ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO INDUSTRIAL SUPERIOR MECÁNICO

ANALYSIS OF ENERGY-KPIS WITH RESPECT TO PRODUCTION PLANNING IN COMBINATION WITH A FORMULATION OF POSSIBLE MEASURES TO ENABLE ENERGY FLEXIBILITY

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Madrid

Febrero de 2015

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RESUMEN DEL PROYECTO

Introducción

En la actualidad, la importancia de las energías renovables está creciendo mucho en contraste con otras fuentes de energía no renovables debido a su coste e impacto en el medio ambiente. Esa tendencia queda muy bien reflejada en la publicación del Ministerio de Medio Ambiente alemán llamada “Erneuerbare energie in Zahlen” (Las energías renovables en los números) la cual revela que hacia el año 2050 las energías renovables representarán el 80% de la energía generada en Alemania.

Sin embargo, las energías renovables tienen el inconveniente de no poder asegurar el suministro de energía ya que dependen de condiciones externas para ser generadas. Un ejemplo es la energía eólica, la cual depende de la velocidad del viento para generar electricidad. Este factor hace que los precios de generación de la energía sean fluctuantes y por consiguiente, esa fluctuación queda reflejada en el consumidor. Los factores de los que depende el precio de la energía en un determinado momento son: la fuente de la cual se obtiene, la cantidad generada en cada una de las fuentes y la demanda por parte de los consumidores.

El objetivo final de esta tesis es obtener una reducción de los costes energéticos de un país. Se pueden distinguir cuatro grupos de consumo de energía en los países de la OCDE: uso residencial, comercial, transporte e industria, siendo la industria el más importante en términos de consumo energético.

Particularizando en la industria, se pueden distinguir dos líneas de actuación para reducir el consumo eléctrico que a su vez se combinan entre ellas para obtener mayores reducciones: Medidas de eficiencia energética, mediante la utilización de maquinaria de bajo consumo; y medidas de efectividad energéticas mediante la adaptación del consumo de las fabricas a periodos de precios de energía más bajos, los cuales son variables por las razones anteriormente mencionadas. Mediante esta medida se pretende consumir más energía en periodos de tiempo en que la energía renovable tiene mayor participación en la generación y reducir así el gasto total de la fábrica. Esta capacidad de adaptación es lo que a lo largo de la tesis se denomina “Flexibilidad Energética”.

El objetivo principal de esta tesis es introducir el concepto de flexibilidad energética mediante la adaptación del consumo eléctrico a los precios. Y esta adaptación se conseguirá mediante la planificación de la producción.

Metodología

El consumo energético de una fábrica será más o menos adaptable a los precios de la energía dependiendo de la flexibilidad que tenga la propia fábrica. La flexibilidad en este contexto es entendida como la capacidad de adaptación a diferentes condiciones de producción de manera rápida y a bajo coste. Esta flexibilidad se traduce en tres líneas diferentes:

- Flexibilidad en la capacidad, que es la habilidad de una fábrica de variar las cantidades de producción
- Flexibilidad de productos, relacionado con que producto se fabrica en un determinado momento.
- Flexibilidad operacional, relacionada con las diferentes rutas y secuencias de producción que puede seguir un producto y el tiempo de ajuste para pasar la producción de un producto a otro.

Estos tipos de flexibilidad presentados anteriormente, son utilizados en la planificación de la producción, con el objetivo de satisfacer la demanda y sirven igualmente para planificar el consumo energético. Dependiendo de lo flexible que sea una fábrica en los tres puntos explicados anteriormente, tanto el coste como el gasto energético pueden variar en función cantidad producida, las maquinas utilizadas y el momento del día en que se produzca (precios variables de la energía).

La planificación del consumo energético se consigue introduciendo en la planificación de la producción como factores adicionales, la energía a consumir en los procesos y los precios medios de la energía para los periodos de tiempo considerados.

Para llevar a cabo esta planificación se ha de cuantificar el consumo energético de todos los procesos relacionados con la producción. Esa cuantificación se realiza mediante la determinación de “Key Performance Indicators (KPIs)” energéticos. Los KPIs energéticos propuestos están relacionados con los niveles de agregación de una fábrica. El nivel de agregación más alto es el sistema de producción, entendido como el conjunto de todas las máquinas que producen todos los productos. En los sistemas de producción se fabrican los productos y esos productos, a su vez, se producirán en una serie de máquinas, las cuales pueden tener distintos estados de funcionamiento. A los efectos de esta tesis, se proponen los siguientes KPIs de tipo termodinámico y físico-termodinámico:

- Para maquinaria: medición de KWh consumidos por actividad realizada en una máquina para un producto determinado.
- Para producto: medición de KWh por unidad de producto. Se trata del sumatorio de la energía consumida en cada una de las máquinas en las que se ha producido el producto.
- Para el sistema de producción: cuantificación en KWh consumidos mediante sumatorio del consumo de todos los productos.

Teniendo el dato del consumo energético, los precios de la energía por unidad de tiempo y los demás factores que intervienen en la planificación de la producción (cantidad demandada por el cliente, fecha de entrega), se presenta un método de planificación de la producción que tiene como objetivo cumplir los plazos de entrega del cliente al coste más bajo posible.

La toma en consideración del factor energético se realiza tanto en la planificación a corto como a medio plazo. Sin embargo, no se valora en la planificación a largo plazo ya que ésta es de tipo estratégico y no se ve afectada por el consumo de la energía.

En primer lugar se presenta un modelo de planificación agregada a medio plazo con el objetivo de establecer cuando y cuanto se va a producir teniendo en cuenta el precio medio de la energía por periodo considerado. Acto seguido, se presenta la planificación semanal estableciendo los lotes de producción óptimos para satisfacer la demanda al coste más reducido posible (coste energético incluido). Por último, en el nivel temporal de planificación más bajo, se planifican el tamaño de los lotes secuenciales y simultáneos con el objetivo de crear una secuencia optima de producción minimizando el "makespan" y el coste energético, si se consideran diferentes precios de energía a lo largo de un día. Adicionalmente, se propone mover los turnos de producción a momentos del día en los que los precios sean más bajos.

Caso práctico

De cara a demostrar los conceptos anteriormente propuestos y la bondad del método, se ha realizado la "planificación agregada mensual" y la "planificación semanal de los lotes producción" de dos fábricas con consumo energético diferente:

- Caso 1: se trata de una fábrica con un consumo medio de 1.5 MWh al día.
- Caso 2: se trata de una fábrica con un consumo medio de 15 MWh al día.

En ambos casos, se ha realizado la planificación con el método propuesto teniendo en cuenta el consumo energético y los precios de la energía (se consideran conocidos), y con los métodos convencionales sin tener en cuenta el factor energético con el objetivo de comparar los beneficios que se obtienen en ambos casos.

El modelo utilizado para obtener los precios se basa en el precio del "spot market" añadiendo los impuestos pertinentes dependiendo de la energía consumida, como sigue:

*Precio de la energía después de impuestos (Euro/ MWh) = Spot Price medio antes de impuestos por periodo considerado + T*Q(impuestos)*

Siendo T el impuesto de 10 Euros por MWh consumido y Q los MWh consumidos en el periodo considerado.

El modelo impositivo propuesto es una simplificación del modelo real pero muestra muy bien lo que se pretende mostrar en esta tesis. Este modelo implica que se penalice más a las fábricas que más consumen.

La planificación agregada planteada es mensual de enero a junio de 2010. Se considera la demanda mensual de los productos, la capacidad mensual de la fábrica y el precio medio de la energía por mes (dato conocido). El coste de inventario por periodo y el beneficio obtenido son datos invariables (1 Euro y 100 Euro, respectivamente).

La planificación semanal de los lotes de producción es de ocho semanas, de febrero a marzo de 2010. En este caso, también es conocida la capacidad de producción semanal, demanda semanal y el precio medio de la energía en cada una de las semanas propuestas. El coste de producción, de inventario y de preparación son también conocidos (10 Euros por periodo, 0.2 Euros por periodo, 10.000 Euros por periodo, respectivamente).

Para ambos tipos de planificación se desarrollan unos algoritmos de programación lineal para obtener los resultados pertinentes.

Resultados

En la planificación agregada de la fábrica de bajo consumo considerada en el caso 1, los ahorros obtenidos planificando el consumo energético son muy bajos en comparación con los ahorros obtenidos de la planificación realizada para la fábrica del caso 2 (69.504,89 Euros). El porcentaje de ahorro es, no obstante, muy bajo (cercano al 0.2% respecto a la planificación sin tener en cuenta la energía)

En el caso de la producción semanal de lotes de producción, para la fábrica de bajo consumo del caso 1, el ahorro obtenido es bajo frente al beneficio obtenido en la fábrica de alto consumo del caso 2 (78.901 Euros). En este caso el ahorro obtenido responde a un 4.5 % respecto a la planificación sin tener en cuenta la energía.

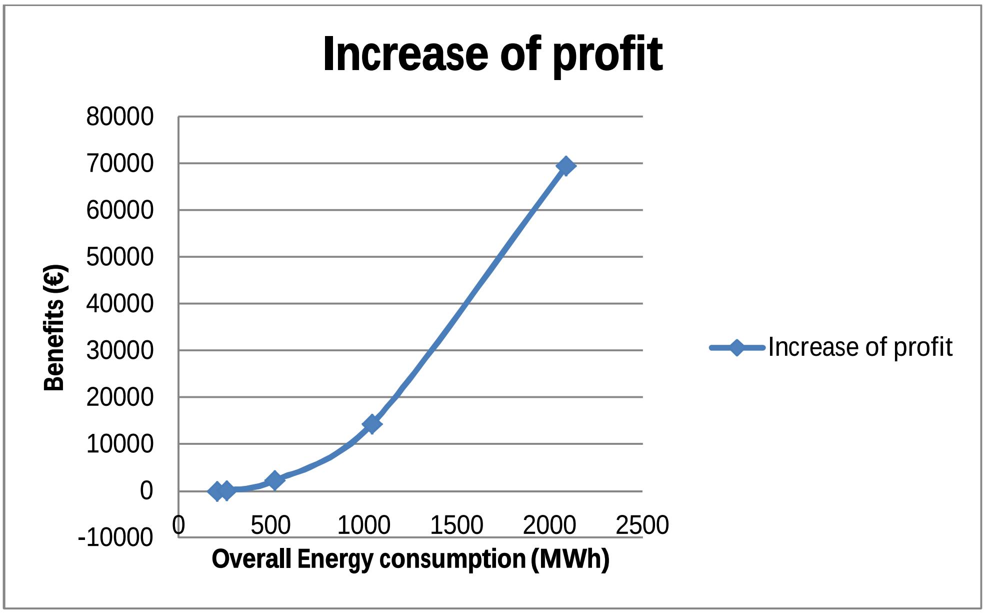

Figura 1: Beneficios obtenidos mediante la planificación energética dentro de la planificación agregada en función de la energía media que consuma una fábrica.

Queda reflejado que las fábricas de alto consumo tienen más posibilidades de obtener beneficios planificando el consumo energético y que cuanta mayor flexibilidad tenga la fábrica, más posibilidades hay de ahorro. Además, en periodos de planificación pequeños se pueden conseguir beneficios significativos ya que, los precios medios por semana son más dispares entre ellos. Además, si se considera una fábrica de alto consumo energético, un porcentaje alto del coste de producción sería computado al gasto energético y el ahorro de 4.5 % anteriormente mencionado podría ser la llave para conseguir vender los productos a precios más competitivos.

A la hora de obtener los ahorros presentados, no se han tenido en cuenta costes de mano de obra, ni ningún tipo de amortización de máquinas, alquileres de terrenos etc. Por tanto, se muestran los ahorros solo desde el punto de vista energético.

Conclusiones

En el proceso de elaboración de esta tesis, se han generado algunas contribuciones importantes a la planificación de la producción. La primera ha sido la recopilación bibliográfica donde se han recogido todas las tendencias mundiales en la planificación de la producción incluyendo el consumo de energía durante la producción así como los "Key Performance Indicators (KPIs)" energéticos para describir y controlar el consumo de energía.

Como enfoque innovador, el consumo de energía eléctrica es introducido a todos los niveles de planificación de la producción, desde la planificación de la producción agregada a la programación a nivel de maquinaria. Para ello, se han desarrollado unos algoritmos de programación lineal teniendo en cuenta conjuntamente los objetivos de planificación de producción convencional y reducción del coste energético, teniendo en cuenta los precios de la energía por periodo de tiempo evaluados.

Las conclusiones obtenidas de la tesis son:

- Las fábricas de alto consumo energético serán más susceptibles a la aplicación de estas técnicas y tendrán, por tanto, mayor potencial de ahorro. Sin embargo, estás no pueden ser introducidas si la producción no es flexible.
- Cuanto mayor sea la flexibilidad de la fábrica en términos de capacidad, productos y maquinaría, mayor capacidad tendrá para ahorrar en el coste de la energía en periodos de planificación de corto plazo.
- La flexibilidad hace que podamos planificar la producción en periodos más cortos de tiempo. Cuanto más flexible sea la fábrica, los periodos de planificación serán más cortos y por tanto, mayores serán los ahorros.

Una interesante continuidad a esta tesis sería formular una optimización multi-objetivo en la planificación a nivel de secuenciación de producto en las maquinas teniendo en cuenta lo factores importantes en la planificación de la producción, tales como la minimización del “makespan”, el consumo de energía y los precios. Adicionalmente, sería importante evaluar los costos que implica la implementación de estas estrategias en términos de recursos (como la instalación de sistemas de control adicionales) con el fin de compararlos con los ahorros que se espera alcanzar y valorar económicamente la rentabilidad de la inversión.

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ABSTRACT

Introduction

Nowadays, the importance of renewable energy is growing remarkably in contrast to other non-renewable energy sources due to its cost and impact on the environment. This trend is clearly reflected in the publication of the German Ministry of the Environment called "Erneuerbare energie in Zahlen" (Renewable energies in numbers) which reveals that by 2050 renewable energy will account for 80% of the energy generated in Germany.

However, renewable energies have the disadvantage of not being able to secure the energy supply and depend on external conditions to be generated. An example is wind energy, which depends on the speed of the wind to generate electricity. This factor makes the prices of energy generation volatile and therefore the fluctuation is reflected in the consumer. The factors on which depends the price of energy at a given time are the source from which it is obtained, the amount generated in each sources and demand from consumers.

The ultimate goal of this thesis is to obtain a reduction of energy costs of a country. Four groups of energy consumption in OECD countries can be distinguished: residential, commercial, transport and industry use, being industry the most important in terms of energy consumption.

Particularizing in industry, there are two lines of action to reduce power consumption which can be combined in order to get greater reductions: Energy efficiency measures, using low consuming equipment; and energy effectiveness measures by adapting the consumption of factories to periods of lower energy prices, which are variables because of the above reasons. This measure is intended to consume more energy in periods that renewable energy participation has increased in the generation and reduce the total cost related to the factory. This adaptability is what along the thesis is called "Energy Flexibility".

The main objective of this thesis is to introduce the concept of energy flexibility by adapting the electricity consumption to the electricity prices. And this adaptation is achieved through production planning.

Methodology

The energy consumption of a factory will be more or less adaptable to energy prices depending on the flexibility that the factory has. Flexibility in this context is understood as the ability to adapt to different production conditions quickly and at low cost. This flexibility is translated into three different lines:

- Capacity Flexibility, which is the ability of a factory to vary production quantities.
- Products flexibility, related to that product is manufactured at a given time.
- Operational flexibility, related to the different routes and production sequences that a product can follow and set-up time to change from one product to another.

These types of flexibility presented above are used in production planning, in order to meet demand and also can be used to plan energy consumption. Depending on how flexible a factory is in the three points discussed above, both the energy use and energy costs may vary depending on the quantity produced, the machines used and the time of day (variable energy prices).

The energy consumption planning is achieved by introducing into the production planning as additional factors, energy consumption of production processes and the average energy prices for the time periods considered.

To carry out this plan, a quantification of the energy consumption of all processes related to production is needed. This quantification is done by determining "Key Performance Indicators (KPIs)" related to energy. Energy-KPIs proposed are associated with the factory levels of aggregation. The highest level of aggregation is the production system, understood as the set of all machines that produce all products. In Production systems the products are manufactured and the products are produced by certain machines which may have different operating states. For the purposes of this thesis, the following thermodynamic and physical-thermodynamic Energy-KPIs are proposed:

- For Machines: Measuring KWh consumed by activity in a machine for a particular product.
- For product: measuring KWh per unit of output. It is the sum of the energy consumed in each of the machines in which the product has been produced.
- For the production system: quantification in KWh consumed by summing the energy consumption related to all products.

Taking the data of energy consumption, energy prices per unit time and other factors involved in the planning of production (quantity demanded by the customer, delivery date), a method of production planning is presented that aims to meet customer delivery at the lowest cost possible.

Taking into account the energy factor is performed both in planning short and medium term. However, it is not assessed in long-term planning as this is a strategic nature and is not affected by the consumption of energy.

First a planning model added to the medium term in order to establish when and how will occur considering the average price of energy by period considered is presented. Then, the weekly schedule is presented establishing optimal batch production to meet demand at the lowest possible cost (including energy costs). Finally, in the lower level of temporal planning, the size of the sequential and simultaneous batches with the aim of creating an optimal production sequence minimizing the "makespan" and the energy cost are planned, considering different energy prices over a day. Additionally, it is proposed to move production shifts to times of day when prices are lower.

Case Study

In order to demonstrate the previously proposed concepts and goodness of the method a monthly “aggregate planning" and weekly “Lot Sizing Planning" of two factories with different energy consumption has been performed:

- Case 1: This is a factory with an average consumption of 1.5 MWh per day.
- Case 2: This is a factory with an average consumption of 15 MWh per day.

In both cases, the planning has been done with the method proposed taking into account energy consumption and energy prices (considered as a known data), and conventional methods without taking into account energy consumption planning in order to compare the savings obtained in both cases.

The pricing model used is based on the price of the "spot market" adding applicable taxes depending on the energy consumed, as follows:

*Energy price after taxes (Euro / MWh) = Spot Price Average without taxes per period considered + T * Q (taxes)*

Where T is the tax of 10 euros per MWh consumed and Q, the MWh consumed during the period considered.

The proposed tax model is a simplification of the actual model but shows very well what is intended to show in this thesis. This model implies that high-consuming factories are more penalized than low-consuming factories.

Aggregate planning is raised monthly from January to June 2010. Here the monthly demand of products, monthly capacity of the factory and the average energy price per month (known data) are considered. The inventory cost per period and profit data obtained are invariant (1 Euro and 100 Euro, respectively).

The weekly Lot Sizing planning is for eight weeks, from February to March 2010. In this case, it is also known the weekly capacity of production, weekly demand and the average price of energy in each of the proposed weeks. The cost of production, inventory and Set-up are also known (10 Euros per period, 0.2 Euros per period, 10,000 Euros per period, respectively).

For both production planning ranges, two linear programming algorithms are developed in order to obtain methods.

Results

In the Agreggate Planning of the low-consuming factory considered in case 1, the savings obtained from energy consumption are very low compared to the savings obtained from the planning done for the factory of case 2 (69,504.89 Euros). The percentage of savings is, however, very low (around 0.2% over the planning without taking into account the energy prices)

For the weekly Lot Sizing Planning for the low-consuming factory case 1, the savings obtained are also low compared to savings obtained in the factory of case 2 (78,901 Euros). In this case the savings reflects a 4.5% compared to planning without taking into account the energy prices.

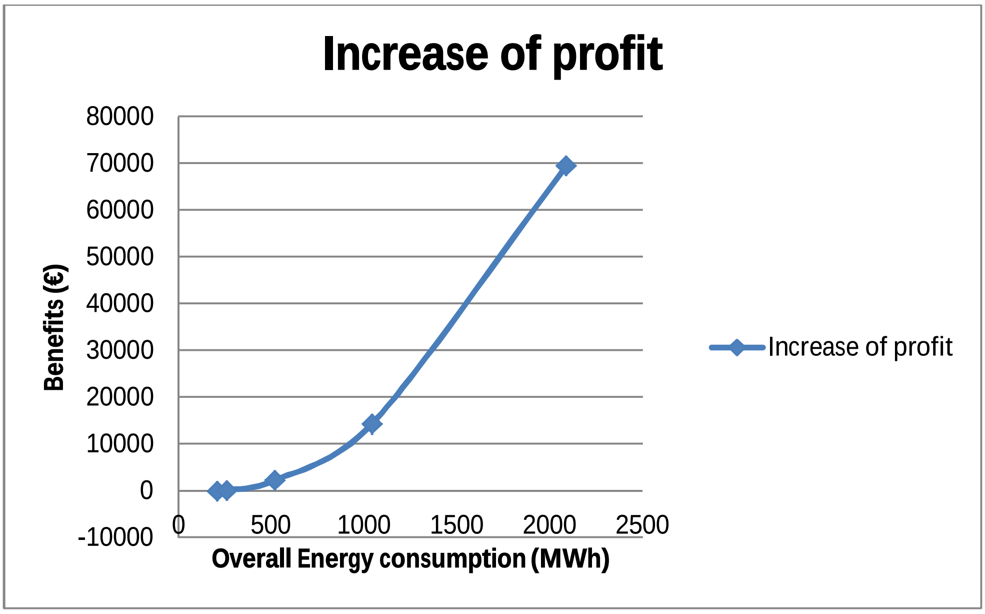

Figure 1: Benefits achieved through energy planning within the aggregate planning dependent on the average energy consumption of a Factory.

It is shown that high consuming factories are more likely to obtain savings by planning the energy consumption and that the greater flexibility factory has, the more savings are going to be obtained. Moreover, in short- term planning significant benefits can be achieved because the average prices per week are more disparate between them. In addition, if a high consuming factory is considered, a high percentage of production cost would be computed energy expenditure and savings of 4.5% above could be the key to sell products at more competitive prices.

The savings presented are obtained without taking into account labor costs, depreciation of machinery, land rentals etc. Therefore, the savings shown are only from the energy point of view.

Conclusions

In the process of preparing this thesis, some important contributions to production planning have been generated. At first a bibliography of all global trends in production planning including energy consumption has been generated as well as a compilation of "Energy-Key Performance Indicators (KPIs)" in order to describe and control energy consumption.

As an innovative approach, the energy consumption is introduced at all levels of production planning, from aggregate-level planning to machine level planning. For this, some linear programming algorithms have been developed jointly considering conventional production planning objectives and the reduction of energy costs, taking into account the energy price per time period evaluated.

The conclusions of the thesis are:

- The energy-intensive factories are more susceptible to the application of these techniques and have therefore greater potential savings. However, those measures cannot be introduced if production is not flexible.
- The greater the flexibility of the factory in terms of capacity, products and machinery, the greater capacity to obtain energy cost savings during periods of short-term planning.

- The flexibility allows us to plan the production in shorter periods of time. The more flexible the factory is, planning periods are shorter and therefore bigger savings can be obtained.

An interesting continuation of this thesis would be to make a multi-objective optimization in machine sequencing taking into account important factors in production planning, such as minimization of the "makespan" and the minimization of energy consumption and the energy cost. Additionally, it would be important to assess the costs of implementing these strategies in terms of resources (such as the installation of additional control) to compare the savings to be achieved and economically assess the profitability of the investment.

Aufgabenstellung

Titel der Masterarbeit: Analysis of Energy-KPIs with respect to production planning in combination with a formulation of possible measures to enable energy flexibility

Inv.- Nr.:	**2014/017-MT**		
Verfasser:	**Lopez Martinez, Inigo**	**Betreuer:**	**Schultz, Cedric**
Ausgabe:	15.03.14	**Abgabe:**	15.09.14

Ausgangssituation:

Nowadays, renewable energies have an increasing importance in contrast to other non-renewable energy sources.

The publication of the German Environmental Ministry called "Erneuerbare energie in Zahlen'' reveals that by 2050 renewable energy will represent the 80% of the energy generated in Germany.

However, renewable energies cannot ensure the power supply because they depend on external conditions. One example is wind power, which depends on the wind speed to generate electricity. Depending on the source of energy, the amount of energy generated and the energy demand, energy prices are fluctuating significantly. Using the energy according to the current supply would be desirable, in order to save energy costs and to use energy effectively and efficiently. Therefore, the industry has to implement the concept of energy flexibility. This concept enables factories to reduce energy costs.

Saving costs due to daily energy prices fluctuation, adapting the energy demand curve of the factory to the energy supply is the motivation of this thesis. Through researching and analyzing the different production planning levels and considering the energy consumption related to the production, an energy flexibility of a factory can be established

Zielsetzung:

Based on the reasons explained above, the goal is to describe the energy flexibility of a factory with Key Performance Indicators (KPIs) in production planning. KPIs are a set of performance indicators of a particular business process from which all aspects of the production process are evaluated. From these indicators, a description of how much energy is used and in which process spent will be obtained, in order to optimize and adapt the power consumption of the factory.

Summarizing, a factory has a number of resources which make possible to perform the production process. Those resources consume a certain amount of energy related to the activity performed. How that energy is being used at different levels of production is subject of this thesis with the following goals:

• Description of energy consumed in a given process of a machine, a set of machines from one area of the factory, and the factory as a whole.

• Evaluation of energy flexibility within these levels in order to improve the production planning process.

• Evaluation of possible alternatives in planning to enable flexible energy consumption and thus reduce the cost of electricity.

Vorgehensweise und Arbeitsmethodik:'

1. Current state of the scientific and technical knowledge: current methods for describing energy consumption in manufacturing processes in a factory.

2. Description of production at various levels of production and KPIs in order to describe energy consumption:
   - Process
   - Machine
   - Area of production
   - Factory

3. An assessment of the different production types:
   - Job shop production
   - Batch production
   - Flow production

4. Research on flexibility and its relation to energy consumption.
   - Research on possible measures to influence energy consumption: Load management, production states, etc.

5. Evaluate energy flexibility in the different levels of production and asses the different planning approaches:
   - Machine occupation
   - Batch size
   - Capacity of production

6. Establish concepts to integrate energy flexibility in production planning: planning energy consumption with KPIs in production planning.

7. Simulation and validation of results

Vereinbarung:
Mit der Betreuung von Herrn cand.-Ing. Iñigo Lopez Martinez durch Herrn Dipl.-Ing. Cedric Schultz ließt geistiges Eigentum des iwb in diese Arbeit ein. Eine Veröffentlichung der Arbeit oder eine Weitergabe an Dritte bedarf der Genehmigung durch den Lehrstuhlinhaber. Der Archivierung der Arbeit in der *iwb*-eigenen und nur für *iwb*-Mitarbeiter zugänglichen Bibliothek als Bestand und in der digitalen Studienarbeitsdatenbank des *iwb* als PDF-Dokument stimme ich zu.

München/Augsburg, den 15.03.14

Prof. Gunther Reinhart; M.Sc. Cedric Schultz cand.-Ing. Iñigo Lopez

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Abstract

In this thesis, a general model to plan the energy consumption has been proposed, in order to adapt the consumption of factories to volatile energy prices. This model has been developed from the point of view of organizational optimization.

First of all, in chapter 3, some concepts and the state of art of methodologies related to production planning have been introduced and some properties of factories related to production have been stated. The most important property explained is flexibility because the more flexible a factory is, the more energy flexible a factory will be. So different types of flexibility have been defined and after their relation to energy consumption have been stated.

In order to plan the energy consumption of a factory, the first step is to know the amount of energy spent and it's done by using Key Performance Indicators(KPIs) related to energy. With those KPIs, the energy consumption per level of the factory is defined. The state of art of energy KPIs is presented and from them different energy KPIs for machines, product and production system as well as methods to obtain these energy data are stated. With the energy consumption data, the energy is planned in different time horizons.

Having the energy data, an aggregate planning model and scheduling approaches have is presented. Those models are based on current planning approaches in which the energy consumption and energy prices are taken into account.

In order to prove all the concepts stated in previous sections, a practical case of production planning has been developed. The aim was to assess the economical results of an aggregate planning and Lot sizing model taking into account the energy prices and compare them to the results obtained by the traditional production planning methods. This economical assessment has been made in two different cases in order to evaluate the cost saving potentials depending on the amount of energy consumed by factories. With energy prices, a tax model related to energy have been presented in order to make the results more realistic

Acknowledgement

First, I would like to express my gratitude to Prof. Gunther Reinhart, Fabian Keller and Cedric Schultz for letting me write this Master Thesis at the Institut für Werkzeugmaschinen und Betriebswissenschaften at the TU München in collaboration with the Fraunhofer Institut and specially Fabian Keller for his continuous support that I've received during this learning period of production planning sector. It's been a very enriching experience in both personal and academic points of view and I will always be grateful of every lesson I've gained.

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Thanks to Javi, Edu, Nacho, Pablo, Pepe, Rafael y Fernando and many others that have been with me during these years.

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Thank you,

I will always remain grateful.

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List of Abbreviations

ATP	Available-To Promise
BOM	Bill of Materials
CPP	Critical Peak Pricing
CRP	Capacity Requirement Planning
CRP	Capacity Requirement Planning
DM	Demand Management
DMS	Dedicated Manufacturing System
DSM	Demand-Side Management
ED-CPP	Extreme Day CPP
EDP	Extreme Day Pricing
EnId	Energy consumed in idle times
EnNPT	Energy consumed in non-production times
EnPT	Energy consumed in production times
ERP	Enterprise Resource Planning
FMC	Flexible Machining Cell
FMS	Flexible Manufacturing System
GDP	Gross Domestic Product
HVAC	Heating, ventilation and airconditioning
ICT	Information and Communication Technology
KPI	Key Performance Indicator
MES	Management Execution System
MPS	Master Production Scheduling
MRP	Material Requirement Planning
MRP II	Manufacturing Resource Planning
MTO	Make to Order
MTS	Make to Stock
NP-HARD	Non Polinomial Algorithms

OEE	Overall Equipment Effectiveness
P-PROBLEMS	Polinomial Algorithms
RCCP	Rough-Cut Capacity Planning
RMS	Reconfigurable Manufacturing System
RMT	Reconfigurable Machine Tool
RTP	Real Time Princing
SFC	Shop Floor Control
TBC	Time based Competition
TOU	Time-of Use Pricing
TQM	Total Quality Management
WIP	Work In Pocess

1 Introduction

Nowadays, renewable energies have an increasing importance in contrast to other non-renewable energy sources.

The publication of the German Environmental Ministry called “Erneuerbare energie in Zahlen’’ reveals that by 2050 renewable energy will represent the 80% of the energy generated in Germany and at the moment, Germany is a regional and world leader on several categories of renewable energy use. (2014)

However, renewable energies cannot ensure the power supply because they depend on external conditions. One example is wind power, which depends on the wind speed to generate electricity. Depending on the source of energy, the amount of energy generated and the energy demand, energy prices are fluctuating significantly.

There are four important end-users of energy in OECD countries: residential, commercial, transportation and industry, being industry most important one in term of energy usage. So in order to reduce the energy cost of a country, the most important field of action is reduce the energy cost related to industry. This can be made by two ways, with energy efficient manufacturing technology in order to reduce the amount of energy spent in industrial processes (Energy efficient manufacturing from machine tools to manufacturing, 2013) (Energy efficiency measurement in industrial processes, 2011) and by adapting the energy usage to the energy supply in order to reduce energy costs because of the fluctuation of energy prices.

2 Motivation of the work

From this point, the main goal of the thesis is going to be presented. Based on the reasons explained in the introduction, the main goal of this thesis is to reduce the energy costs of industry, particularly manufacturing factories by adapting the energy consumption to energy supply. So an energy flexible consumption is desired to be obtained.

In order to achieve the goals, the energy consumption patterns of the different levels of aggregation of a factory have to be described. This description is going to be made by introducing Key Performance Indicators related to energy consumption in factories. Having the energy consumption description, different strategies in production planning are going to be presented in order to make the energy consumption flexible depending on the demand of items and energy prices.

Concretizing, a factory manufactures some products and use a certain kind of resources which make possible to perform the jobs. Those resources consume a certain amount of energy related to the activity performed. Planning what amount of energy and when that energy is being used at different levels of production taking into account energy prices is subject of this thesis.

3 Literature review

First of all, different aspects of factories and energy are going to be presented in order to introduce the reader into the topic and state the base in which the work is going to be sustained.

3.1 Energy prices rates

3.1.1 Demand-side management

First of all, the current situation of the energy prices is going to be explained. Depending on the energy prices contract that the factory negotiates with the utility, the production will be more or less able to obtain benefits by adapting their consumptions. This energy prices contracts depend on the Demand-side management strategies of utilities.

Demand Side Management (DSM) refers to a process by which electric utilities, in collaboration with consumers, achieve predictable and sustainable changes in electricity demand. These changes are effected through a permanent reduction in demand levels through energy efficiency as well as time related reductions in demand levels through load management.

One way to achieve an effective demand-side management is implementing load curtailment programs that pay the customer for reducing peak load during critical times. And another way, and the most important for this thesis, is implementing dynamic pricing programs in order to give customers an incentive to lower peak loads and reduce their electricity bills. Both types of programs are largely designed to relieve peak capacity constraints.

Dynamic tariffs are designed to lower system costs for utilities and bring down customer bills by raising prices during expensive hours and lowering them during inexpensive hours. Their load shape objective is to reduce peak loads and/or shift load from peak to off-peak periods (Using Time Of Use (Tou) Tariffs In Industrial, Commercial And Residential Applications Effectively).

Four types of energy prices are going to be presented:

- Time-of-Use Pricing (TOU). This rate design features prices that vary by time period, being higher in peak periods and lower in off-peak period. The simplest rate involves just two pricing periods, a peak period and an off-peak period.
- Critical Peak Pricing (CPP). This rate design layers a much higher critical peak price on top of TOU rates. The CPP is only used on a maximum number of days each year, the timing of which is unknown until a day ahead or perhaps even the day of a critical pricing day.
- Extreme Day Pricing (EDP). This rate design is similar to CPP, except that the higher price is in effect for all 24 hours for a maximum number of critical days, the timing of which is unknown until a day ahead.

- Extreme Day CPP (ED-CPP). This rate design is a variation of CPP in which the critical peak price and correspondingly lower off-peak price applies to the critical peak hours on extreme days but there is no TOU pricing on other days.
- Real Time Pricing (RTP). This rate design features prices that vary hourly or sub-hourly all year long, for some or all of a customer's load. Customers are notified of the rates on a day-ahead or hour-ahead basis.

Some other pricing frames are presented in the following figure 3-1. These prices frames are classified in respect with the risk taken by the customer and the risk taken by utilities.

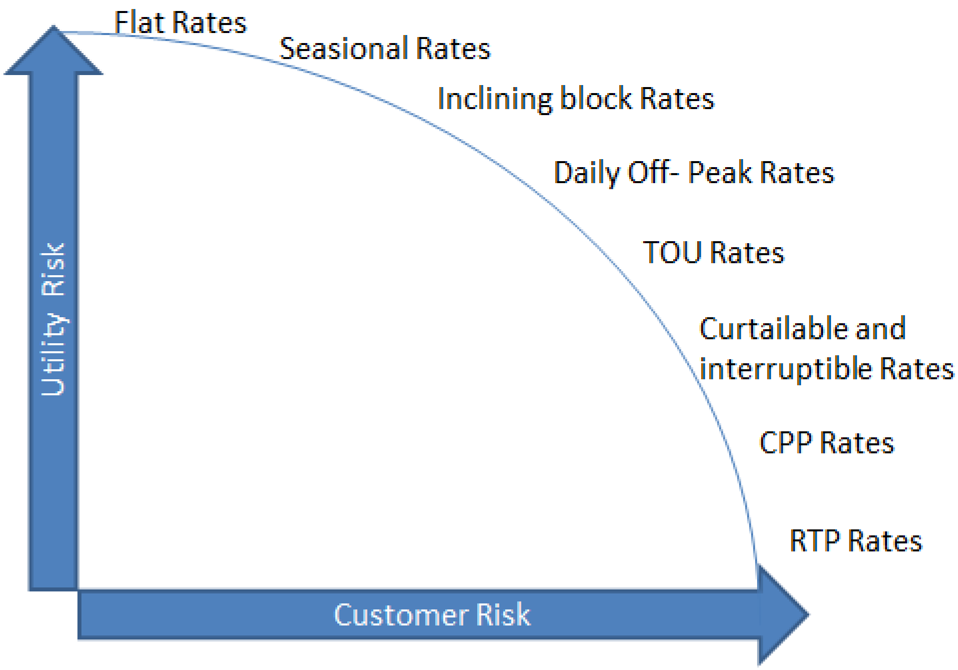

Figure 3-1: *Customer vs. Utility Rate Design (Using Time Of Use (Tou) Tariffs In Industrial, Commercial And Residential Applications Effectively)*

As it can be seen, depending on the energy prices negotiated there will be more or less possibility to achieve benefits. If the factory has a flat rate contract, only implementing energy efficiency measures in order to reduce the amount of energy spent on every process would be the only approach in order to reduce energy costs. On the other hand, a RTP rate the energy prices vary every hour and hence there are possibilities to obtain benefits by adapting the production to lower pricing hours.

In between flat rates and RTP rate, one of the most used tariffs is TOU rates. Although the simplest rates involve two time periods, more than two periods can be configured. More complex designs feature a peak period, one or more intermediate peak periods, and an off-peak period. It can be shown in the following figure:

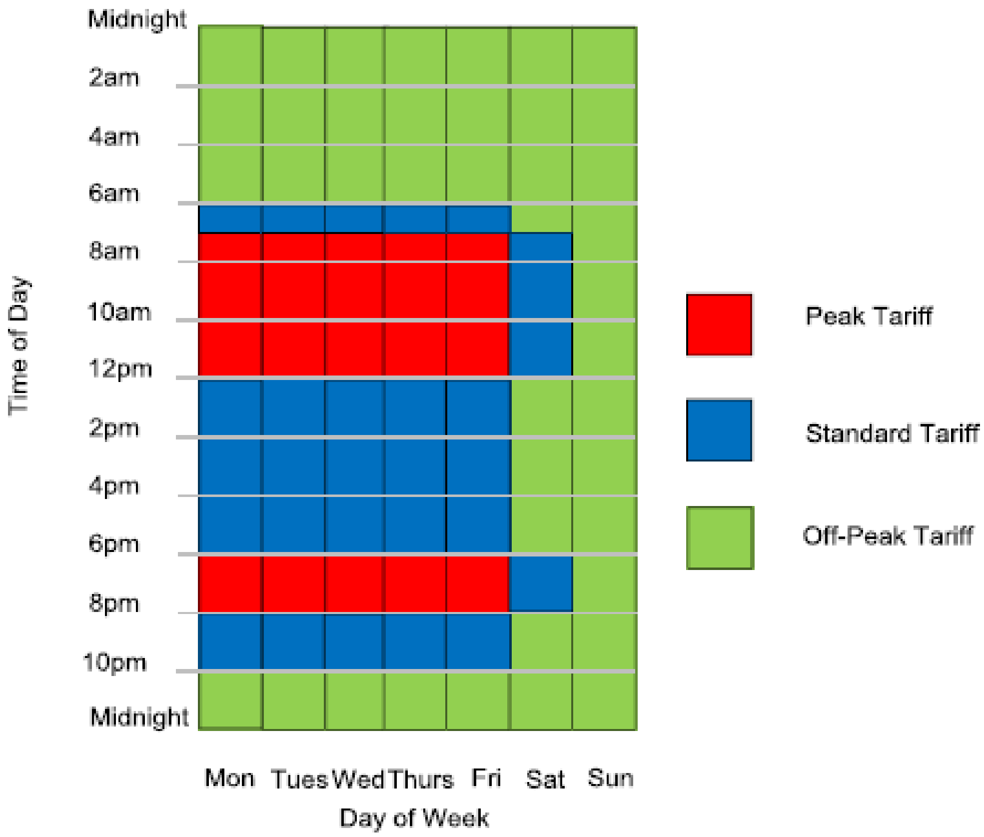

Figure 3-2: *More Complex Time Period TOU Tariff[(Using Time Of Use (Tou) Tariffs In Industrial, Commercial And Residential Applications Effectively)*

This tariffs can be configured for long time periods such as summer and winter, or concrete days.

3.1.2 Role of energy prices in production planning

Using TOU rates would be the most suitable model to use in industry because the production would be easier adaptable and the energy prices are known from day zero in advance. In this thesis, also RTP prices are going to be considered into the day consumption.

From this point a production planning procedure will be presented taking into account energy consumtion and energy prices. The maintarget is to present strategies in order to satify the demand and reduce the energy costs.

The energy prices data that is going to be used is the average energy price per period of time, and considering the prices into a day, TOU prices and RTP prices, which vary every hour, are going to be considered.

3.2 Factory levels of aggregation

This first step that is being carried out is a description of what a factory is. A factory is the building or group of buildings in which some products are manufactured and are structured into different levels. Two different points of view are going to be presented in order to describe them: *Resource view* and *Space view* (Digital Manufacturing in the global Era, 2006), (Evaluation of Factory Transformability, 2005). Seven structuring levels of a factory can principally be identified in both views presented in figure 3-3. On the left side the proposal by (Digital Manufacturing in the global Era, 2006) is depicted and on the right side the proposal from (Evaluation of Factory Transformability, 2005).The *Resource view* looks for the technical and human resources and the *Space view* considers the architectural objects which have to be designed in accordance with these resources.

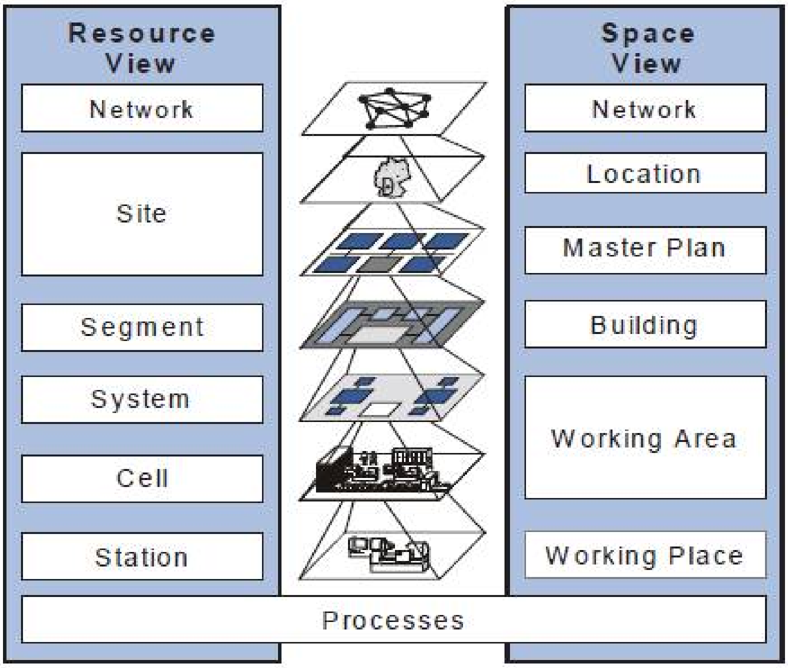

Figure 3-3: *Structuring levels and view of the factory (Digital Manufacturing in the global Era, 2006) (Evaluation of Factory Transformability, 2005)*

The *Resource view* is defined as follows:

- Workstation/ Machine: Individual device or machine tool in the manufacturing system, which is performing a unit process. It includes also tool handling.
- Cell: Often several machines are arranged into *cells* that typically perform most of the necessary operations to finish a work piece or an assembly including quality assurance.

- System: If the processes are more or less automatically interlinked, the terms manufacturing *system* and assembly *system* are commonly used.
- Segment: The next level up refers to *segments* in which whole products are typically manufactured ready to ship. Segments are commonly structured into manufacturing, assembly, buffers, quality measurement devices, etc.
- A site describes a production unit with more than one product segment and serves as a node of a production network or a supply chain.

When talking about space view, the working area consists on cells and systems merged. A working area is a zone with the same conditions regarding floor load, height, climate and light and the provision with energy and media (ICT).

The description of the levels is necessary to be made in order to understand the main energy consumers, which are the machines. Then the energy consumption of the different levels can be obtained. Having the description of the factory levels, the next step is to describe the activities and processes that factories perform. It’s important because those processes are going to be the main energy consumers of the factory. The main energy consumers of a factory are the aspects related to production.

3.3 Production

Production is a process of combining various material, inputs and immaterial inputs (plans, know-how), in order to develop something for its consumption (the output). It is the act of creating output, a good or service which has value and contributes to the utility of individuals. In this thesis the focus is going to be about production related to manufacturing (Ballesteros, 1978).

Depending on the production process type there is going to be different production patterns and hence the energy consumption profile during the production is going to be obtained. So first the production types are going to be explained.

3.3.1 Types of production processes

Manufacturing environments vary greatly with regard to their process structure, that is, the manner in which material moves through the plant. Hayes and Wheelright (1979) classify manufacturing environments by process structure into four categories as it's showed in the figure below (Hopp, y otros, 2011i):

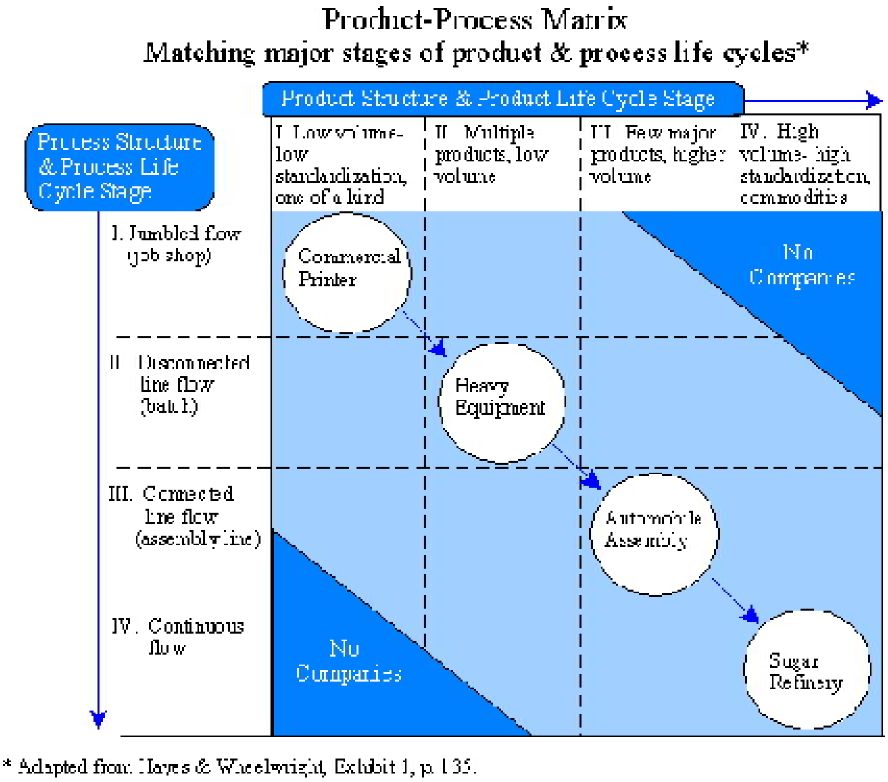

Figure 3-4: *production processes matrix made by Hayes and Wheelright (Martin, 2014)*

<u>Job shop</u>

Small lots are produced with a high variety of routings through the plant. Flow through the plant is jumbled, setups are common, and it's related to project works. For example, a commercial printer, where each job has unique requirements, will generally be structured as a job shop.

Disconnected line flow (Batch)

Product batches are produced on a limited number of identifiable routings (i.e., paths through the plant). Although routings are distinct, individual stations within lines are not connected by a paced material handling system, so that inventories can be built between stations. The majority of manufacturing systems in industry resemble the disconnected flow line environment to some extent. For example, a heavy equipment (e.g., tank car) manufacturer will use well-defined assembly lines but, because of the scale and complexity of the processes at each station, generally will not automate and pace movement between stations.

Connected line flow (Assembly line)

This is the classic moving assembly line made famous by Henry Ford. Product is fabricated and assembled along a rigid routing connected by a paced material handling system. Automobiles, where frames travel along a moving assembly line between stations at which components are attached, are the classic application of the connected flow line. But, despite the familiarity and historic appeal of this type of system, automatic assembly lines are actually much less common than disconnected flow lines in industry.

Continuous flow processes

Continuous product (food, chemicals, oil, roofing materials, fiberglass insulation, etc…) flows automatically down a fixed routing. Many food processing plants, such as sugar refineries, make use of continuous flow to achieve high efficiency and product uniformity. Continuous production is called a continuous process or a continuous flow process because the materials, either dry bulk or fluids that are being processed are continuously in motion, undergoing chemical reactions or subject to mechanical or heat treatment. Continuous processing is contrasted with batch production. Continuous usually means operating 24 hours per day, seven days per week with infrequent maintenance shutdowns, such as semi-annual or annual. Some chemical plants can operate for more than one or two years without a shutdown. Blast furnaces can run four to ten years without stopping.

An example of this kind of production process would be the production of glass bottles or Coca-Cola production process.

3.3.2 Assessment of production types in relation to energy

As stated at the beginning of this chapter, depending on the production type, different production patterns are going to come up, and hence, different energy consumption patterns will be observed.

If continuous flow processes are considered, the energy consumption is going to be the same and near impossible to be influenced because the line needs to be working 24 hours a day. Hence, the only way to influence the energy consumption is through more energy efficient machinery in order to spend less energy for the same processes. In case of job shop production and batch production, the production volume is going to be smaller and hence the production can be planned according to different criteria.

So there are two different ways to reduce energy costs: through more energy efficient equipment or planning the energy consumption with energy prices. And the energy consumption planning is extremely related to production planning.

3.4 Production planning and control

In order to achieve the objectives that a concrete manufacturing company has and obtain benefits, the production needs to be studied and planned. Currently, the study of manufacturing is focused on the following aspects: Product design, process development, plant design, capacity management, product distribution, plant scheduling, quality control, workforce organization, equipment maintenance, strategic planning, supply chain management, interplant coordination and direct production functions like cutting, shaping, grinding and assembly.

If the energy consumption is wanted to be analized and optimized, only the factory operations refered to the application of resources (capital, materials, technology and human skills and knowledge) to the production of goods are going to be considered. So the production planning and control is focused on the operation management.

Nowadays, the production planning and control is focused on the following dimensions (Hopp, y otros, 2011h):

- Cost: It is related to the efficient utlization of labor, material and equipment to keep the cost competive. Here the reduction of cost and volume enhancement are the objectives
- Quality: Stattistical process control,human factors and material flow control are factors included in the Total Quality Management (TQM) strategies.
- Time: Rapid developments of new products, coupled with quick customer delivery, are the pillars of the Time-Based Competition(TBC) strategies that have been adopted by leading firms in many industries. Responsive delivery, without ineffienct excess inventory, requires short manufacturing cycle times and reliable processes are very important in production planning.

This three dimensions are the areas of action of the production planning because its main objetive is to optimize each dimension in order to obtain benefits.

From this point, the production planning and control is going to be defined by explaining each strategy and their corresponding step related to it.

3.4.1 Production planning strategies

Companies are able to implement two different strategies for the production: make-to stock and make-to-order.

- Make-to-stock: A traditional production strategy to match production with consumer demand forecasts is the Make-To-Stock production. The make-to-stock (MTS) method forecasts demand to determine how much stock should be produced. One example of a make-to-stock strategy would be McDonalds because they make a batch of sandwiches which are waiting for the customer to be consumed. Therefore customer orders can be filled immediately (Investopedia).

- Make-to-order: On the other hand, the Make-to-Order is presented. It is a business production strategy that typically allows consumers to purchase products that are customized to their specifications. The make to order (MTO) strategy only manufactures the end product once the customer places the order. This creates additional wait time for the consumer to receive the product, but allows for more flexible customization. An example of this kind of production would be Dell computers or the Subway restaurants, in which the people order a sandwich and then the sandwich is prepared, not before (Investopedia).

After the selection of the production strategy, the production has to be planned. The production planning steps are going to be presented in different time horizons and after that the most common production planning systems are going to be presented.

3.4.2 Production planning ranges

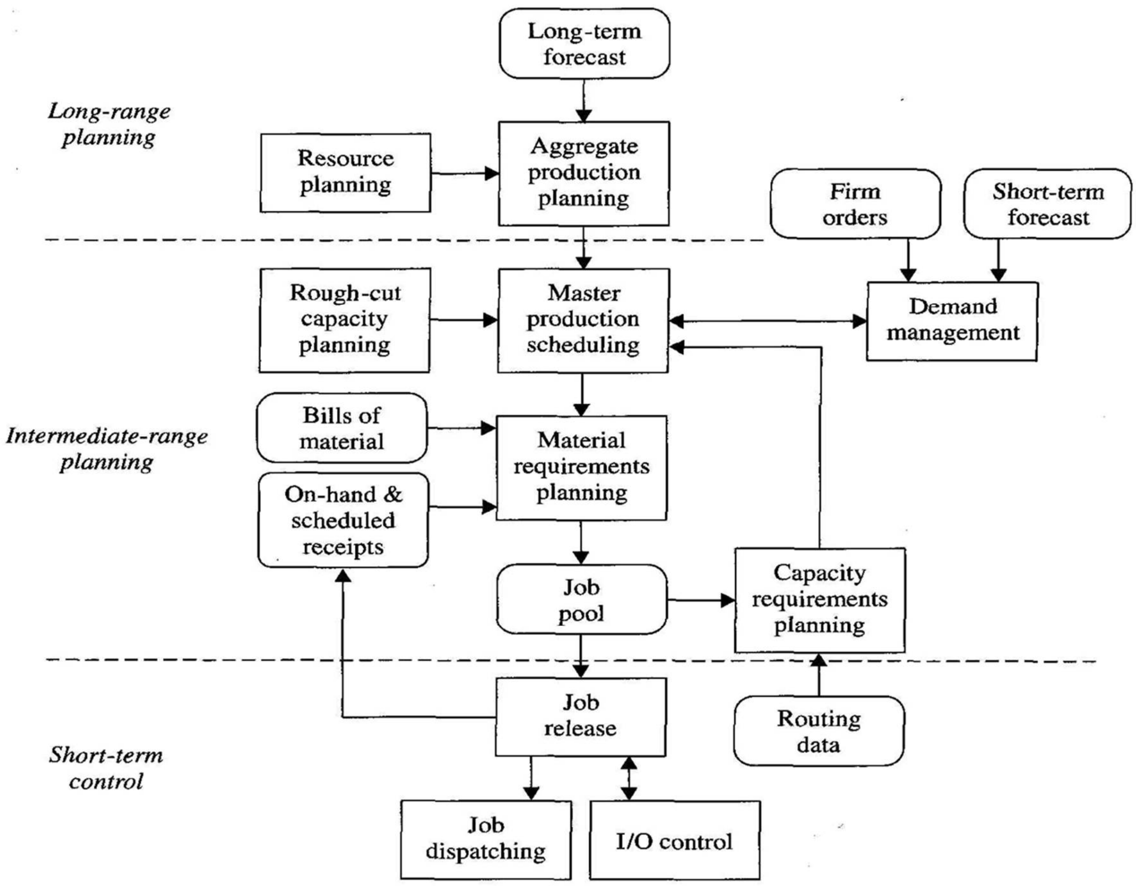

Figure 3-5: *Production planning Hierarchy (Hopp, y otros, 2011k)*

The different planning ranges shown in figure 3-5 are going to be presented in order to understand the production planning procedure (Hopp, y otros, 2011j).

Long-term planning approaches

Long-range planning is basically based on demand forecasting, resource planning and aggregate planning and the time horizon for this is from 6 months to 5 years.

Resource planning decides whether to expand the current factory or to build a new one. So it is capacity planning in a long time horizon.

Aggregate planning is used to determine what products are going to be made and when, so the levels of inventory, staffing and overtime is going to be taken into account. The level of detail is typically by month and by part families. Here linear algorithms are used to solve this problem.

Mid-term planning approaches

The majority of the planning approaches are going to take place in mid-term range. These are Demand Management, Master Production Scheduling, Rough-Cut Capacity Planning, Capacity Requirement Planning, and Material Requirement Planning.

The Demand Management (DM) converts the long-term aggregate forecast into a detailed forecast. The output of the Demand Management part is a set of actual customer orders plus a forecast of anticipated demand. This is achieved by the technique Available-To-Promise (ATP) which allows the planner to distinguish which orders are committed and which are available to promise. With this technique it is possible to propose realistic due dates.

The Master Production Scheduling (MPS) takes the demand forecast along with the firm orders from the demand management and, using capacity limits, generates an anticipated build schedule at the highest level of planning detail. These are the demands (part number, quantity and due date) used by the MRP. Thus, the MPS contains an order quantity in each time bucket for every item with independent demand, and for every planning date.

Rough-cut capacity planning (RCCP) is used to provide a quick capacity check of a few critical resources to ensure the feasibility of the MPS. RCCP make use of bill of resources for each product on the MPS. The bill of resources gives the hours required at each critical resource to develop a product

Capacity Requirement Planning (CRP) provides a more detailed capacity check on MRP-generated production plans than RCCP. Necessary inputs include all planned order releases, existing WIP positions, routing data, as well as capacity and lead times for all working stations. CRP predicts job completion times. In figure 3-6, and example of CRP is provided.

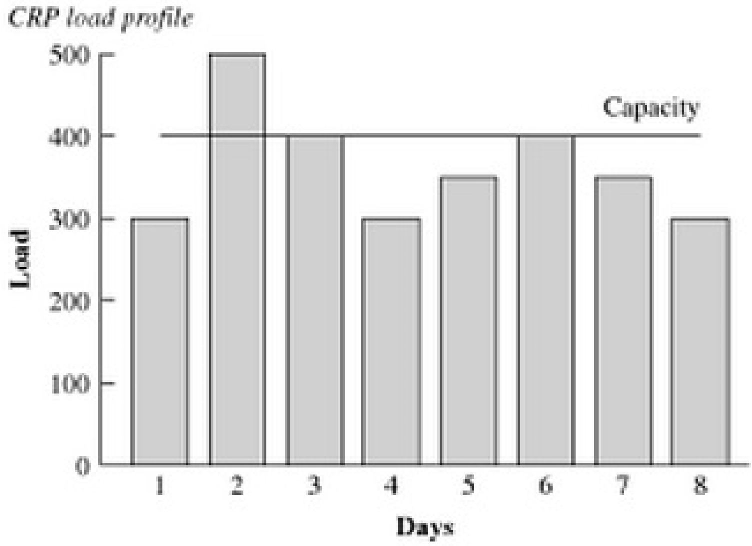

Figure 3-6: *Example of a CRP load profile (Hopp, y otros, 2011j)*

Straightaway comes the **Material Requirements Planning (MRP)** (Hopp, y otros, 2011m). **MRP** is used to coordinate plant orders (jobs) and outside orders (purchase orders). The system must determine appropriate production quantities of all types of items, from final products that are sold, to components used to build final products, and to inputs purchased such as raw materials. It must also determine production timing (i.e., job start times) that ease meeting order due dates. In order to develop a MRP, some data is necessary:

- Bill of materials (BOM), which describe the relation between end products and their constituents, called lower-level items.
- On-hand inventory which is the current inventory status
- Scheduled receipts, which are the status of outstanding orders (both purchased and manufacturing.
- Master Production Schedule (MPS), from which the independent demand of the products is going to be obtained.

Having all this data, the procedure of the MRP is presented. For each level of materials, beginning with the end products, MRP has the following procedure:

1. <u>Netting:</u> determine net requirements by subtracting on-hand inventory any scheduled receipts from the gross requirements. The gross requirements for level-zero items come from the MPS, while lower-level items are the result of previous MRP iterations or are independent demand for those parts (e.g., spares). If the projected-on-hand becomes less than zero, there is a material requirement.
2. <u>Lot sizing:</u> divide the netted demand into appropriate lot sizes to form jobs.
3. <u>Time phasing:</u> Offset the due dates of the jobs with lead times to determine start times.
4. <u>BOM explosion:</u> use the start times, the lot sizes, and the BOM to generate gross requirements of any components at the next levels.
5. <u>Iterate:</u> repeat these steps until all levels are processed.

Short-term planning approaches

The plans generated in the long and midterm planning are implemented in the short-term modules of **job release**, **job dispatching** and **input/output control** (Hopp, y otros, 2011g)

Job release converts planned order releases to scheduled receipts. One of the important functions of job release is allocation. When there are several high-level items that use the same lower-level part, a conflict can arise when there is an insufficient quantity on hand. By allocating parts to one job or another, the job release function can rationalize these conflicts.

Once a job order is released, some control must be maintained to make sure it is completed on time with the correct quantity and specification. The job is going to be tracked by **Shop Floor Control (SFC)**. Within SFC there are 2 functions: **Job dispatching** and **input/output control**.

Job dispatching (sequencing) consist on developing a rule for arranging the queue in front of each workstation that will maintain due date integrity while keeping machine utilization high and manufacturing times low. There are many rules to fix this problem when talking about a simplified problem with one or two machines. But for solving scheduling problems in more complex systems, some complex algorithms are necessary to be implemented (Hopp, et al., 2011f).

There are two types of dispatching mathematical problems:

- **Class P problems**, which are problems that can be solved by algorithms whose computational time grows as a polynomial function of problem size.
- **NP-Hard problems**, which are problems for which there is no known polynomial algorithm, so that the tie to find a solution grows exponentially in problem size.

The input and output control is used to keep lead times under control. The procedure is the following:

1. Monitor the **Work in Process (WIP)** level in each process center.
2. If the WIP goes above a certain level, then the current release rate is too high, so reduce it.
3. If it goes below a specified lower level, then the current release rate is too low, so increase it.
4. If it stays between these control levels, the release rate is correct for the current conditions

Reducing and increasing procedure is made by changing the MPS.

3.4.3 The evolution of production planning systems

Material Requirements Planning (MRP) is a production planning and inventory control system used to manage manufacturing processes. Most MRP systems are software-based, while it is possible to conduct MRP by hand as well.

An MRP system is intended to simultaneously meet three objectives:

- Ensured materials are available for production and products are available for delivery to customers.
- Maintain the lowest possible material and product levels in store
- Plan manufacturing activities, delivery schedules and purchasing activities.

At the beginning, the main benefit obtained from the implementation of the MRP was a substantial reduction of inventory. Therefore, that reduction offered significant cost savings to companies. But the functions needed from the MRP were getting higher and soon began to require to undertake the planning function of plant capacity of the factory. At first the results obtained with an MRP program were introduced as input data in other programs, called CRP (Capacity Requirement Planning), taking into account capacity constraints, and determining whether offered planning was possible or not.

Nevertheless, later on the CRP systems were included in the MRP systems, obtaining the so called in the 70's MRPII (Manufacturing Resource Planning) and right now ERP (Enterprise Resource Planning) (Navarra University) (Princeton University). Another production planning system so used nowadays is the so-called Manufacturing Execution System (MES).

A Manufacturing Execution System (MES) is a process-oriented production management system or operating control system. It is distinguished from similar efficient systems for production planning, such as ERP (Enterprise Resource Planning) through the direct connection to the automation and allows for timely monitoring and control of production.

3.4.4 Assessment of production planning in relation to energy

Nowadays, as stated at the beginning of this chapter, the production planning is focused on three dimensions: time, cost and quality.

In the production planning procedure explained, many factors are considered but one important factor is missing: energy consumption. Having the energy consumption patterns related to the production processes, the energy could be introduced as an additional factor able to be planned. But, as stated at the beginning of this paper, depending on the production type introduced in the factory there will be more or less possibilities to influence the energy consumption. This important factor is Flexibility.

Flexibility is known as the ability of a system to adapt itself with little penalty in time, effort, cost and performance to changes in market environment (Wikipedia). It can be seen that the more flexible the production, the easier will be to reduce energy costs. In the following section, the flexibility is going to be explained.

3.5 Flexibility in Manufacturing Systems

Production systems, to cope with market uncertainties, have to be flexible. As stated before, Flexibility is understood as the ability of a system to adapt itself with little penalty in time, effort, cost and performance to changes in market environment (A Petri-net based approach for evaluating energy flexinility of production machines, 2013). So in addition to cost, time and quality, flexibility have to be considered when making manufacturing decisions.

A distinction between flexibility and re-configurability has to be made. Traditionally flexibility is interpreted as the ability of a system to change its behavior without changing its configuration. Conversely re-configurability is interpreted as the ability to change the behavior of a system by changing its configuration. These definitions however can be used only if the boundary of the system is clearly defined. So many authors unify both concepts in one that is called Changeability (A Petri-net based approach for evaluating energy flexinility of production machines, 2013) (Flexibility and Its Meausrements) (The flexibility of Manufacturing Systems) (Changeable Manufacturing - Classification, Design and Operation).

3.5.1 Changeability in factory levels

The term flexibility is not going to be used on all levels of a factory. If the five structuring levels are combined with the associated product levels, a hierarchy emerges that allows the definition of five types of changeability (Changeable Manufacturing - Classification, Design and Operation).

The hierarchy of product levels starts from the top with the product portfolio a company offers to the market. Then the product or a product family follows downwards. The product is usually structured into sub-products or assembly groups that contain work-pieces. The work-pieces themselves consist of features.

From that separation, different kind of changeability can be described depending on the level of aggregation of the factory, which is going to be showed in the following figure:

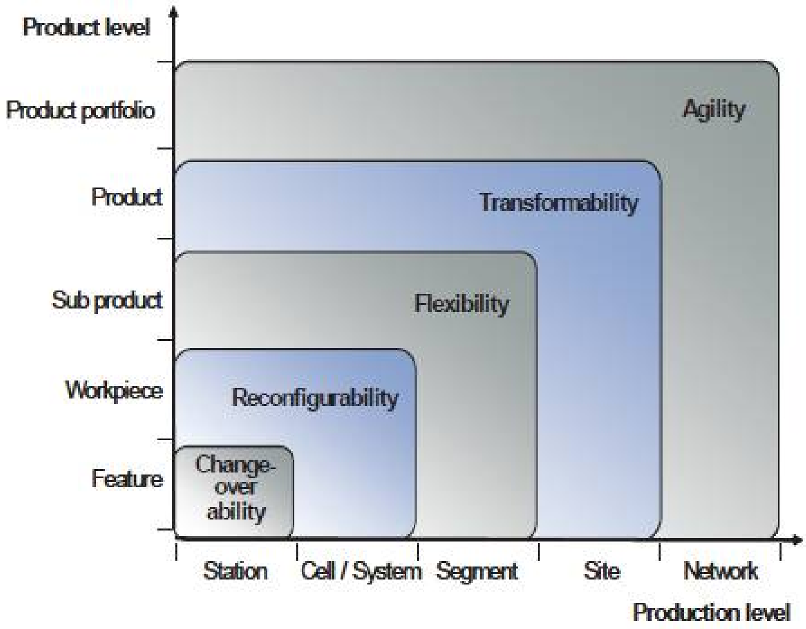

Figure 3-7: *Classes of Factory Changeability (Changeable Manufacturing - Classification, Design and Operation)*

In this thesis, the focus is going to be in the changeover ability of stations, re-configurability of cell or Manufacturing Systems and flexibility of segments.

- *Changeover ability* designates the operative ability of a single machine or workstation to perform particular operations on a known work piece or subassembly at any desired moment with minimal effort and delay.
- *Re-configurability* describes the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of work.
- *Flexibility* refers to the tactical ability of an entire production and logistics area to switch with reasonably little time and effort to new – although similar – families of components by changing manufacturing processes, material flows and logistical functions (Changeable Manufacturing - Classification, Design and Operation).

3.5.2 Flexibility objectives and types

There are three main objectives when flexibility is wanted to be introduced:

- *Product flexibility,* which enables a manufacturing system to make a variety of part types with the same equipment.
- *Operation flexibility,* which refers to the ability to produce a set of products using different machines, materials, operations, and sequence of operations.
- *Capacity flexibility* which allows a manufacturing system to vary the production volumes of different products to accommodate changes in demand, while remaining profitable.

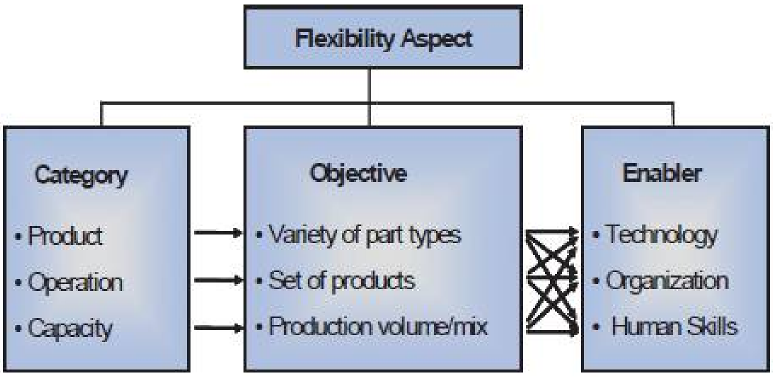

Figure 3-8: *Flexibility aspects of manufacturing Systems (Changeable Manufacturing - Classification, Design and Operation)*

As it's shown in the figure 3-8, not only technology but also organization and human skills are necessary enablers for all objectives to be achieved.

These objectives are going to be discussed more deeply into manufacturing systems. There is plenty of literature in which the different kinds of flexibility in manufacturing systems are explained (Flexibility in manufacturing systems: definitions and Petri net modelling, 2007) (Flexibility and Its Meausrements) (Flexible Manufacturing Systems: Characteristics and assessment.) (Flexibility of manufacturing systems: Concepts and measurements, 1989). Ten types of manufacturing flexibilities are explained and are going to be divided according to the production planning time horizons that are related to (Flexibility in manufacturing systems: definitions and Petri net modelling, 2007) (Flexibility of manufacturing systems: Concepts and measurements, 1989).

a) *Short-term and Mid-term flexibility types*

- *Machine flexibility* :the ability, without human interference or long set-up times, to replace worn-out or broken tools; change tools in a tool magazine; assemble or mount the required fixtures
- *Process sequence Flexibility*: the ability to interchange the ordering of several operations for each part type.
- *Process Flexibility*: the ability to vary the steps necessary to complete a task. This allows several different tasks to be completed in the same system using a variety of machines.
- *Routing Flexibility*: the ability to vary machine visitation sequences (for example, in case of breakdowns) and to continue producing the given set of part types. This ability exists when there are several viable processing routes or when each operation can be performed on more than one machine.
- *Volume Flexibility*: The ability to vary production volume profitably within production capacity.
- *Control Program Flexibility*: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software.

b) <u>*Long-term flexibility types*</u>

- *Expansion Flexibility*: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system.
- *Production Flexibility*: Number of all part types that can be produced without adding major capital equipment.
- *Product Flexibility*: Ease (time and cost) of introducing products into an existing product mix.
- Product mix flexibility is the ability of the system to manufacture, not necessarily simultaneously, a particular mix of products within the minimum planning period used by the company.

These types of flexibilities, when implemented, enable a manufacturing system to have many economic benefits because they are able to adapt the production to many circumstances that can occur within the production and out of it.

3.5.3 Flexible Manufacturing System (FMS)

A factory that is designed to be changeable must have certain inherent features or properties that will be called flexibility enablers. And on manufacturing level, Flexible Manufacturing Systems are assumed to be the appropriate answer to introduce flexibility.

The term **Flexible Manufacturing System** is used to describe a network of automated work stations which are linked by a common computer- controlled material handling device to transport work pieces that are to be processed from one work station to another. Unlike a transfer line where all work pieces follow a sequential route through the system, an FMS permits work-pieces to visit work stations in any arbitrary sequence as desired. Typically, machines used in an FMS are designed to operate in a flexible manner. But they are designed for a defined spectrum of work-pieces. Retrofitting to exceed this spectrum can take weeks or months. Because most FMS have more capacity and features than normally used, they are complex and not adaptable enough to changing needs in terms of capacity and gradual changes in functionality. FMS are configurable but not reconfigurable after some years (Flexible Manufacturing Systems: Characteristics and assessment.) (Design principles of reconfigurable machines, 2006) (Trends and perspectives in flexible and reconfigurable manufacturing systems, 2001).

FMS, when the flexibility characteristics explained in the previous chapter are implemented, yield a system which has the following operational behavior:

- A variety of parts can be produced by a simple change of software.
- Material handling and queueing times can be reduced by the use of machine centers since these centers can do multiple operations on a work piece.

- Set up times can be reduced by the use of quick-change tooling mechanisms.
- We effect of breakdowns can be reduced by re-routing work pieces to available machines.

There are different types of flexible manufacturing systems, depending on the flexibility that it has (Flexible Manufacturing Systems: Characteristics and assessment.):

- Flexible machining cell, which is the simplest and hence most flexible type of FMS is a Flexible Machining Cell (FMC). An FMC is composed of one general-purpose CNC machine tool interface with an automated material handling device, which provides raw castings or semi-finished parts from an input buffer for machining, loads and unloads the machine tool, and transports finished work pieces to an output buffer for final removal to its next destination
- Flexible machining system: This type of FMS usually has real-time, online control of part production. It should allow several routes for parts, with small volume production of each, and consists of FMCs of different types of general-purpose metal-removing machine tools. Flexible machining systems are highly machine flexible, process flexible, and also routing flexible.
- Flexible transfer line: For all part types each operation is assigned to and performed on only one machine. This results in a fixed routing for each part through the system. The layout is process driven. The material handling device is usually a carousel or conveyor. The storage area is usually local and between each machine. This type of FMS is less process flexible and less capable of automatically handling breakdowns.
- Flexible machining multi-line: This type of FMS consists of multiple interconnected flexible transfer lines. This duplication does not increase process flexibility. The main advantage of this type of FMS is the redundancy that it provides in a breakdown situation to increase its routing flexibility.

3.5.4 Assessment of flexibility related to energy

As stated before, the flexibility objectives are product flexibility, operation flexibility and capacity flexibility. Each flexibility objectives have different types of flexibility related to them. For example, the operation flexibility objective is related to process sequence flexibility, process flexibility or routing flexibility while capacity flexibility objective is production volume flexibility, as stated on Figure 3-8.

These factors of flexibility previously explained can also influence the energy cost related to production. As explained at the beginning of this work, it’s possible to reduce energy costs by using energy efficient machinery. But it’s possible also to plan the energy consumption and influence the cost related to energy by planning its consumption depending on the energy prices. It can be done when the production system has high flexibility.

An energy price tariff with varying rates and adapted behavior of the production system can lead to significant energy cost savings. An important requirement for that is, that production systems know their energy demand and know how to adapt it. This capability is called energy flexibility. Energy flexibility can be defined as the ability of a production system to adapt itself fast and without remarkable costs to changes in energy markets.

In order to plan the energy consumption, it would be necessary to have indicators that measures and control the energy consumption of the production system. Those indicators are called Key Performance Indicators (KPIs). Currently, there are plenty of KPIs related to production planning but KPIs related to energy are missing.

3.6 Key Performance Indicators (KPIs)

For a successful performance management system, it is required that performances are linked to the strategy and vision of the company. In order to create this link, one requires a Key Performance Indicator (KPI) profile which can be used as a standard for the alignment of the organization's strategy and performance objectives.

3.6.1 Definition of Key performance indicators

Key Performance Indicators represent a set of measures focusing on aspects of organizational performance that are the most critical for the current and the future success of an organization. The KPI profile describes the outputs (results) expected in a particular aspect and will evaluate if this aspect is moving into the planned parameters. The KPIs reflect a balance between cost, quality, quantity and time. These indicators must therefore, be critical factors which can immediately alert the manager if something goes wrong, so that he can react to it (Determining the effectiveness of key performance indicators in a steel manufacturing company) (Metrics for Sustainable Manufacturing, 2008) (A Key Performance Indicator System of Process Control as a Basis for Relocation Planning).

3.6.2 Types of KPIs in production planning

The Key Performance Indicators that are going to be described are separated into 3 groups; **planning units**, **time units** and **logistic units** (Manufacturing Execution Systems, 2009).

Planning times measures

- Order time :The order time is the scheduled time for the implementation of a manufacturing order based on the work plan data. It is calculated from the production time per unit multiplied by the order quantity plus the planned set-up time.

- Operating time :The operating time is the time in which a production unit can be used for the production and maintenance of operational and personal. The operating time is a scheduled time.

- Planned set-up time :The proposed set-up time is the race for a production unit scheduled for an order period.

- Planned production time.:The planned production time is the operating time minus the planned downtime (scheduled downtime).

- Production time per unit :The production time per unit is the scheduled time to produce a single unit.

Real time measures

- Processing time :The processing time is the time used for setup and for the principal use in one station.
- Flow Time: Time it takes a flow unit to go from the beginning to the end of the process.
- Production time : The production time is the time in which the machine produces. It includes only the value-added processes.
- Waiting time :The wait time is the time in which the material in the manufacturing process is not working and is not in transportation.
- Downtime :The downtime is the time in which the machine is not busy with orders, even though they have for this job.
- Delay time :The Delay times are times that unplanned occur and because of this inadvertently prolong the occupation times during order processing.
- Real set up time / effective set up time : The real set-up time is the time that was spent for preparation of an order of a production unit.

Logistic measures

- Production order quantity: The production order quantity is the planned quantity for a production order (lot size, production order quantity).
- Scrap quantity: The Scrap quantity is the amount produced which did not meet the qualitative requirements and must be either scrapped or recycled.
- Planned scrap quantity: The planned scrap quantity is the process-related rejects, which is expected to produce a product (e.g., on / startup phases of manufacturing systems, etc.).

- Good quantity / Yield : The good quantity is the amount produced that meets the qualitative requirements.

- Rework quantity: The rework quantity is the quantity produced, which did not meet the qualitative requirements. However, these requirements can be obtained by reworking.

- Produced quantity / output quantity: The produced quantity is the amount that has produced a manufacturing unit based on a production order. The quantity produced is the sum of good quantity, scrap and rework quantity amount.

These KPIs are utilized in order to plan the production of a factory and with all them, the production amounts produced in a concrete period of time and the time required to produce both a product and all the products of a lot. Having all this data, a very important KPI is obtained: Overall Equipment Effectiveness (OEE).

3.6.3 Overall Equipment Effectiveness (OEE)

OEE measurement is also commonly used as Key Performance Indicator (KPI). OEE is an abbreviation for the manufacturing metric Overall Equipment Effectiveness. OEE takes into account the various sub components of the manufacturing process – Availability, Performance and Quality. After the various factors are taken into account the result is expressed as a percentage. This percentage can be viewed as a snapshot of the current production efficiency for a machine, line or cell (Vorne Inc.).

$$OEE = Availability\ x\ Performance\ x\ Quality$$

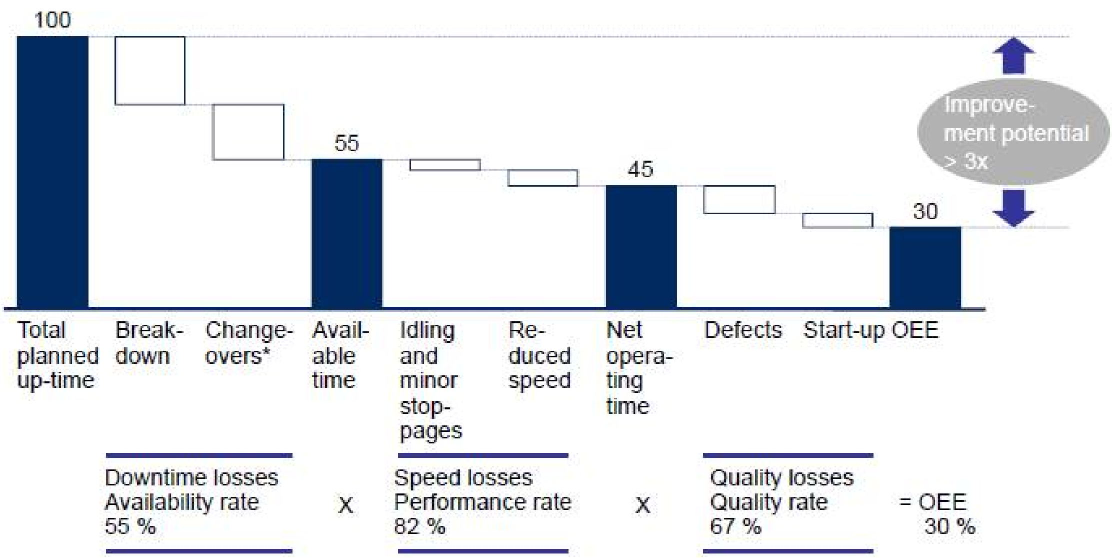

Figure 3-9: *Overall Equipment Effectiveness (Terwiesch)*

3.6.4 Introduction to Energy-Related Key performance indicators

Currently, energy awareness has gained significant attention from the industry due to the environmental and economic impacts associated with consumption of energy due to global warming and climate change, scarcity of resources and unsecured energy supply. Thus, manufacturing firms must put more efforts on in-depth analysis of energy and resource performance within their manufacturing processes and facilities. In this regard, energy monitoring is of paramount importance for effective energy management since it supports decision-makers in identifying opportunities for improvement and in recording the impacts of their decisions on energy use. For effective monitoring, performance indicators are necessary beyond measurement of data to evaluate energy efficiency performances.

In this vein, performance indicators play a significant role in evaluating the efficiency and effectiveness of manufacturing systems. KPIs are essential for effective energy management in manufacturing since it supports energy related decision making. However, existing knowledge on energy related production performance indicators is limited. (Energy Related Key Performance Indicators – State of the Art, Gaps and Industrial Needs).

To obtain this energy related KPIs, energy and power measurement technologies are necessary to be implemented. That energy and power measurement technologies also provide a broad quantitative perspective on their day to day consumption. The implementation of energy metering technologies is a very important factor in order to introduce an Energy Management System. An Energy Management System is a systematic framework for continuously improving the energy performance of a site and can help industrial enterprises reduce energy costs and improve performance and productivity (Industrial power and energy metering: a state-of-the-art review, 2013). Both EN16001 and EN50001 are Europe's most advanced energy management standards encouraging the implementation of energy metering systems. Within annex A3 of EN50001, the installation of appropriate sub metering is advised in order to allow further information of energy consumption to be derived. Further to this, annex A.3.3 requires the development of energy consumption targets and alarms forming an advanced notification system capable of monitoring a facilities energy performance; this cannot be achieved without an appropriate designed energy metering system (Industrial power and energy metering: a state-of-the-art review, 2013). An example of an energy metering chain is showed in the following figure

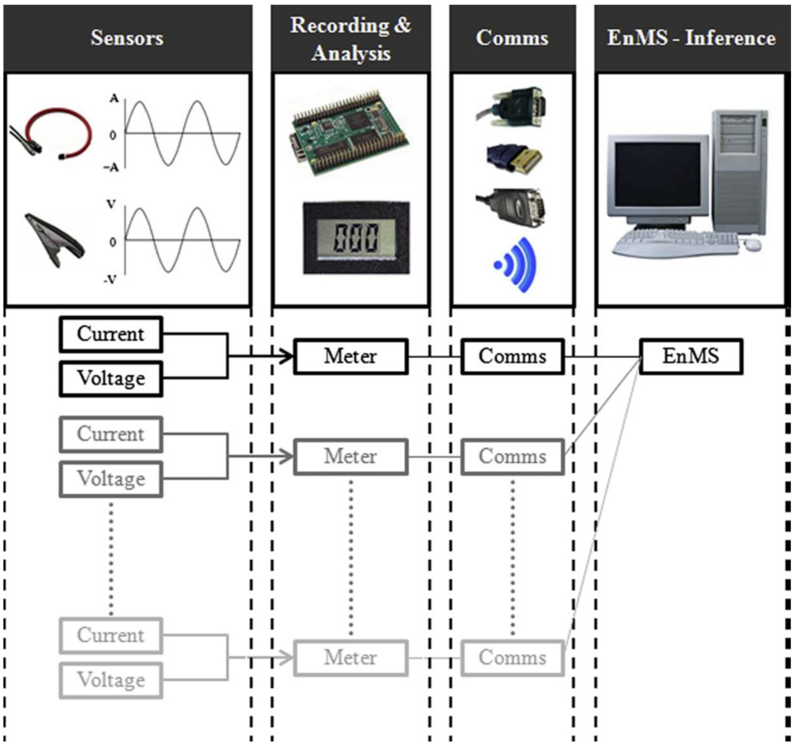

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Figure 3-10: *Modern Electrical measurement chain (Industrial power and energy metering: a state-of-the-art review, 2013)*

Some other monitoring systems in order to improve energy usage have been presented in literature. One example would be the automated monitoring system presented by (Automated energy monitoring of machine tools, 2010). They present a software-based approach for automated energy reasoning, which can support decision making across the multiple temporal levels from days to seconds. An example of the analysis across temporal scales can be seen in the following figure:

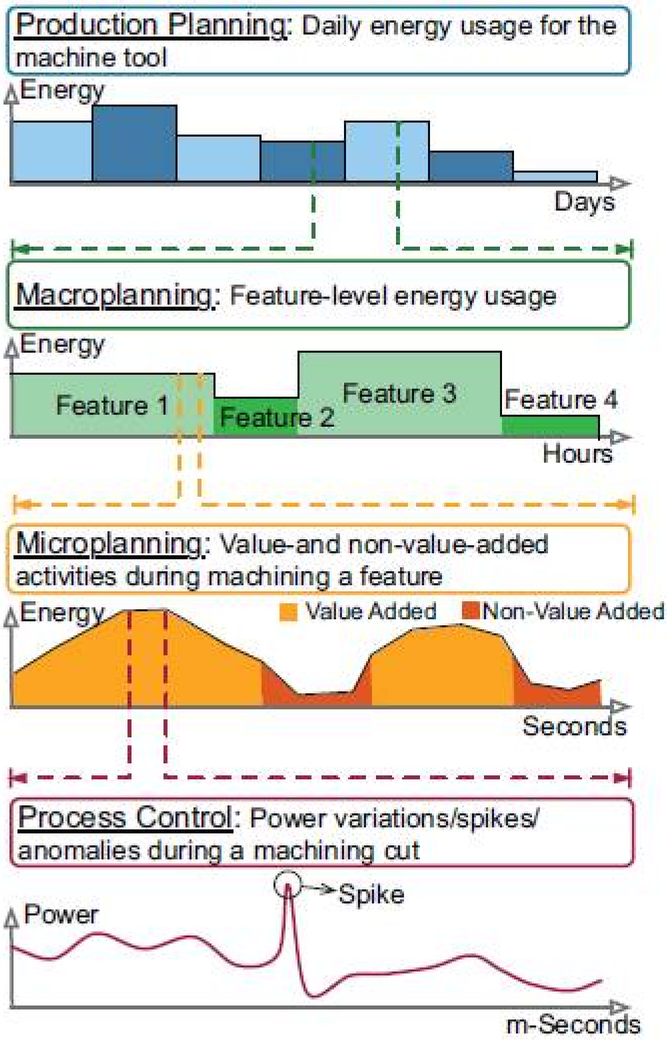

Figure 3-11: *Examples of analysis across temporal scales (Automated energy monitoring of machine tools, 2010)*

Here complete description of the energy consumption and the power requirements is obtained by this software.

3.7 Summary

Having all the literature review related to production planning and Key performance indicators related to production planning the following work is going to be presented.

The aim of the work is to have a complete description of the energy consumption related to production in factories and in combination with energy prices, introduce them as an additional factor that have to be taken into account to plan the production . By introducing this energy data, a reduction of the total cost related to production is expected.

From this point, the work will have the following structure: First, a description of the energy consumption of machine level, product level and production system will be made. This description is going to be based on energy related KPIs. After that, the energy consumption data in combination with energy prices are going to be a additional factor of a production planning model that is going to be proposed.

4 Energy in Production Systems

4.1 Introduction

Traditional performance measures considered in manufacturing include factors such as quality, cost, delivery time and safety. When considering the costs, the energy is included but not as a factor to be planned. Therefore, integrating energy as another performance dimension in manufacturing on traditional performances would be relevant (Energy Related Key Performance Indicators – State of the Art, Gaps and Industrial Needs).

The energy-related information allows the assessment of the optimization potential and improvements of energy effectiveness measures. So, providing data of the overall state of the factory and its performance regarding energy consumption is necessary. And KPIs mainly serve as a measure to decide whether a system is working as it is designed for and to define progress towards a defined target value.

The power demand of a production system stays within a lower and an upper boarder. The lower boarder represents the base-load of the production system, i. e. the power demand of the production system when all machines are switched off or not in use. The upper boarder is given by the sum of the maximal power demands of the machines of the production system. Within these boarders the power demand can vary depending on the state of the production system and its machines. The energy demand of a machine depends on process parameters. This leads to the opportunity for production systems to generate economic benefits out of volatile energy prices. An important requirement for that is that production systems know their energy demand and know how to adapt it. Figure 4-1 shows an example of an adaptation of production systems to energy prices.

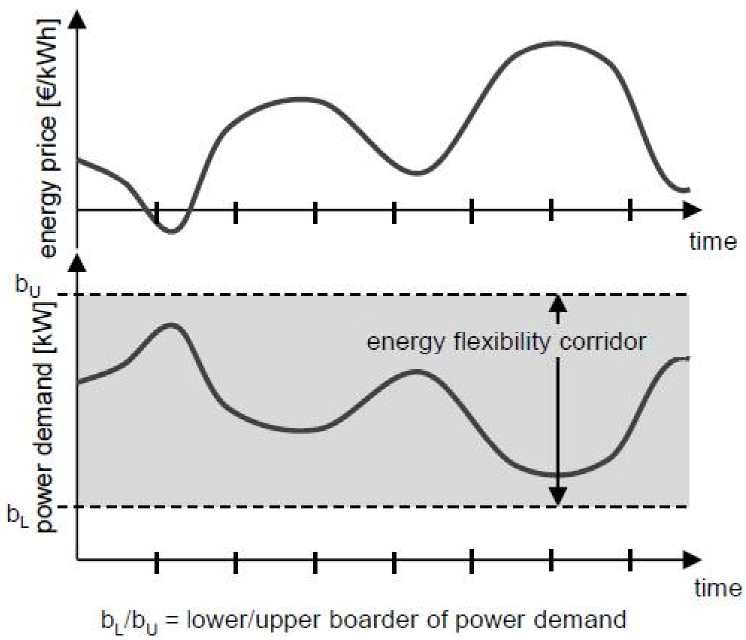

Figure 4-1: *Example of energy prices and its correspondent power demand in a factory (A Petri-net based approach for evaluating energy flexinility of production machines, 2013)*

The energy demand of a production system is a variable of the energy consumption of the machines of which the production system is composed in order to manufacture some products. So depending on the energy consumption flexibility of those machines and the flexibility of the production processes, the system will be more or less able to adapt its energy consumption to energy prices.

So from this point, different types of energy KPIs are going to be presented in a general way and then those KPIs are going to be linked with production systems.

4.2 Energy Key Performance Indicators

Having introduced the scope of energy KPIs, a classification of the different energy KPIs that are currently used is going to be presented. Many studies have been made in order to classify the different possibilities to express the energy consumption (Energy Intensity in the Iron and Steel Industry: a Comparison of Phys. and Econ. Indicators., 1997).

Currently, the KPIs related to energy have the purpose of expressing energy efficiency. In general, energy efficiency refers to using less energy to produce the same amount of services or useful output. That is for example, having the amount of energy required to produce an amount of product, the energy efficient target would be to diminish that amount of energy. There are different KPIs used to express that energy efficiency.

Although achieving energy efficiency is a very important target, it is not the main purpose of this thesis. In this paper, the energy effectiveness in production is going to be studied and some of the KPIs used to energy efficiency are going to be utilized in order to describe energy consumption of all the processes.

There are four different categories of energy KPIs presented in literature (Energy Related Key Performance Indicators – State of the Art, Gaps and Industrial Needs) (What is energy efficiency? Concepts, indicators and methodological issues, 1996).

4.2.1 Classification of Energy KPIs

- Thermodynamic Energy KPIs

These are energy efficiency indicators that rely entirely on measurements derived from the science of thermodynamics. Some of these indicators are simple ratios and some are more sophisticated measures that relate actual energy usage to an 'ideal' process. Energy efficiency is often broadly defined by the simple ratio:

$$\frac{Useful\ output\ of\ a\ process}{Energy\ input\ into\ a\ process} \qquad [\ 1\ ]$$

In (MES-Kennzahlen: Erweiterung des OEE um den Faktor Energie) an extension of the OEE is developed in order to express the energy effectiveness of a process by separating the energy consumed in different time periods. It is separated into production time (EnPT), idle times that include machines breakdowns and so on (EnId), and no production time (EnNPt). So the number is obtained as follows:

$$Energy\ effectiveness = \frac{EnPT}{EnPT+EnId+EnNPt} \qquad [\ 2\ ]$$

- Physical-thermodynamic energy KPIs

These are hybrid indicators where the energy input is still measured in thermodynamic units, but the output is measured in physical units. These physical units attempt to measure the service delivery of the process - e.g. in terms of amount of product.

One criticism of traditional thermodynamic indicators of energy efficiency is that they don’t adequately encapsulate the end service required by consumers in the output measurement. In order to fix this, some efficiency ratios that measure the output in physical units rather than in thermodynamic terms are developed. These physical units are specifically designed to reflect the end use service that consumers require. An example of a measure like this one could be amount of product per unit of energy or vice versa.

An important advantage of using these physical measures is that they can be objectively measured and directly reflect what consumers are actually requiring in terms of an end use service.

Depending on the industry treated, different Physical- Thermodynamic KPIs will be used. For most industries the product can be measured in terms of its mass - e.g. tons of butter, tons of bricks, tons of wheat, tons of aluminium. Hence appropriate indicators may be:

  - Energy input/ tons of butter;
  - Energy input/ tons of bricks;
  - Energy input/ tons of wheat;
  - Energy input/ tons of aluminum;

But in other industries other industries, volumetric output measurements may be appropriate - e.g. liters of milk, cubic meters of wood or timber, liters of oil.

- Economic-thermodynamic Energy KPIs

These are also hybrid indicators where the service delivery (output) of the process is measured in terms of market prices. The energy input, as with the thermodynamic and physical-thermodynamic indicators, is measured in terms of conventional thermodynamic units. These indicators can be applied to various levels of aggregation of economic activity - product, sectorial or national levels.

An example would be the Energy/GDP measure. The energy /GDP ratio is the most commonly used aggregate measure of a nation's energy efficiency. The main problem of the Energy/GDP is that it does not measure underlying the technical energy efficiency. But some methods presented by (An accounting framework for decomposing the energy-to-GDP ratio into its structural components of change, 1993) isolate the technical factors of this measure.

Another KPIs presented is the energy productivity ratio. The more goods an economy produces per unit of energy, the more productive or efficient it is said to be with respect to energy.

- Economic Energy KPIs

These indicators measure changes in energy efficiency purely in terms of market values ($). That is, both the energy input and service delivery (output) are enumerated in monetary terms.

Many studies have been made in order to develop new KPIs. A good review of the different energy related KPIs presented in literature can be seen in table 4-1 (Integrating energy efficiency performance in production management - gap analysis between industrial needs and scientific literature, 2010):

Table 4-1: *Energy classification*

Reference	Indicator	Indicator Type	Application	Formula/Unit
(Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO2 emissions, 2002)	Energy Intensity	Economic	Aggregated level	Energy consumption/economic term
	Degree efficiency consumption	Physical	Disaggregated level	GJ per t
(Der EnergieSparFonds für Deutschland., 2006)	Energy Intensity	Macro-economic	Aggregated level	Energy consumption/monetary variables (GDP)
	Degree of efficiency	Engineering view	Aggregated level	Net energy/used primary energy
	Final energy efficiency improvement	Physical	National level	Energy savings per year
(What is energy efficiency? Concepts, indicators and methodological issues, 1996)	Thermodynamic energy efficiency	Thermodynamic	Measurements derived from the science of thermodynamics	Actual energy usage related to an 'ideal' process
	Physical-thermodynamic energy efficiency	Hybrid	Measure the service or delivery of the process	Actual energy usage /tonnes or passenger miles
	Economic-thermodynamic energy efficiency	Hybrid	Measure the service or delivery of the process	Energy usage in conventional thermodynamic units/output in terms of market price
	Economic energy efficiency	Economic	Measure in terms of market value	Energy input in monetary terms/output in monetary terms
(Energy efficiency developments in the pulp and paper industry: a cross-country comparison using physical production data, 1997)	Energy efficiency measurement	Economic	Activity of a sector	Energy consumption/value added or value of shipments

	Specific energy consumption	Physical	Process leverl, cross country comparison	Energy use/physical unit of production
(IEA, 2008)	Thermal energy efficiency of equipment	Physical	For single equipment	Energy value available for production/input energy value
	Energy consumption intensity	Physical	Broader than thermal indicator: companies, etc.	Energy consumption/physical output value
	Absolute amount of energy consumption	Physical	With indication of production volumes	Engery value
	Diffusion rates of equipment	Physical	Focusing on specific energy efficient technology	Rate of deployment of technology
(IEA, 2007)	Industrial energy intensity	Physical	Comparison of efficiency data on a sub-sector level between countries.	Energy use/unit of industrial output, e.g., GJ/t
	Specific energy consumption	Physical	On a secto level	e.g. GJ/t
(The evolution of the ENERGY STAR energy performance indicator for benchmarking industrial plant manufacturing energy use, 2008)	Energy performance indicator	Statistical	On plant level	Percentile ranking of the energy efficiency

4.2.2 Integration of energy indicators in production

Having explained the different types of energy KPIs, the definition of the scope of using those indicators in production is necessary to be defined. As explained in the literature review, there are different levels of aggregation when talking about a factory. And every level has their related energy consumption.

In (Metrics for Sustainable Manufacturing, 2008) a scale has been presented in order to separate the energy consumption per level of aggregation:

- Machine level
- Line Level, which is the family of manufacturing equipment grouped to produce a specific part or assembly. That includes cell level and production system level explained before.
- Factory level, where the HVAC and other auxiliary consumers are taken into account.

In this thesis only the energy consumed in machines and production lines is going to be treated because it’s the energy that can be planned related to production. As it’s going to be explained, many of the indicators used are going to be simple ratios of the output of an activity to the energy used to carry out that activity (e.g., specific energy consumption (SEC) e the ratio of energy consumption to units).

In the following parts the energy consumption of machines and production systems is going to be explained.

4.3 Energy consumption in Machines

4.3.1 Factors of influence in energy consumption of machines

The energy consumption of a machine depends on the production states that a machine has, the time the machine is going to spend in those production states and additional activities that are not directly related to the production of a part type, but are necessary to be done. Depending on the total amount of tasks that a machine has to perform, the energy consumption will be different.

For example, a modern milling machine can include a wide variety of functions including work handling, lubrication, chip removal, tool changing, and tool break detection, all in addition to the basic function of the machine tool. The result is that these additional functions can often dominate energy requirements.

This is shown in the following example of an automotive machining line showed in the figure below. In this case, the maximum energy requirement for the actual machining is only 14.8% of the total. (Electrical Energy Requirements for Manufacturing Processes, 2006).

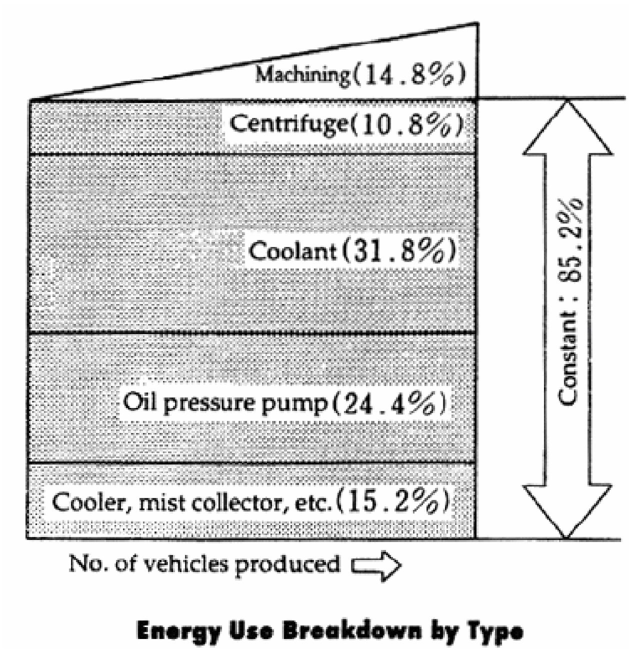

Figure 4-2: *Energy used as a function of production rate for an automobile production machining line (Electrical Energy Requirements for Manufacturing Processes, 2006)*

It can be seen that at lower production rates the machining contribution is even smaller so depending on the process parameters, the energy consumption will be different

In general, there is a significant energy requirement to start-up and maintain the equipment in a “ready” position. Once the machine is ready to start manufacturing, there is then an additional requirement which is proportional to the quantity of material being processed (Electrical Energy Requirements for Manufacturing Processes, 2006). In the following figure, a power profile of a turning machine can be seen

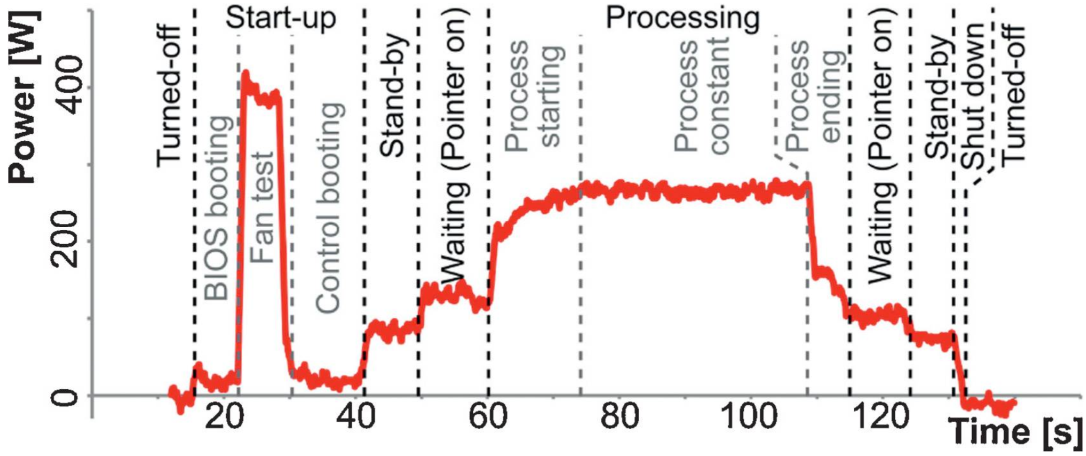

Figure 4-3: *Power profile of a laser of plastic welding (Methodology for planning and operating energy-efficient production systems, 2011)*

4.3.2 Machine-related energy Key Performance Indicators

From the previous description part, complete information of how the energy can be spent in a machine is provided.

As stated before, the energy consumption of machines depends on the production states; the time the machine is going to spend in those production states (can be stated a minimal and maximal time stay t_{min} and t_{max} but it’s not necessary). One way commonly used to describe the production states that a machine has and their corresponding energy consumptions is through a Petri-net model. Petri net models are useful for representation of systems with concurrent activities (Flexibility of manufacturing systems: Concepts and measurements, 1989). They have been used as a design representation of information and control flow in systems, mostly to analyze the set of possible states. It is recommended the use of Petri-nets for the modelling of machine states, since it enables manageability of complex systems with several states. (A Petri-net based approach for evaluating energy flexinility of production machines, 2013) (Flexibility in manufacturing systems: definitions and Petri net modelling, 2007)]. An example can be showed in the following figure:

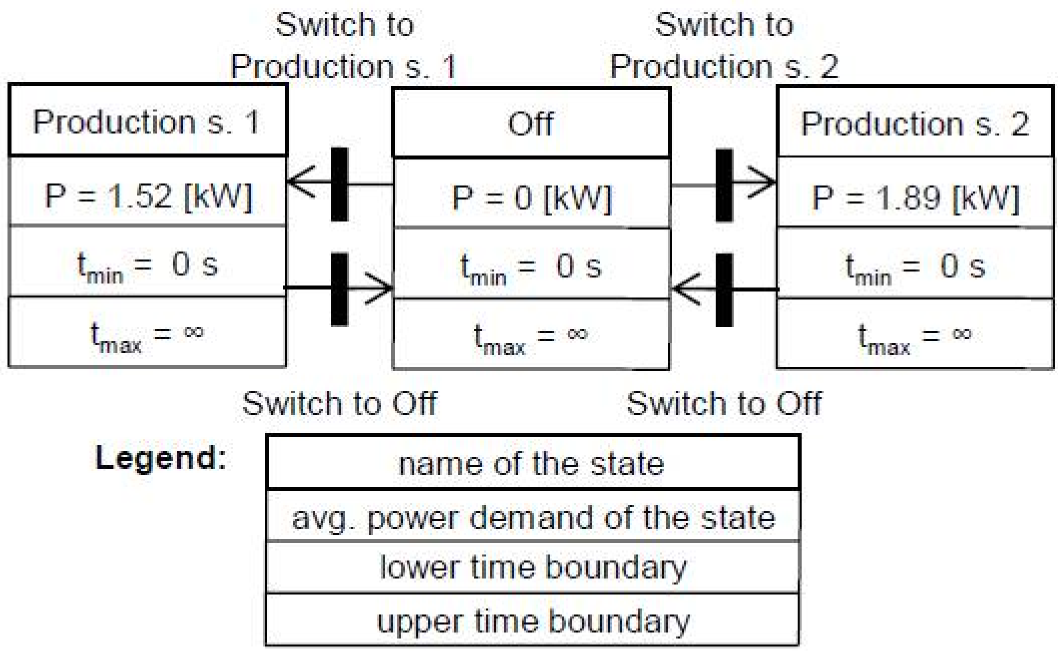

Figure 4-4: *Petri-net model of a grinding machine (A Petri-net based approach for evaluating energy flexinility of production machines, 2013)*

Having all this data, the concept of energy flexibility in machines can be introduced. As expressed before, flexibility in manufacturing can be regarded as a function of variability, cost and time. So to describe the energy flexibility of a machine, variability is regarded as the number of states the machine can adopt and the power consumption of each one. The other factors are the time required to change states and the cost associated to it.

In order to quantify how energy flexible is a machine, in (A Petri-net based approach for evaluating energy flexinility of production machines, 2013) a KPI have been developed. It goes from 0 to 1 (from no Energy flexibility to complete energy flexibility). Its quantification depends on the number of states that the machine has and the set up time and cost of changing between each one.

The Energy KPI wanted to be presented is a physical-thermodynamic KPI which is the total amount of energy consumed per product per machine. Having the power consumption of every machine state, which can be obtained either measuring with the technology explained in the previous chapters or looking it in catalogues, the energy consumption related to a product in that machine will be calculated when adding the power data to the time spent by the product on it (processing time). Using the example of figure 17, the amount of energy spent to perform a product which work with production state 1 (1.52 KW) for 0.25 hours, will be 0.38 KWh. This amount will correspond to the Energy KPI the machine related to that certain product.

4.3.3 Scope of description of energy consumption of machines

Having all the data of energy consumption in every machine, a complete description of the energy consumed by product manufactured is obtained.

In the next part, different factors will be presented in order to describe how to influence energy consumption related to a product.

4.4 Product-related energy consumption

4.4.1 Flexibility as a factor that influence the energy consumption related to a product

The product-related energy consumption KPIs can be defined as the sum of the energy consumption of all processing steps involved in manufacturing that product. Depending on the machines used to manufacture a part, different amount of energy will be consumed.

Depending on the flexibility that a production system has to manufacture a part type, the energy consumption of the process will be more or less able to be influenced. If a “Flexible Manufacturing System (FMS)” is considered, more than one routing possibility may be available and hence different energy consumption data related to a product will be collected. Having these data and depending on the machine availability in a certain moment, the less energy consuming routing can be selected.

An example has been taken from (Methodology for planning and operating energy-efficient production systems, 2011) to explain this. The manufacturing of a swash plate expander is being considered. The product has rotational symmetry so that the main housing parts like the swash plate housing, cylinder head and cylinder head cover require turning operations. Most housing parts also require milling and/or drilling operations. Taking the cylinder head the manufacturing has to start with milling operations. The second operation, the manufacturing of flanges, can be done either by milling or turning.

Figure 4-5: *Time and energy required to manufacture a cylinder head (Methodology for planning and operating energy-efficient production systems, 2011).*

So depending on the route selected, the total energy amount per product and the processing time per machine is going to be different as showed in figure 4-5. Here can be seen that using the milling and turning route the amount of energy required to produce the cylinder head is 815 Wh and using the milling and milling route the energy required will be 900 Wh. These data are considered as energy consumption KPIs for the cylinder head.

As a conclusion, the total amount of energy consumption can be influenced varying the machines that are going to be used to perform a part.

In order to visualize the different possibilities previously exposed, a Petri-net model would be a useful tool because the different processing steps and their related energy consumption can be stated in a very easy way.

4.4.2 Energy consumption in production systems

Gathering the energy consumption data related to all the products manufactured, the energy consumption of the whole production system could be obtained.

The main target of having all the energy consumption data presented in the previous parts of this chapter is to introduce it as another factor that influences the production planning. This data is organized into three different levels of aggregation as showed in figure 4-6:

- Production system level, which is introduced in aggregate production planning
- Product level, which is going to be introduced in the MPS and MRP
- Machine/Equipment level in order to establish the production sequence in machines.

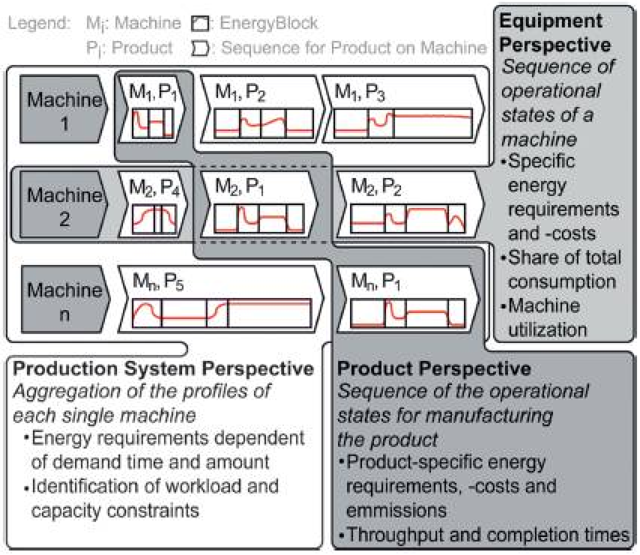

Figure 4-6: *Energy description of a Manufacturing System (Methodology for planning and operating energy-efficient production systems, 2011)*

In the following chapters, the production planning taking into account the energy consumption will be treated deeper.

Having the data of the production systems in which the factory is composed and adding the auxiliary consumption (HVAC), as expressed in the previous chapter, the whole consumption of the factory in collected.

In production planning, only the consumption of production systems and subjacent levels are going to be considered because the main strategy is to plan every production system in an energy effective way so the whole factory is energy effective.

4.5 Energy data required in production planning

As stated before, KPIs will be very useful in order to predict the energetic behavior of a manufacturing system and in the control part be able to measure and compare the consumption, being sure that the numbers are within normal limits.

Having the data of energy consumption in all level of aggregation of the factory, the production planning taking into account the energy consumption and the energy prices can be made. Depending on the planning step, different energy data is going to be necessary.

There are also production-related indicators that are used to evaluate the energy consumption during the productive and non-productive times. For this purpose, the energy consumption during a day, a shift or production time are considered. Having this data and having also the energy prices, it's possible to adapt the production and to those energy prices and obtain more benefits.

4.5.1 Mid-term planning

As stated before, the long-term planning is related to the strategy of the company, related to what products are going to be made, in which fields would be necessary to invest etc. Having the strategy of the company clear, now the tactical phase of the production starts and there is where the energy can be introduced at first. In the tactical production planning the total energy consumption (KWh) necessary to produce a part is going to be used and it's going to be another factor of decision making in order to select how many parts are going to be made and in which moment, depending on the energy prices. So all the energy data is going to be introduced in the MRP II procedure. (Optimizing the production scheduling of a single machine to minimize consumption costs, 2013).

So from here can be said that the production planning would be divided into two major steps when talking about energy: the first step is the whole factory planning, in which the quantity of jobs and when are going to be made is decided taking into account the energy prices and the amount of energy consumed (mid-term); and the second step, planning at machine level to define the job sequences as explained before in chapter 2.3 (short-term).

4.5.2 Short-term planning

In planning on machine level, different energy data will be necessary. In addition to energy consumption, the power consumption (KW) of each operation is going to be needed. Having the power consumption of each production step, some strategies can be adopted in order to adapt the production and reduce energy costs.

5 Production planning procedure

Having all the energy consumption data related to machines, products and the whole production system explained in the previous chapters and the average energy prices that correspond to the different planning horizons, strategies are going to be adopted in order to obtain a profitable production planning.

The energy prices framework that would be necessary to be used in reality is a Time-Of-Use pricing. Using a RTP pricing it's very difficult to plan the production because the energy prices every hour and it's known only a day before. However, It's not going to be a problem in this thesis because the energy prices considered are related to the past.

First of all, it's assumed that long term planning decisions like maximum capacity of the factory, the days of work of each month and the working shifts of the workers have been previously defined.

Afterwards, the rules that allow selecting the jobs or products included in the planning have to be defined. The jobs selected are only those which are going to be included in the scheduling for that concrete period. Different data will be needed:

- Machine data in order to know the capacity that I have in a period of time (for example a week)
- Product data such us different routing possibilities, set-up times, processing times per machine, bill of materials, energy consumption related to each product and routing etc.
- Order data such as quantity, due date and client. The lot sizes are going to be prepared in order to have the least energy cost possible taking into account the demand of products.

Finally, those jobs will be sorted according to dispatching rules or algorithms applicable in each case. As a previous phase of sequencing, the bottleneck of the process has to be found so a differentiation of which products go through the bottleneck and which don't.

Having all this data, different sequences and loading in machines are going to be made.

5.1 Capacity planning

The first step in production planning is to know the capacity that the production system has installed. Different capacity planning strategies can be used depending on the planning time horizon (Goldratt, 1984) (Krajewski, et al., 2008b) .In the following table, different strategies are showed:

***Table 5-1**: Different capacity measures depending on the time horizon (Goldratt, 1984) (Krajewski, et al., 2008b)*

	Modify capacity	*Use current capacity*
Long term	*Expand factory*	
Mid-term	*Subcontract* *Add equipment*	*Add workforce* *Add and use inventory*
Short-term		*Job scheduling and personal scheduling* *Machine allocation*

Depending on the planning horizon in which the capacity planning is desired to be made, different strategies are used.

In this thesis the focus is going to be in mid and short term planning because in those time frames is where the factor of energy consumption is going to be considered.

As explained in the previous chapter, depending on the time of the day, there are different energy prices. A good approach for mid-term planning to reduce the energy consumption would be to adapt the shifts of the workers as much as possible to prices hours and try to schedule workers breaks in those hours taking into account that the total working hours cannot be reduced. This strategy can be implemented in an easier way if the factory has a TOU prices with more than 2 periods, so the prices from today in advance are determined.

In order to know the total capacity of the factory and have the data necessary to planning the production on mid-term and short term, the capacity of the equipment is obtained. This can be obtained with the theory of constraints of (Goldratt, 1984). Having the data of each workstation (capacity, processing times per product and number of machines in which the workstation is composed) the bottleneck of the process can be obtained.

An important part of the capacity calculation is the batch sizes that are necessary to be implemented if some machines involved in the process have setup times

There are two different kinds of batches: transfer batches and process batches. Transfer batches are many parts moved at once. Process bathes are many transfer batches processed together.

There are two types of process batches: sequential and simultaneous. Sequential batches represent the number of transfer batches that are processed before the workstation is changed or to another part or family. The parts are produced sequentially on the workstation. A simultaneous batch represents the number of parts produced simultaneously in a workstation, such as a furnace or heat treatment operation.

Traditionally, the size of the process batches is related to the length of a changeover and setup. The longer the setup, the more parts must be produced between setups to achieve a given capacity. The size of the simultaneous batch depends on the number of parts that can be processed together.

Transfer batches are the number of parts that are accumulated before being transferred to the next station. The smaller the transfer batch is, the shorter the cycle time, since there is less time waiting for the batch to form. However, smaller transfer batches also result in more material handling (Hopp, y otros, 2011c). Many production planners assumed that these two batches should be equal. But these need not to be so. In a system where setups are long but processes are close together, it might make good sense to keep process batches large and transfer batches small in order to reduce cycle times. This is called Lot Splitting.

From this point, an approach to obtain the optimal batch sizes in order to reduce cycle times is presented (Hopp, et al., 2011d).

Having this data of the machines, the working hours per day and the working days per month, the maximal capacity per product manufactured in the factory is obtained.

5.2 Aggregate planning

The next step after knowing the capacity of the factory is the aggregate planning, in which the production rates, inventory, workforce, shifts, extra hours and subcontracted are planned. In this model, it's going to be assumed that every workstation is composed by one machine.

Here different data will be needed as the base of the planning that is going to be made:

- Machine data: the data related to machines needed is the maximum capacity of the different machines involved in the process and their energy KPIs related to machines explained in the previous chapters
- Product data: here the data required will be time required per machine in which the product is produced, the product-related energy KPIs presented before with every routing possibilities (depicted with a Petri-net model)
- Order data such as quantity, due date and client
- Energy prices
- Cost related to production, which is going to be explained in the next part of the work.

Having this data, the objective of the aggregate planning is going to be presented with the LP approach taken from (Hopp, et al., 2011b) but expanded by introducing the energy consumption related to the production:

i = an index of product, $i = 1, \dots, m$, so m represents total number of products

j = An index of workstation, $j = 1, \dots, n$, so n represents total number of workstations

k = An index of route, $k = 1, \dots, l$, so l represents total number of routes that a product i has.

t = An index of period, $t = 1, \dots, \bar{t}$, so $\bar{t}$ represents planning horizon

$\bar{d}_{it}$ = Maximum demand for product i in period t

a_{ij} = Time required on machine j to produce one unit of product i

c_{jt} = Capacity of machine j in period t in units consistent with those used to define a_{ij}

r_i = Net profit from one unit of product i

h_i = Cost to hold one unit of product i for one period t

X_{it} = Amount of product i produced in period t

S_{it} = Amount of product i sold in period t

e_{ijk} = Energy consumption of machine j to produce product i with the route k

p_t = Average energy price in period t

I_{it} = Inventory of product i at end of period t (I_{i0} is given as data)

Maximize $\quad \sum_{t=1}^{\bar{t}} \sum_{i=1}^{m} r_i \, S_{it} - h_i I_{it} - \sum_{j=1}^{n} X_{it} e_{ijk} p_t \quad$ *for all k* $\quad$ *[3]*

Subject to:

$$S_{it} = \bar{d}_{it} \qquad \textit{for all } i, t \qquad [\,4\,]$$

$$\sum_{i=1}^{m} a_{ij} X_{it} \leq c_{jt} \qquad \textit{for all } j, t \qquad [\,5\,]$$

$$I_{it} = I_{it-1} + X_{it} - S_{it} \qquad \textit{for all } i, t \qquad [\,6\,]$$

$$X_{it}, S_{it}, I_{it} \geq 0 \qquad \textit{for all } i, t \qquad [\,7\,]$$

The objective function computes net profit related to the products sold and subtract the inventory cost of the products that are not sold in that period but are going to be sold in next periods.

The constraint [4] limits sales to demand. The constraint [5] is the capacity constraint of the production. Having the machines that are involved in production processes, the working force and the time of production available for production in a concrete time period, the capacity can be obtained.

The constraint [6] is known as balanced constraints related to inventory. This constraint is common to all multi-period aggregate models.

Using this algorithm, the planning of how many items and when are going to be produced in every period of time in order to maximize the benefits in the whole planning period will be achieved.

As explained in the previous chapter, there can be different routes in order to produce a product. In the algorithm presented, the idea wanted to be expressed is the following: The optimal amount of products produced of each type is going to be obtained for every time period varying the level of inventory of each period taking into account the energy prices and the energy consumption of every route that a product has. Having that, the decision maker will be able to decide which option is the best for the factory.

The model can be more realistic if the following factor are included in the model

- Constraints of utilization have to be included because any source of randomness can diminish it (machine failures, setups, errors in scheduling, etc.).

- Backorders
- Overtime
- Yield loss

Having the constraints of capacity, inventory and demand, the concrete quantity of production per period is known. Having that planned, the next step of the production planning has to be assessed.

5.3 Material Requirement Planning (MRP)

When the aggregate production planning is made, the next step is the scheduling. The demand is disaggregated in the MPS, and from the MPs, the MRP is going to be made in order to know when the manufacturing orders are going to be released.

There are many rules that stablish the lot sizing necessary to be made in order to meet the demand in every period analyzed. One of the most common rules used is the Economic Quantity Order. Economic Quantity Order is the order quantity that minimizes total inventory holding costs and ordering costs. It takes into account the inventory cost, production costs, and setup cost. But when demand varies over time, a continuous time model, like the EQO model, is awkward to specify. When demand is divided into discrete periods, which could correspond to days and weeks, dynamic lot sizing approaches are necessary to be implemented.

One important procedure of dynamic lot sizing is The Wagner-Whitin procedure (Hopp, et al., 2011a) which take into account the following data:

- t = time period. The range of time periods is t=1 to T where T is the planning horizon.
- D_t = the demand over the period t
- C_t = production costs in monetary units per unit
- A_t = setup cost to produce a lot in period t in monetary units
- h_t = inventory cost of a unit over a time period
- I_t = inventory quantity at the end the period.
- Q_t = Lot size in period t
- p_t = Average energy price in period t

Having this data, the energy data as average energy prices per period and energy consumption per product is going to be introduced in that procedure.

The Wagner-Whitin procedure consist on a model to determine the lot sizes by minimizing the sum of setup cost, inventory cost and production costs. The energy cost is going to be introduced in the production cost part. Using that procedure is possible to know theoretically how many items are to be produced in a lot ordered in week *t* and evaluate if it's profitable to produce for the week *t+1* or in both weeks separately. Its principal property is that another order is released when the inventory is zero. With this algorithm, an optimal solution will be obtained in order to meet the demand at the minimum cost.

This algorithm makes some assumptions like known setup cost and demand and production deterministic. Setup cost can be very difficult to determine in manufacturing systems and demand is actually uncertain because order cancelations, yield loss and delivery deviations can occur. So although this model make some assumptions that can approximate to reality, for example in case of schedule literally frozen over the time horizon considered, often it's not like that. But in this thesis, these concepts are assumed in order to ease the explanations. If demand is uncertain, there are two approaches to take: Model demand as if it were deterministic for modeling purposes and then modify the solution to account for uncertainty; or explicitly represent uncertainty in the model, which are the statistical inventory models (Hopp, et al., 2011e).

Having the planned order releases, a calculation of how many products are going to be manufactured in a day taking into account the inventory cost and average energy prices per day, the next step is planning the machine level of aggregation. In the following chapter, the machine level planning is going to be explained, taking into account energy consumption.

5.4 Machine level planning

Having the production orders released, and making an optimal production quantity planning per day taking into account the lot sizes of released orders, maximum capacity per day and energy data like energy prices an energy consumption per product, planning at machine level is the next step. The main objective here could be reduce the peak load on moments of high energy prices during the days and to do so a multi-objective problem can be solved by using the proper algorithms in order to minimize completion times and reduce the maximal peak load (A new approach to scheduling in manufacturing for power consumption, 2011). By reducing the peak load of the factory, a reduction of energy cost is expected.

At this level, the planning is based on stating optimal batches and loading.

5.4.1 Optimal batch sizes

Batching consist on given a production order of part types with known tools and processing time requirements, determine a subset of part types for immediate and simultaneous processing over the upcoming period of the planning horizon (such as daily or next shift), according to an appropriate objective and within the limited capacity and the available processing time of each machine.

<u>Sequential batch sizes</u>

The first step is state the optimal sequential batch sizes per day. As stated before, depending on the day different amount of products are going to be produced due to average energy prices per day. Given the demand in that day the optimal batch sizes are going to be calculated when setups are needed (Hopp, et al., 2011d). The demand is going to be split in the working hours of the day or shift and having that data, the batch sizes are going to be configured.

Some studies like (Batching in production planning for flexible manufacturing systems, 1995) (A novel approach to production planning of flexible manufacturing systems, 2004) propose algorithms for optimal batching in FMS.

<u>Simultaneous batch sizes</u>

Another interesting batch size evaluation would the optimal simultaneous batches. An example would be a heat treatment for some products in an oven, where the energy consumption per heat treatment is the same, regardless of how many parts are in the oven, the logical energy consumption related batch size would be to fulfill the capacity of the oven in order to use it the least amount of time and hence reduce the energy consumption demand per product. But in reality, it may not be a suitable solution if the capacity of the oven is much bigger than the interarrival times per product. It would lead to long waiting times If that happens, a consequence is that the completion times become so high. Some algorithms are presented in literature to reduce the completion times of products that require simultaneous batch sizes (Scheduling hybrid flowshop with parallel batching machines and compatibilities, 2008) and main objective would be to minimize the peak load to avoid energy cost surcharges

5.4.2 Load shifting

Load shifting can be a very important approach in order to obtain profits during the production of a day. Using a RTP pricing, a factory that is able to curtail processes on short notice in order to respond to hourly varying energy tariffs, may be able to get benefit from RTP prices. Having the data of the maximum power demand of the production system and the base power consumption, the system can adapt its consumption depending on the prices. The energy costs during the day are going to be minimized but the productivity of the factory is going to stay as planned. A formulation of a load shifting problem can be showed in (Industrial Power Demand Response Analysis for One-Part Real-Time Pricing, 1998) in which the production is adapted to the hourly varying energy tariffs.

Systems with high volume flexibility and sequence flexibility are better to adapt their consumptions with RTP prices. Systems with less flexibility can adapt their consumptions easier if a TOU pricing program is used. One approach can be seen in (An optimal control model for load shifting – With application in the energy management of a colliery, 2008). Here, an approach for minimizing the energy cost taking into account a TOU rate pricing is presented. Another study like (Parallel-machine scheduling to minimize tardiness penalty and power cost, 2012) presents an algorithm to minimize the energy cost of scheduling of system of parallel machines with sacrificing the completion times of the work.

5.4.3 Job sequencing

Many rules are presented in literature in order to sequence the jobs that are going to be made in the different machines which compose production systems. Using a proper job sequence in a production system, the energy cost can be very influenced depending on the production type considered.

Depending on the flexibility that a production system has, the production can be more or less adaptable to energy prices. For example, considering a job shop with a high process sequence flexibility for the products involved and routing flexibility, the production process is easily adaptable.

Having the energy KPIs per product on each machine, the optimal sequence of jobs made on each machine can be defined by manufacturing the most energy consuming jobs at times of low prices and producing the least energy consuming jobs at times of higher prices. This measure can be introduced as long as the amount of production scheduled for that day does not vary.

5.4.4 Operational strategies to make a flexible energy consumption

Different operational measures are presented in literature in order to avoid peak of energy demand and adapt the consumption in order to achieve energy flexibility. As stated before, the main purpose of planning a t machine level is reduce cycle times to meet the demand and now some measure are going to be introduce in order to reduce the energy costs.

One approach to solve this problem would be load shifting. In (An optimal control model for load shifting – With application in the energy management of a colliery, 2008) an approach for minimizing the energy cost taking into account a TOU rate pricing is presented. The model presented adds the constraints of energy prices.

Turn-off machines

Taking into account one machine, another operational method is to turn off machines if they are not in use. In order to do that, a controller can be introduced and it will make two types of decisions: either leave the machine idle, or turn the machine off for a predetermined amount of time. The decision to leave the machine idle or shut it down will be made with dispatching rules.

As explained before in the description of machine consumption, when a machine is turned on, it takes warm-up time before the machine is ready to process a part. A warm-up consumes Start up (turn on) energy, i.e. the energy required to start up the machine. To process a part the machine consumes processing energy per unit time. Idle power is the power required per unit time by the machine when staying idle. The machine requires Stop Time to be turned off, which consumes stop (turn off) energy. The ability to predict the interarrival times of jobs is the key in order to decide if the machine should be turned off or not. (Operational methods for minimization of energy consumption of manufacturing equipment, 2007) define the following ratio S:

$$S = \frac{(Turn\text{−}On\ enenrgy + Turn\ off\ enenrgy)}{Idle\ power\ consumption\ per\ unit\ time} \qquad [8]$$

When the interrarrival times are bigger than maximum of the time required to turn off and turn on the machines or S, then the machine can be turned off for a particular length of time and then turned on to process some other jobs.

6 Show case

In this chapter, a practical example will be presented in order to validate the production planning procedure previously explained.

For the simulation, a fictional factory will be considered and the energy consumption related to production will be changed in order to difference the benefits obtained depending on the energy consumption of the factory.

In the next chapter the data related to the simulation will be presented. This simulation will be carried out with Microsoft Excel using the tool SOLVER.

6.1 Simulation data

6.1.1 Energy prices

The energy prices are obtained from the spot market in (European Energy Exchange (EEX)). But these prices stated there don’t take into account taxes. The taxes model that is going to be used is the following:

$$Energy\ price\ before\ tax\ (spot\ price\ in\ €\ per\ MWh) + 10\ € * (MWh\ consumed) \qquad [9]$$

The price after taxes is going to be considered as the spot price plus ten euros per MWh consumed. Actual taxes model related to energy is more complex but it’s a good approach for the concepts wanted to be explained in this thesis. so a factory that consumes more energy have more energy cost per MWh. This happens because when the energy needs of the factory are high, some substations are needed to be installed to supply the energy. The cost of the infrastructure is for the utility so they introduce the cost into the electricity bills.

In this example, the energy prices considered are going to be from January to June (both included) of 2010. Depending on the production planning horizon, different energy prices are going to be used:

- In aggregate planning, the average energy prices per month will be used
- In scheduling, for the MPS and MRP the average energy prices per week will be considered.

6.1.2 Production data

In the simulation, two different scenarios of energy consumption are going to be presented:

- Case 1: The first scenario is going to be a factory that consumes a maximum of 1.5 MWh per day
- Case 2: The second will be a factory that consumes 15 MWh per day.

The aggregate planning and scheduling will be made in both cases taking into account the energy planning and not taking it into account, so the energy savings and overall savings can be observed.

The production line characteristics are presented. This is going to be composed by two machines: a turning machine with numeric control and a milling cutting machine. The characteristics of the machines are the following:

Table 6-1: *Characteristics of the machines (Universidad Politecnica de Catalunya, 2014)*

Machine	*Trademark*	*Model*	*Weight(Kg)*	*Power consumption (KW)*
Turning Numeric control	*Nakamura*	*TMC 200*	*4100*	*11*
Milling-cuting	*TCI Waterjet*	*BP 2-1530-2*	*2800*	*12*

It can be noticed that the processing time required to manufacture the units that are going to be considered in the problem are included. Having the power consumption and the time required to perform a product, the energy consumption per product is going to be obtained. In this case, the energy consumption is 4.83 KWh

In addition, in order to plan the production it’s necessary to know how many working days are in each month. It’s presented in the following table.

Table 6-2: *Work planning from January to June 2010*

Month	*Working days*	*Working hours per day*	*working days per week*
January	*26*	*8*	*6*
February	*24*	‘’	‘’
March	*27*	‘’	‘’
April	*26*	‘’	‘’
May	*26*	‘’	‘’
June	*26*	‘’	‘’

Having all this data, the production planning will be made.

6.2 Aggregate planning

6.2.1 Problem statement

The aggregate planning is going to be made in both cases and the energy cost savings are going to be obtained

From the formulation stated in the section of aggregate planning, each parameter will have the following values:

- i = 1
- j = 1 and 2
- k = 1.
- t = each month from January to June
- $\bar{d}_{it}$ = Demand of products on each month
- a_{ij} = Time required on machine j to produce one unit of product i
- c_{jt} = Capacity of machine j in period t in units consistent with those used to define a_{ij}
- r_i = Net profit from one unit of product: 100€/ unit
- h_i = Cost to hold one unit of product i for one period t= 1€/ unit
- X_{it} = Amount of product i produced in period t
- S_{it} = Amount of product i sold in period t
- e_{ik} = Energy consumption per product i with the route k
- p_t = Average energy price in period t after taxes
- I_{it} = Inventory of product i at end of period t (I_{i0} is given as data)

The objective function is the following:

Maximize $\sum_{t=1}^{\bar{t}} \sum_{i=1}^{m} r_i S_{it} - h_i I_{it} - X_{it} e_{ik} p_t$ *for all k [10]*

And the model is constrained by:

$S_{it} = \bar{d}_{it}$ for all i, t *[1]*

$\sum_{i=1}^{m} a_{ij} X_{it} \leq c_{jt}$ *for all* j, t *[2]*

$I_{it} = I_{it-1} + X_{it} - S_{it}$ *for all* i, t *[3]*

$X_{it}, S_{it}, I_{it} \geq 0$ *for all* i, t *[4]*

The variables are X_{it}, S_{it} and I_{it} and p_t is equal to the average spot price plus ten times energy consumption of the period considered.

The problem is going to be solved with two different objective functions:

- The first one is without planning the energy consumption. That is erasing the energy cost part of the objective function.

$$\sum_{t=1}^{\bar{t}} \sum_{i=1}^{m} r_i S_{it} - h_i I_{it} \qquad [\,11\,]$$

- The second one is with energy cost planning

$$\sum_{t=1}^{\bar{t}} \sum_{i=1}^{m} r_i S_{it} - h_i I_{it} - X_{it} e_{ik} p_t \qquad [\,12\,]$$

6.2.2 Resolution of case 1

The case 1 have been solved with Microsoft Excel SOLVER with the data presented in the following table:

Table 6-3: *Production requirements per months in case 1*

Period	*Accumulated Capacity*	*Accumulate Demand*	*Overall Capacity (Units per month)*	*Overall Demand (Units per month)*	*Average energy price per month (€ per MWh) before taxes*
January	*8320*	*8320*	*8320*	*8320*	*42,21*
February	*16000*	*15820*	*7680*	*7500*	*41,73*
March	*24640*	*24620*	*8640*	*8800*	*39,19*
April	*32960*	*29620*	*8320*	*5000*	*40,04*
May	*41280*	*38620*	*8320*	*9000*	*41,17*
June	*49600*	*43220*	*8320*	*4600*	*43,35*

The production quantities per month obtained with the optimization are the following:

Table 6-4: *Production quantities per month in case 1*

Month	January	February	March	April	May	June
X_t without energy planning	8320	7660	8640	5680	8320	4600
X_t with energy planning	8320	7660	8640	5936	8064	4600

And these production strategies led to the following economic results:

Table 6-5: *Aggregate planning economic results in case 1*

	Revenues Production (profit - inventory cost)	*Energy costs (€)*	*Total(€)*
Without energy planning	*4321160*	*-84566,16*	*4236593,84*
With energy planning	*4320905*	*-84280,61*	*4236624,39*
Differences (with energy planning - without energy planning	*-255*	*285,55*	*30,55*

It can be seen from the table that planning the energy consumption has given an increase of the benefits of 30.55 Euro. It’s not a very big benefit when talking about planning month by month but a remarkable result is that the inventory cost over those 6 months is bigger than the traditional planning.

6.2.3 Resolution of case 2

This case, also solved by Microsoft Excel SOLVER is made with the following data:

Table 6-6: *Production requirements per month in case 2*

Period	*Accumulated Capacity*	*Accumulated demand*	*Overall Capacity (Units per month)*	*Overall Demand (Units per month)*	*Average energy price per month (€ per MWh) before taxes*
January	*83200*	*83200*	*83200*	*83200*	*42,21*
February	*160000*	*158200*	*76800*	*75000*	*41,73*
March	*246400*	*246200*	*86400*	*88000*	*39,19*
April	*329600*	*296200*	*83200*	*50000*	*40,04*
May	*412800*	*386200*	*83200*	*90000*	*41,17*
June	*496000*	*432200*	*83200*	*46000*	*43,35*

The production quantities per Month are the following:

Table 6-7*: Production Quanties per month in case 2*

Month	*January*	*February*	*March*	*April*	*May*	*June*
X_t *without energy planning*	*83200*	*76600*	*86400*	*56800*	*83200*	*46000*
X_t *with energy planning*	*83200*	*76800*	*86200*	*68936*	*71064*	*46000*

And the economic results obtained are the following:

Table 6-8: *Economic results of aggregate planning in case 2*

	Revenues Production (profit - inventory cost)	*Energy costs (euro)*	*Total*
Without energy planning	*43211600*	*-7682831,78*	*35528768,2*
With energy planning	*43199264*	*-7600990,89*	*35598273,1*
Diferences (with planning - without energy planning	*-12336*	*81840,89*	*69504,89*

In this case, It can be seen that the savings are much bigger than case 1. The inventory costs in energy planning case are bigger than traditional aggregate planning but the energy cost are much smaller. This energy cost reduction gives an overall cost saving in the production of 69504.89 €.

6.2.4 Conclusions

From these results, one important conclusion obtained is that an energy oriented aggregate production planning is worth it only in case of high consuming factories. The bigger the energy consumption of the factory, the bigger are the energy cost savings using an energy oriented aggregate planning.

If the energy consumption of the factory is low, there will be a point in which the benefits using the energy oriented aggregate production planning and the traditional aggregate production planning are going to be the same.

It's shown in the following figure, obtained from the simulation previously made:

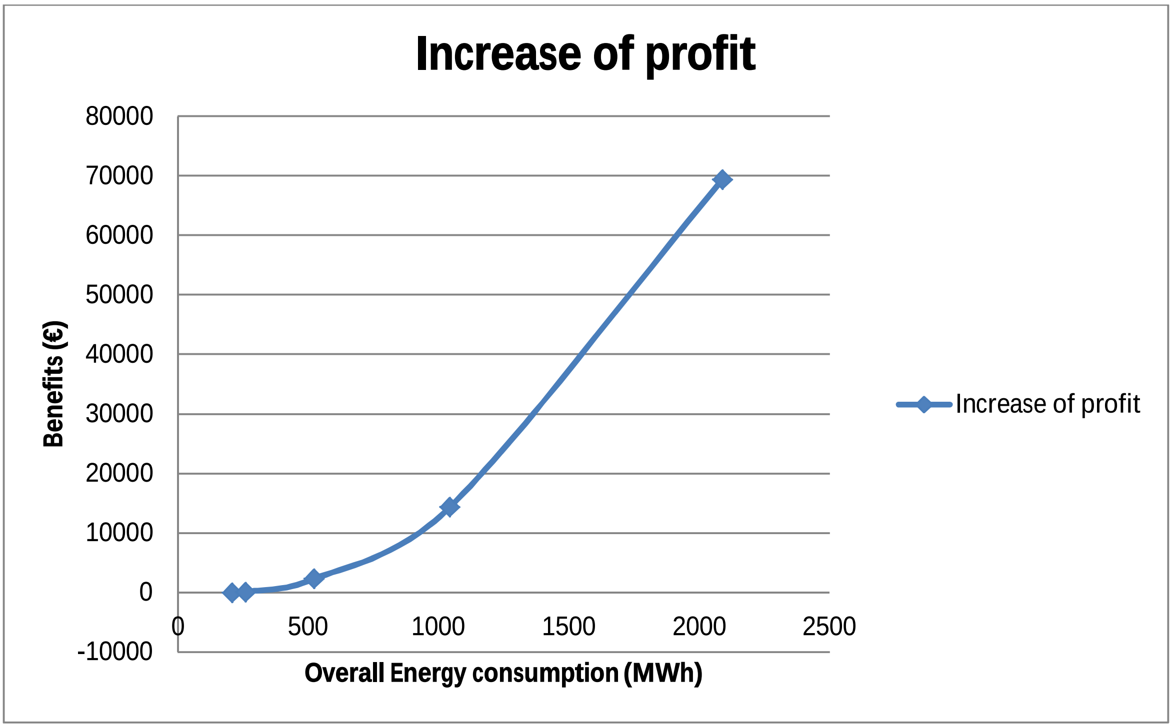

Figure 6-1: *Difference between aggregate planning taking into account energy cost and without taking it into account dependent on the energy consumption of the factory*

In the figure can be seen that when the overall consumption of all planning periods considered as a whole is gets high, the energy savings are higher.

6.3 Scheduling: Lot sizing

6.3.1 Problem statement

As stated in previous chapters, the next step of aggregate planning is the MPS and MRP, where the demand is disaggregated and as a consequence, the production orders are released in order to satisfy the demand.

In this chapter an extension of the algorithm of Wagner-Whitin is going to be developed for the two cases exposed at the beginning of this chapter.

The following data will be needed for one product:

- t = time period. In this case, the periods are going from week 1 to week 8 corresponding to February and March 2010
- D_t = the demand over the period t
- C_t = production costs in monetary units per unit. In this case, production costs will be 10€
- A_t = setup cost to produce a lot in period t in monetary units. In this case it will be 10000 € per setup
- h_t = inventory cost of a unit over a time period. In this case, it will be 0.2 €
- I_t = inventory quantity at the end the period.
- Q_t = Lot size in period t
- p_t = Average energy price in period t after taxes
- e_i = Energy consumption per product
- B_t= Binary number that indicates whether a lot is produced in period t or not.
- K_t =Capacity of the factory in week t

The formulation of the problem is the following:

1. Objective function is:

   Minimize $\sum_1^t (Q_t C_t + A_t + Q_t p_t e_i) B_t + (I_t\, h_t)$ *[13]*

2. Constraints

$I_i = I_{t-1} + Q_t - D_t$ *for all* t *[14]*

$Q_t - K_t\, K_t \leq 0$ *for all* t *[15]*

B_t binary

$Q_t, I_t \geq 0$ *for all* i, t *[16]*

In this model, the variables are $\mathrm{Q_t}, \mathrm{I_t}$ and B_t and also p_t is equal to the average spot price plus ten times energy consumption of the period considered.

As happens in the previous section, the problem is solved with two different objective functions:

- The first one is without planning the energy consumption. That is erasing the energy cost part of the objective function.

$$\sum_1^t (Q_t C_t + A_t) B_t + (I_t\, h_t) \qquad [17]$$

- The second one is with energy cost planning

$$\sum_1^t (Q_t C_t + A_t + Q_t p_t e_i) B_t + (I_t\, h_t) \qquad [18]$$

6.3.2 Resolution of case 1

Having the model stated, the data related to the case 1 is presented:

Table 6-9: *Production requirements per week of case 1*

Period (week)	*Accumulated Capacity*	*Accumulated demand*	*Capacity per week*	*Demand of each week*	*Energy prices before taxes € per MWh*
1	*1920*	*500*	*1920*	*500*	*43,52*
2	*3840*	*2500*	*1920*	*2000*	*48,25*
3	*5760*	*3500*	*1920*	*1000*	*45,16*
4	*7680*	*3600*	*1920*	*100*	*36,44*
5	*9600*	*3900*	*1920*	*300*	*38,88*
6	*11520*	*7900*	*1920*	*4000*	*48,15*
7	*13440*	*10400*	*1920*	*2500*	*41,04*
8	*15360*	*11400*	*1920*	*1000*	*36,58*

This data in combination with the inventory cost, setup cost and production cost gives the lot sizes of every week distinguishing between with and without energy planning:

Table 6-10*: Optimal Lot sizes for every week in case 1*

Week	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Q_t without energy planning	*580*	*1920*	*1000*	*1140*	*1920*	*1920*	*1920*	*1000*
Q_t with energy planning	*1060*	*1440*	*1000*	*1329*	*1731*	*1920*	*1920*	*1000*

This different strategies lead to the following economic results and benefits:

Table 6-11: *Economic results of Wagner-Whitin in Case 1*

Results	*(production+ setup+ inventory) cost €*	*Energy cost €*	*Total Cost €*	*Cost reduction €*
Without energy planning	*194872*	*6648,34*	*201520,34*	*124,46*
With energy planning	*195005,81*	*6390,06*	*201395,87*	

For the factory of case 1, a reduction of overall cost of 124.46 € is obtained by using this adaptation of the Wagner-Whitin procedure. The savings are not so big because the amount of energy spent is not that big.

6.3.3 Resolution of case 2

The data for the case 2 is the following:

Table 6-12: *Production data case 2*

Period (week)	*Accumulated capacity*	*Accumulated demand*	*Capacity per week*	*Demand per week*	*Energy prices before taxes € per MWh*
1	*19200*	*5000*	*19200*	*5000*	*43,5*
2	*38400*	*25000*	*19200*	*20000*	*48,25*
3	*57600*	*35000*	*19200*	*10000*	*45,16*
4	*76800*	*36000*	*19200*	*1000*	*36,44*
5	*96000*	*39000*	*19200*	*3000*	*38,88*
6	*115200*	*79000*	*19200*	*40000*	*48,15*
7	*134400*	*104000*	*19200*	*25000*	*41,04*
8	*153600*	*114000*	*19200*	*10000*	*36,58*

In this case the lot sizes obtained in both cases are the following:

Table 6-13: *Optimal Lot sizes for every week in case 2*

Week	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Q_t without energy planning	*5800*	*19200*	*19200*	*19200*	*19200*	*19200*	*19200*	*0*
Q_t with energy planning	*13568*	*13947*	*14407*	*14926*	*15328*	*15661*	*16162*	*10000*

And the economic results obtained from the model are presented in the next table:

Table 6-14: *Economic result of Case 2 with Wagner-Whitin extension*

Results	*(production+ setup + inventory) cost*	*Energy cost*	*Total Cost*	*Cost reduction*
Without energy planning	*1227160*	*496849,4*	*1724009,4*	*78901,05*
With energy planning	*1236174,01*	*408934,34*	*1645108,34*	

In this simulation, the cost reduction for this 8 periods are very big. As happened in the previous parts, the cost related to inventory, setup and production are bigger in the case of energy planning but it's compensated with really great savings in energy costs.

6.3.4 Conclusions

In this part, an optimization of the lot sizes is made. It can be shown that the more energy consumer the factory is, the more cost savings have been obtained.

It can be derived from the past simulations that the smaller the planning period is, the bigger savings are achieved. This is logic because these simulations are done this average energy prices so the average energy prices between months are going to be more similar than energy prices between weeks due to the amount of data used to make each average.

If production planning in machine level is made, big energy savings can be achieved too.

7 Summary, Conclusion and Outlook

In the process of developing this thesis, some important contributions to the production planning have been generated. The first has been the bibliographic compilation where all the global trends on the production planning including energy consumption during production have been collected as well as the energy KPIs to describe and control energy consumption and energy efficiency in various sectors and specially focusing on manufacturing.

As an innovative approach, the energy consumption and energy prices are introduced in every level of production planning, from aggregate production planning to machine level scheduling. Some Linear programming algorithms have been developed taking into account jointly the usual production planning targets of time and costs with the optimal energy consumption strategies taking into account the energy prices per time period evaluated.

This approaches presented are going to be suitable for production systems that are flexible, like job shops and FMS. In assembly lines and continuous flow lines, these approaches are impossible to be implemented due to their lack of flexibility. The main objectives of this technics are to reduce the overall production cost and hence obtain more benefits

In order to prove these concepts, a practical case of production planning has been developed. The procedure was to assess the economical results of an aggregate planning and Lot sizing model taking into account the energy prices and compare them to the results obtained by the traditional production planning methods. This economical assessment has been made in two different cases in order to evaluate the cost saving potentials depending on the amount of energy consumed by factories.

The results obtained are very interesting. First important conclusion is that in every production planning level, more savings are going to be achieved if these methods are introduced in factories with high energy consumption. If a factory with low energy consumption is considered, small benefits are obtained and if a high consuming factory is considered, big benefits are obtained. At the end, a proposal of a machine level planning is stated and an interesting continuation to this thesis would be to formulate a multi-objective optimization taking into account more factors important in production planning such as minimizing the makespan.

With the purpose of consolidating this theoretical proposal, some new fields of research are going to be proposed.

First of all, an assessment of the cost that implies implementing this strategies in terms of resources(like additional control systems) and organization in order to compare them with the savings expected to be achieved an value if it’s worth it or not.

Another investigation would be to asses in which energy prices rates it's worth it to implement these strategies by comparing the savings obtained on each case.

On the other hand, these approaches are implemented assuming that the RTP prices are known. But in reality, those prices are uncertain. So another line of research would be to try to predict the energy prices in advance so a mid-term planning a short-term planning is possible to be made.

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Inhalt der Daten-CD

- Electronic version of the Master thesis
- Literature used to write this thesis
- Excel data to perform the Show case

Eidesstattliche Erklärung

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Ich, Iñigo López Martínez, erkläre hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt.

Garching/Augsburg, den 14.10.2014

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