production. A flexible reaction to fluctuations in demand is possible. In addition, eight case study firms purchase spares from suppliers (the manufacturers prefer the same suppliers for a primary product part and spare part if possible) and five obtain spares by reconditioning used parts during this phase. The latter alternative requires a system for returns and a sufficient stock of returned primary product parts. Hence, this option is practicable only after a certain amount of time and in combination with other supply alternatives.

Supply in the Utilization Phase

The planning of the spares supply in the utilization phase is the most challenging part of the product life cycle, because the supply of spares must be ensured over a long period, and it is no longer possible to pick them out of the regular series production. Furthermore, the selected supply option determines and influence in the required inventory options. Consequently, the planning of the spares supply in the utilization phase should ideally be initiated during the production phase and should be arranged with the inventory options. A spares supply in the utilization phase can be ensured with the seven different supply alternatives presented in the figure above. Nine of the ten case study firms change the supply option during the utilization phase depending on the product life cycle. An internal and external spares production as well as a reconditioning of used parts are the supply options pursued by most of the case study firms. The supply option reutilization of used parts is only pursued by one firm. The remaining supply options are pursued by half of the case study firms.[64]

3.5.4 Inventory control level 2

In order to ensure a determined service level, due to variability of the demand of spare parts, a level of stock need to be established. Moreover, the inventory control process is concerned with the decision of which part to stock, in which location and in which quantities.

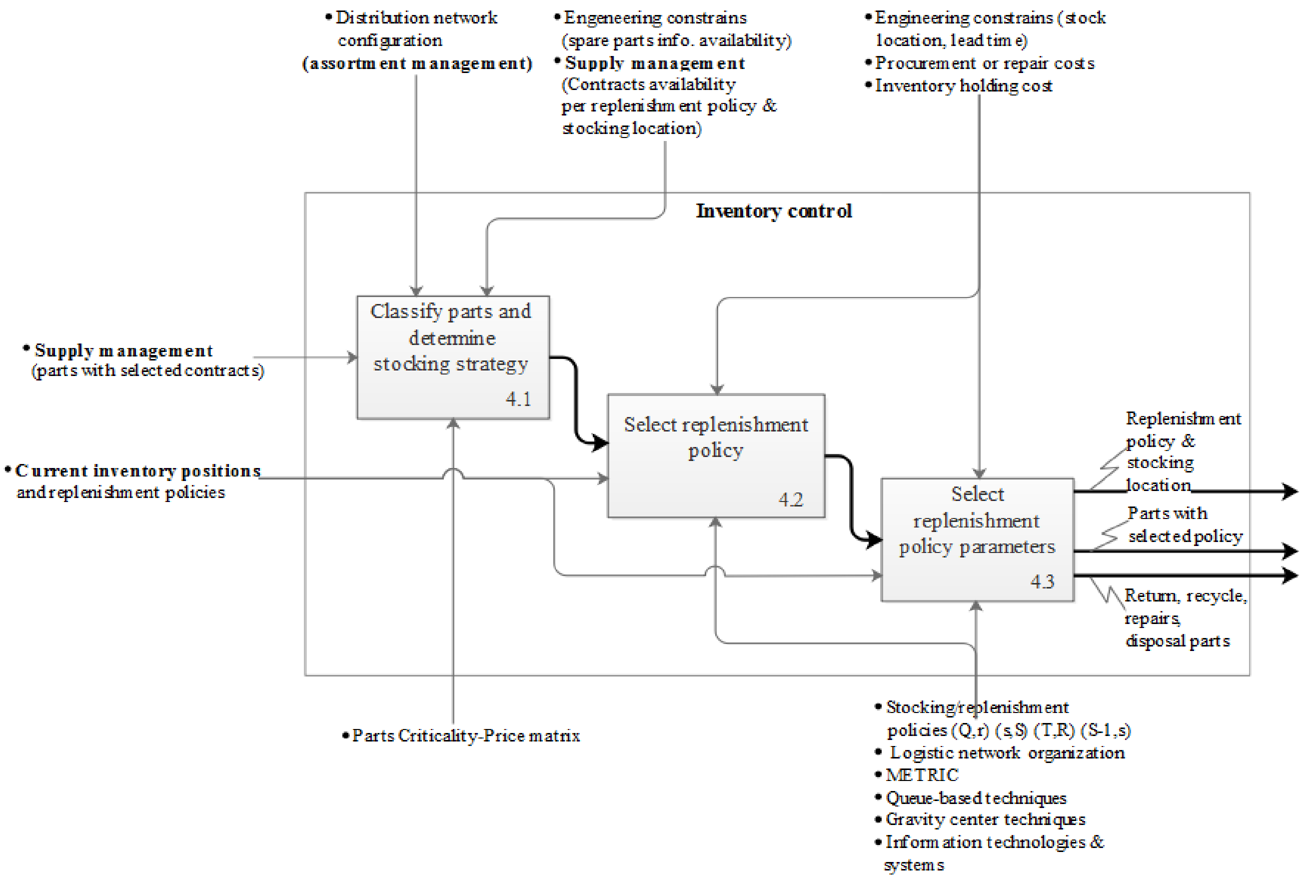


Figure 50 Inventory Control framework, second level

The MLO is in charge of this step in the methodology. First the parts need to be classify in order to decide which stocking policy suits best. Once the stocking strategy is defined, the following decision is to establish the replenishment policy. And finally establishing the parameters for the replenishment policy. In order to succeed while facing this very common problem (It is the most studied in the literature), the decision should be based on the information accumulated during the whole process. Information about the assortment, predictions about demand forecasting and the information about suppliers, settle the starting point to take this decision.

Connections classify parts and determine stocking strategy 4.1

To classify the parts to determine the stocking strategy necessary inputs are the supply management that determines the supply lead time that influences the level of stock, and the classification made in the assortment management, [Out-4.1L]. The tool received by this step is the parts criticality-price matrix. [Out-4.1U].

The output are parts classified depending the convenient stocking strategy and it nourishes 4.2, [4.1R-4.2L]. Depending on the criticality of the part and the risk of obsolescence, the decision to choose one policy or the other will set a balance between reaction time and costs of implementation.

Connections select replenishment policy 4.2

Once information from 4.1 is received, the actual stocking strategy is received and information about different options as well. Constraint are represented by holding costs and ordering costs extracted from the contracts with the supplier. [Out-4.2U].

The output consists of the stocking strategy and replenishment policy selected. [4.2R-4.3L]. It can be either periodical review or continuous review. It depends mainly on the type of spare part and the budget available for the stocking policy.

Connections select replenishment policy parameters 4.3

[4.2R-4.3L], in addition to the inputs received by the previous step (Constraint are holding costs and ordering costs extracted from the contracts with the supplier. [Out-4.2U]). Joining this information together parameters of the optimal ordering policy can be established.

The output corresponds to the global output, parts with their ordering policy, and their stocking level and location. Three different fluxes of information are the stocking policy, inventory location and parts availability, three arrows characterized as: [4.3R-Out].

3.5.4.1 Classify parts and determine stocking strategy

We distinguish the following subsets of parts based on service level differentiation: (i) (partially) critical spare parts and (ii) non-critical spare parts. Both subsets are split up into two different subsets based on supply characteristics. In addition other parameters are used to classify spare parts. The classification for inventory control is nourish of the assortment management because both classification are related.

Different criteria used to classify:

- **Actual demand**. Curve ABC: Pareto Law, 20% of the articles are responsible for 80% of the total order frequency. If the demand of the spare parts is accumulated, sorting the parts by decreasing total uses, three different zones can be differentiated.
  "A classification", special control is applied to this parts, individualized as it is possible and with constant feedback and modification of the decisions.

  "B classification" parts with normal importance, an automatic model can be applied with only periodic revision.

  "C classification" Marginal products, sophisticated revisions are not economical, these items are usually stocked with very low quantities or not at all due to the high carrying costs associated with the stock levels.

This classification is useful for the detection of non-moving stock parts. An alternative use for this parts would be a possible solution.

- **Price of the spare part**. High costs increase obsolescence risks. ABC classification can be implemented as well.
- **Rotation or movement of the part**. Parts can be classified in three groups: Fast-moving, slow-moving and non-moving items.
- **Supply difficulties or scarcity**. As it has been explained before in supply chain management this parameter influence inventory decision. In the figure below it distinguishes between spare parts with centralized logistical support or not.
- **Demand behavior**. Depending on the behavior of the demand, the chosen inventory management method varies. Two situations are identified stochastic demand and deterministic, in decreasing order of complexity.

Classifying spare parts for inventory control allows the identification of risky supplies, to catalog high value stocked parts, the identification of residual parts and critical parts with important economic repercussion.

The figure below shows a classification made by S. Cavlieri et al. [15] in their paper that summarizes the classification.

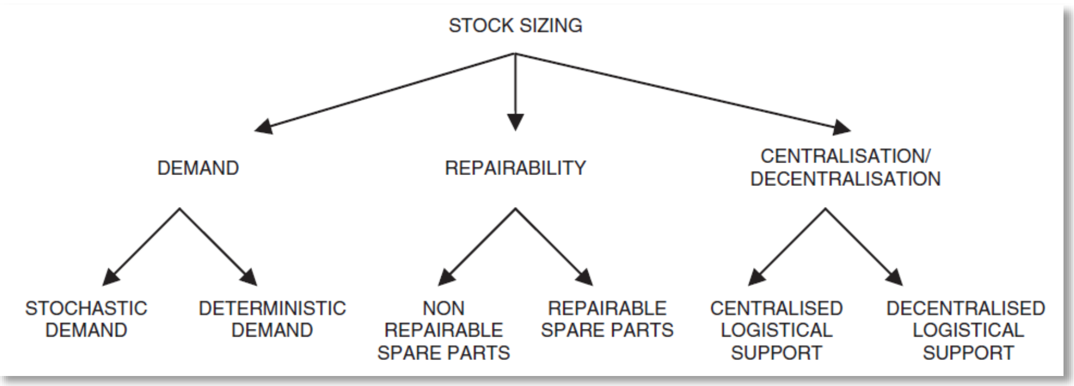


Figure 51 Classification and selection drivers of stock sizing models, S. Cavalieri et al.

3.5.4.2 Select replenishment policy

To classify the work on the problems of determining the EOQ spare parts inventory management, we need to distinguish between static and dynamic inventory management.

To meet the demand of spare parts from maintenance services, which have generally a stochastic nature, the manufacturer must set an effective strategy of inventory control.

Static inventory control

We distinguish in replenishment policies, the policy for a continuous review system and the policy for a periodic review system as the two option when facing this problem. Continuous review means higher costs of implementation, however it provides a lower reaction time for any change in the demand of spare parts. Another possible disadvantage for continuous review policy could be that the accumulated character of the inventory used is not able to absorb the variability of special variability causes, predicting as normal inventory when it is an extraordinary situation.

The periodic system is generally preferred in spare parts management because of the convenience of regular ordering days for the stocker and for the supplier, who can plan efficient routing of delivery vehicles. This inventory control system has been claimed theoretically to be the best for the management of low and intermittent demand items [27][15]

Dynamic inventory control

Dynamic inventory control refers to the situation where the demand is considered to be stochastic. There are methods in the literature to calculete the lot size in this cases such as:

Lot sizing methods: Lot sizing methods are inventory control methods often used in MRP systems to run grouped commands in order to minimize costs. The method performance is obtained after comparing the total costs, the total cost is defined as the sum of control costs (start-up costs), costs of remaining stocks from one period to another (holding costs) and costs resulting from constraints to the system.

If the periods are short and discrete, and the demand reduced, it can be concentrated at the beginning of each period. Wagner-Whitin gave an algorithm for finding the optimal solution by dynamic programming.

$$Min \sum_{t=1}^{L} [A\delta(Q_t) + v * rI_t]$$

$$s.a\ I_{t-1+}Q_t - I_t = D_t$$

$$Q_t, I_t \geq 0$$

Q= Quantity to order.

I= Inventory.

v*r = Holding costs.

A= Ordering costs.

To avoid the complexity of dynamic programming, two metaheuristics are implemented, starting by two properties of the optimal quantity to order:

Silver-Meal Heuristic: It requires determining the average cost per period as a function of the number of periods the current order is to span and stopping the computation when this function first increases.

Part period balancing: The part period balancing procedure adheres to the classic lot size formula for the minimum costs whereby variable costs (storage costs) are equal to the lot size independent costs.

[29] [38]

3.5.4.3 Select replenishment policy parameters.

An inventory model is composed by two main parameters:

- A criterion (Q) that specifies the conditions under which a new order of spare parts should be issued. (In periodic review policies it would be S the parameter).
- A reference point (s) for the quantity to be ordered. [15]

Real situations are not deterministic, variability is implicit in every operation due to human factor and machinery defects. In order to absorb variability in the demand and to avoid an undesirable stock-out situation, the concept of safety stock rises.

The probability of a stock out or break of stock is P (u>s), being u the number of units required in the period and s the level of inventory.

Safety Stock (SS) = s (level of stock) – u (Average demand on during the reaction time. Depending on the type of demand calculation varies.

For a continuous review policy the reaction time to a possible stock out is shorter so the level of safety stock reduced. U= Supply lead time, and for periodic review policies, U= Supply lead time+ T (revision time).

SS=$\int_0^{\infty}(s-u)f(u)du$ Then a cost B is associated to a stock out, and it is included in the total cost to minimize.

To calculate SS, the formula used is:

SS= k (coverage rate)*σ_{SL} (reaction time variability. K can be extracted from the probabilities depending on the distribution of the demand.

The whole inventory level then would be: for continuous review policies: s (point of reordering) =u+ss for periodic review policies: S (maximum stock) = u+ss (with a different u than before as it has been explained.

4 RESULTS

In it is presented, the first general framework level: the phases' contributions and their interdependences are depicted, expressed by arrows and identified through texts.

This thesis work has the aim to develop and offer a worthwhile support for the acknowledgments and the decision-making processes in spare parts maintenance field.

Recognizing that maintenance involves a huge body of concepts and even more possible scenarios, instead of focusing the efforts on a limited industrial sector and providing a deep analysis, it has been decided to adopt a trade-off between details investigations and accessibility to the reader.

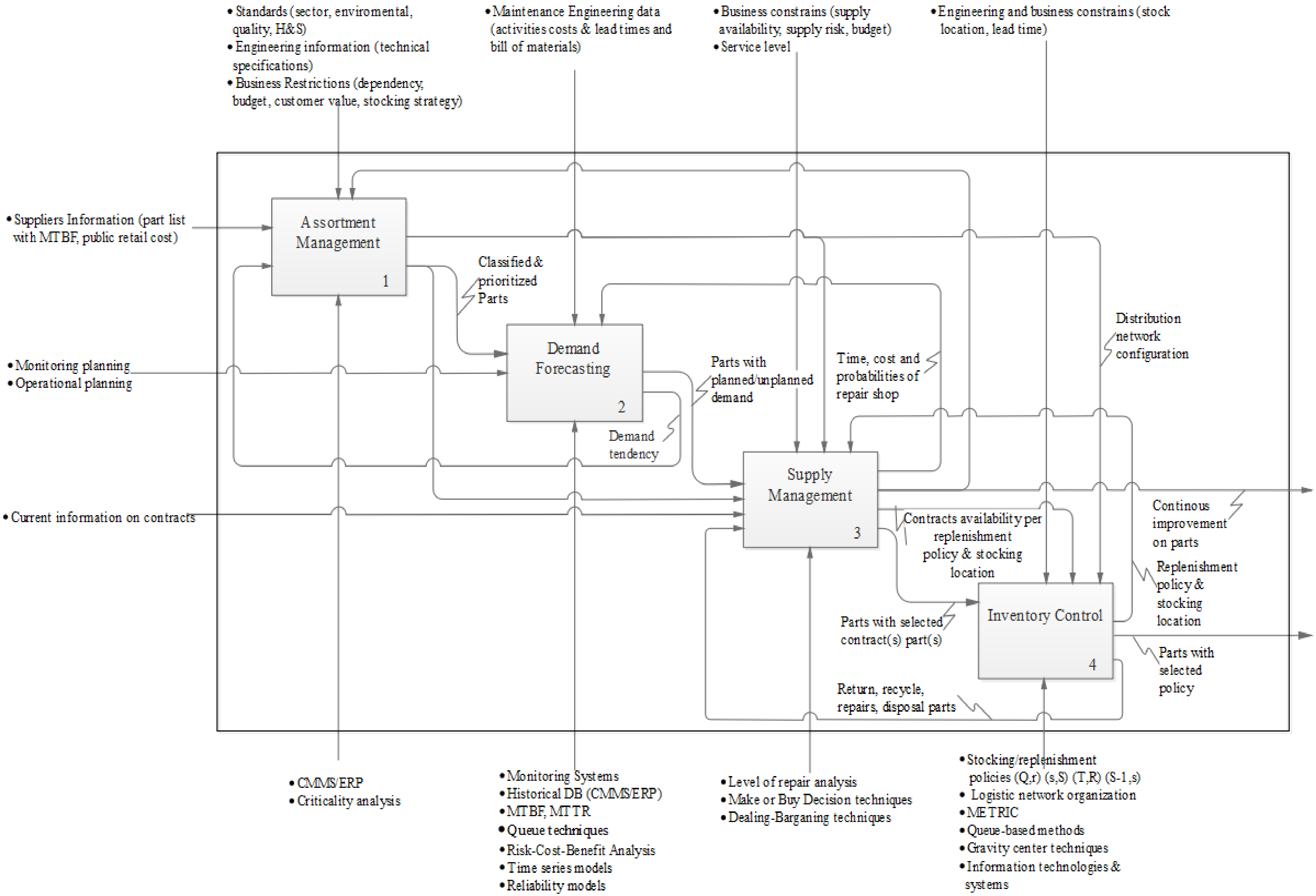
It should be highlighted the fact that when constructing a framework, as complete as the one presented, the definition of many concepts is necessary so that the phases composition could be understood. Therefore the first section with the theoretical background has been included.

The framework in , intending to picture a general view, provides much information which is needed in order to follow the objective; this information, can be similar in the purpose but differently operated, depending on the case. Therefore if the user is willing to apply the knowledge extracted from this methology, a final step is needed, which consist on the addition of the necessary information fluxes that depends on the firm characteristics. Thus, the tools proposed will be subjected to a selection also because of the budget and necessities of the firm; the constraints will acquire a specific weight, value and structure. Starting from the resources available, in terms of facilities and possibilities, relationship and interdependences will be defined and the useless connections (for the specific issue) deleted or avoided.

The final result correspond to a general framework, in order to make it applicable to a real situation it would be necessary to have a deeper insight that would determine information fluxes and which of the tools should be applied.

4.1 Final framework

(Figure 52 General framework, level 1)



4.2 RACI matrix

There is the possibility of exploiting this methodology not only where a procedure for spare parts management is not implemented, but also, departing from the existent model, if a problem arises it is possible to manage it and to go directly to the root of the problem by using this methodology presented.

In order to present this other potential of the methodology, regarding issue control, RACI Matrix well supports the environment comprehension. RACI methodology is configured as a suitable tool to clarify roles and responsibilities in cross-functional/departmental projects and processes. RACI is an acronym derived from the four key responsibilities most typically used: Responsible, Accountable, Consulted, and Informed [25].

In particular:

- **Responsible (R):** It correspond to the phase that assigns the task, the epicenter.
- **Accountable (A):** It correspond to the steps of the process which affected somehow to the task result, the possible 'causes'.
- **Consulted (C):** It correspond to the phase which helps and support the responsible of the task.
- **Informed (I):** It correspond to the phases that need to be informed of the result of the task discussed so that information and parameters are updated for future decision making.

The table below represents the exploitation of RACI Matrix methodology. The first column reports common issues, taken as instances, found during the literature review phase, for both theoretical and practical (case studies). It serves as an example of the use once implemented of this methodology.

Representation of the RACI Matrix

RACI Matrix		Spare parts maintenance phases											
		Assortment management		**Demand forecasting**			**Supply management**				**Inventory control**		
		1.1 Spare parts assortment	1.2 Spare parts analysis and classification	2.1 Classify parts with respect to demand forecasting	2.2 Parts return forecasting	2.3 Demand pattern for planned and unplanned demand	3.1 Manage supply availability and characteristics	3.2 Control supply lead time & supply parameters	3.3 Select supply source and contracts	3.4 Repair shop control	4.1 Cassify parts and determine stocking strategy	4.2 Select replenishment policy	4.3 Select replenishment policy parameters
Problems as instances	Safety stock	I	C, I	C, I	I	C, I	C, I	C, I	I, A	I	R, A	R, A	R, A
	Repaired material flow	I	C, I	C, I	I	I	R, A	C, I	I, A	R, A	I	I	I
	Spare Criticality	C, I, A	R, A	C, I	I	I	I	I	C, I	I	I	I	I
	Order quantity	I	C, I	C, I	I	C, I	I	C, I	I	I	C, I	R, A	R, A

Safety stock

The safety stock refers to inventory carried in excess and used as a cushion against uncertainty in demand or in replenishment lead time. Depicted in the matrix the phases involved. The phases 4.1, 4.2 and 4.3 are responsible and accountable in the evaluation on the spares safety quantity to keep in stock. In this case the process accounts on most of the sub-phases, in fact, the decision on the policies to adopt (considering also quantity and lead times) follows the regular decision-making process. Phases consulted are the assortment management and the supply management. In the details the information gathering is at the basis of the inventory control, the supply management phase must be consulted and informed. The remaining are retained to need only the updating but not others responsibilities.

Repaired material flow

This is the decision on detain or not a repair shop. Phases responsible and accountable can be identified in the 3.4 repair shop control, manage the supply availability and characteristics and part return forecasting establishing key parameters. 3.1 sets info on the decision of make or buy the spares, if the facilities needed are available. Into this classification 3.2 should be consulted cause of all parameters must be controlled. Parts classification and demand forecasting for suggestions and support for task elaboration are identified as consultable.

Spare parts classification

Assessments on spare parts criticality, as many authors agree, is at the basis of the maintenance management: from a financial perspective (establishing if the spare is a durable item or consumable), form logistic point of view (managing on-demand or detaining it in stock) and from a maintenance perspective. The process sees 1.2 as the responsible step, developing information in input from the demand forecasting and external suppliers' information on components. The phases consulted, in this evaluation represent the second level for importance and these are the demand classification phase because provides assessments on parts features, then supply characteristic management. Others Phases manage lower information flows or indirect contribution to the task.

Order quantity

A technical decision or an issue may be represented by the spare parts quantity to set in the replenishment policy. In this case, can be recognized the main responsible phases in the selection of the replenishment policy and the selection of the parameters: these processes elaborate the upstream information in order to accomplish the most suitable values selection. Other phases that must be cited for their contribution in the process are 1.2 and 2.1, respectively form the assortment management and from the demand forecasting these steps are worthwhile for the acknowledge of the technical spares data and consequent features to keep in consideration in inventory control phase. "Control supply lead time and supply parameters" is the phase that lead the classification of the suppliers and the consequent supply risk: aspect that need attention for the possibility that supplier leave the market. Other phases represent part of the process that have only to be informed on the results of the task.

5 CONCLUSIONS AND FURTHER RESEARCH

The present thesis work had two main objectives: the first was to provide a multi-echelon analysis of the spare parts logistic phases and, the second, to generate a related framework worthwhile for practitioners and researchers.

The first objective has been pursued through a specific documents and articles research on the spare parts supply chain in maintenance field. The studies and analysis have been developed, first, assuming a general and broad approach in order to understand structures and dynamics that affect the processes, then, once selected the main areas, the researches have been brought in the deep. The results of the literature review task, have been organized explaining and elaborating the theory and case studies contributions. Afterwards, the phases recognized as the most important and meaningful have been contextualized and taken as cardinal concepts, the phases proposed are: the assortment management, the demand forecasting, the supply management and the inventory control. Each process presents its own operational mode and fashion to accomplish its specific purpose and, on the basis of data trackable in literature, its proper requirements and approach to manage the information flows. The analysis has been developed considering more detail levels, within the main phases other processes can be recognized and studied; the behavior of a process in the principal level can, in fact, be explained and reasons con be detected in its composition.

Regarding this section, future researches could take advantage on an even larger literature contribution, recognizing trends of methodology usage, thus, recognizing the direction in which internet as a whole and internet of things would lead these processes.

The second objective has been accomplished adopting IDEF representation methodology. This tool for processes representation allows to develop a multi-echelon analysis, involving, for different levels, different information flows in terms of aggregation level and number. From this method exploitation, a framework based on the literature review has been elaborated and proposed. All the relationships between phases, recognized in previous studies, are depicted, explained and the meanings of information flows are offered. The relationship possibilities are basically four: as an input, providing information that can be managed by the process, as a constraint, representing a limitation for the phase forcing it to develop procedures to respect or avoid it, as a resource, representing a tool available to develop the input and manage the constraints, or without any linkage. The main contribution of the tool, in a period in which studies lead to specific and complex assessment, is to develop an analytical behavior and transmit knowledge in an easy way.

Future researches may develop the framework taking advantage on new and different information, discovering through the study and analysis in the maintenance field others connections or other meaning of the information flow.

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