MASTER

# Design of a control structure to determine tactical parameters with resources of limited capacity

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# Design of a control structure to determine tactical parameters with resources of limited capacity

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# *Abstract*

The increasing volatility of customer demand, increasing consumer expectations about service, product quality and the constant pressure to reduce costs in logistics represent some of the challenges faced by pharmaceutical supply chains. In this environment, we address the problem of determining a production planning and control system in a complex multi-item, multi-stage and multi-resource system with limited manufacturing capacity. The lack of the determination of tactical parameters that are consistent with the environment characteristics often lead to conflicts. These tactical parameters are the result of an aggregate planning that is responsible of the creation of conditions so that at a detailed level we do not meet unsolvable problems, but if relevant factors of the detailed level are not considered, the aggregate plans becomes unfeasible or unrealistic. As a result, a problem in the operation and in capacity requirements at an aggregate level and at the detailed scheduling level is faced. Specifically, this thesis provides an approach to determine two tactical parameters. The first one is lot sizes taking into consideration the capacity and the interaction among the allocated items to a resource, leading to effective use of capacity. The second tactical parameter determined are the safety stock levels through an order-up-to-level policy that considers uncertainty and the distribution of the demand during the uncertainty period consisting of the cycle time and the order queue time to meet a predefined customer service level.

# *Preface*

This report is the result of my master thesis project in order to fulfill my master degree in Operations, Management & Logistics at the Eindhoven University of Technology.

First, I would like to thank my supervisor at the university Prof. dr. Ton de Kok for his support and guidance during the project. I appreciate all the feedback and time spent to answer my questions, even with a full agenda and tight schedule. I find myself very lucky to have worked with him and to have had the opportunity to confirm first hand why he is one of the top professors at the university. And to my second supervisor dr. Zümbül Atan, for the time dedicated to my work.

Also, I would like to thank to the people at the company. To John Koelink who made this project possible, because even with the small road blocks that we faced to start on time, he helped me to make things happen. To Stefan Bokstaller, for taking the time to introduce me to the company. To my direct supervisors Jennifer Hain and Patrick Leonhardt, who believed in me and where willing to give me feedback whenever it was necessary. I can truly say you two made my stay in Kiel very pleasant. A word of thanks to the colleagues in the Supply Center as well, for having the patience to explain the details of the operation in a mix of English and German language. And to all of them for showing interest in my project.

To my friends in Mexico and in Eindhoven who were willing to listen whenever I needed to talk to someone. Thank you for the continuous encouragement. I feel very lucky to have you in my life.

Last but not least, I would like to thank to my parents, my brother and Daniel. Thank you for those long Skype talks and for remembering to me that even though you are miles away, your love will always be unconditional and that you are there for backing me up when needed.

Diana Luna

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# *Management Summary*

The purpose of this project was to design an operation and control structure supported by the determination of tactical parameters through models that were able to capture the systems characteristics. These tactical parameters concern lot sizes and safety stock.

Currently the company is facing several problems to fulfill the upcoming sales orders and resources at the supply center are constantly working at a 100% of capacity, leaving no opportunity to cope with variability or unpredictable events. This is mainly caused by not having a control parameter that regulates the utilization of the resources. Therefore the first tactical parameter that was determined was the lot size.

The second parameter calculated was the safety stock level through an Order-up-to-level policy. At present, the company determines this parameter through an agreement with the affiliate customer based on the forecast accuracy performance and the resulting service level from previous periods. Mostly, the safety stock for each customer is set equal among the product portfolio to the same time supply. This approach is certainly wrong since it doesn't consider the uncertainty of forecast of every item.

Explicitly, this thesis provides insight into the design of a control structure that can address the following hypothesis:

*Hypothesis 1: The implementation of a heuristic for setting tactical parameters will maximize the output at the technology selected.*

*Hypothesis 1.a: Optimization of lot sizes per production line with the consideration of capacity, will lead to effective capacity utilization.*

*Hypothesis 2: Calculation of safety stocks based on lead time, demand variability and requested service level, will provide the necessary buffer to satisfy customers demand.*

## *Diagnosis*

The approach to manage this project was based on the analysis of the most relevant entities in the system. This allowed us to decompose a large and complex system and perform a diagnosis on each business function to gain insight into the state of the system. The business functions that were part of the diagnosis phase were supply and production planning, quality control, workforce planning, information systems and the manufacturing system.

From the supply and production planning function we identified that the activities of setting lot sizes was missing and the safety stock calculation was lacking adequate support to consider uncertainty that differs from item to item.

From the quality control module we confirmed that quality losses were not significant in the system, since the rate of rework and rejection is very low. Furthermore, the lead time to perform and have the results of the quality test is not an issue either, since the production planning of each production unit is delayed by at least 2 weeks due to a queue waiting time.

From the workforce planning module we identified that the available number of workers per week is slightly below of what is required to operate the manufacturing system. These figures alone do not make a clear statement about a correlation between low throughput and available workforce. Rather, we can conclude that the plan is efficient but not effective for an environment with high variability demand since there is no buffer to cope with such changes.

Finally, the analysis of the manufacturing system resulted into three performance measures: Overall Equipment Effectiveness, throughput and utilization. These measures gave us insight into the bottlenecks of the system. From these manufacturing system analyses we can conclude that the filling lines with small pipettes are considered as bottlenecks because of the high utilization and low throughput. In the packaging lines, the production lines that share the sizes of small and big are highly utilized and have a lower throughput compared to the other lines. Because the production process is sequential, we can argue that the low performance in the filling production unit influences starvation or late deliveries in packaging since low inventory is kept between these two phases.

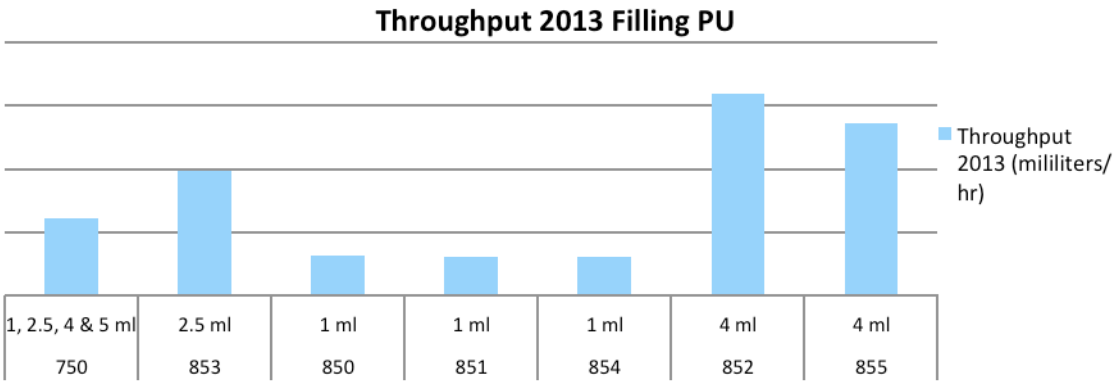


Figure 1. Throughput 2013 Filling PU (ml/hr)

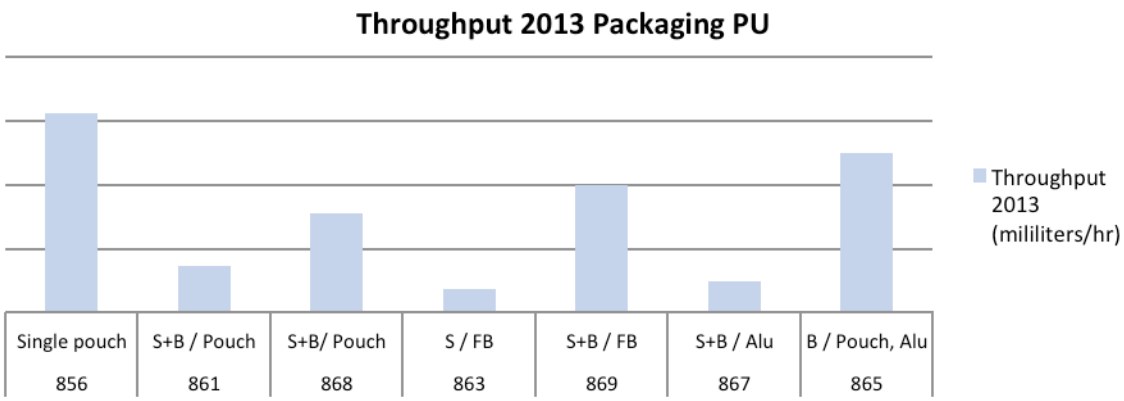


Figure 2. Throughput 2013 Packaging PU (ml/hr)

Moreover, the Overall Equipment Effectiveness measure showed that availability is the component with lower score in comparison to World Class standards in this measure (Figure 3).

Availability is defined as the operating time left after down time losses are considered like breakdowns and setups. The large setup times and frequent changeovers in both production units affect directly the Availability component therefore it was identified as an opportunity area.

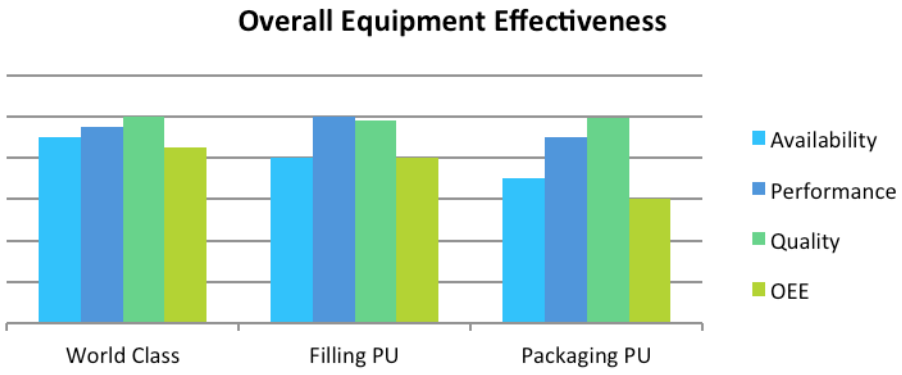


Figure 3. Overall Equipment Effectiveness Comparison

The identified bottlenecks in the system, along with the analysis of the manufacturing system provided the necessary information and insight to design a solution to the current situation.

## *Design*

The designed solution was structured into two parts. First, a procedure to solve the problem for determining the adequate lot sizes with a capacity constraint; and second a model that integrates demand variability during a period of time to fulfill a specific service level.

The approach to solve the production quantity for a multi-item, single-resource with capacity constrains problem is based on the application of a 5 steps heuristic, jointly with a lot size optimization model. These lot sizes were optimized taking into account the allocated items per resource and the different process time, setup times, holding cost and setup cost. This approach is able to include the *hard* constraint of resource capacity and spread the available capacity among the items, based on a cost function as well. Therefore the most relevant information is included in the calculation, which concerns demand, cost and capacity information.

The second model is an order-up-to-level model that considers the uncertainty and distribution of the demand during a time period L. The stochastic behavior is included in the variability of demand and the variability of the lead time. The length of the lead time is determined by the production cycle time and the transit time from the supply center to the affiliate customers. Through statistical planning of safety stocks it is possible to leverage the capabilities of the company to allocate inventory were it is necessary.

## *Conclusion*

This thesis provides an outline of how to approach a complex problem influenced by different subsystems and to identify bottlenecks or flaws on them. Each subsystem was evaluated separately and the design of the solution was guided into the direction of those subsystems with worst performance. The main flaws that were identified were the determination of the tactical parameters, which are responsible for the control of production and the service to be provided.

Moreover, based on the executed diagnosis, we propose two models for the calculation of tactical parameters that were not well supported through models that consider the main characteristics of the environment. With the implementation of a lot size optimization procedure it was possible to release time spent in setups. Therefore throughput is maximized, variability in effective time is reduced and cycle time decreases as well.

The second tactical parameter that was calculated was the safety stock by means of an order-up-to-level model. This model is able to provide the right buffer to cope with the variability of demand and to achieve a determined objective in terms of service level. More stock is allocated to those items with more fluctuations in the forecast, more variation in the lead time and that expect to meet a high service level. Compared to the method that is actually used to define the safety stocks, the proposed inventory model is an opportunity for improvement. This model does include the most relevant characteristics of lead time, demand variability and expected service level, therefore the parameterization and calculation of this last tactical parameter is more accurate.

Finally, the methodology developed has been carefully documented based on data from the pipettes technology of the company but can be applied routinely to other product categories in the same company or in the pharmaceutical industry, where lot sizes and safety stocks have to be reconsidered.

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# 1. Introduction

In this chapter, we give the background of the company where this project was performed. Then, the motivation and scope of the project agreed with the company is stated. Next, the methodology used to conduct this research work is explained, and finally at the end of this section we give an outline of how this thesis report is structured based on the research methodology that was used.

## 1.1. Company Background

Confidential.

## 1.2. Project description

### 1.2.1. Motivation

During the last year the service provided by the prime supply center in the company has been under the specified target of 90%. This service level corresponds to the number of orders delivered within a period of ±7 days from the goods issue date, calculated by the ERP system and based on the required delivery date from customers at different countries. Sales orders are delayed and this has created dissatisfaction among sales department and the whole business. At the same time, demand has grown and volatility remains. The product portfolio is constantly growing representing an increment in change overs. This increment in product portfolio brings more pressure on the limited machine capacity to fulfill the incoming sales demand in the supply center. Therefore, this master thesis project was performed in a production and logistic center from the pharmaceutical industry, with the objective to provide a solution that could help to achieve performance improvement on the service provided to the rest of the organization.

Considering the lost sales from the last year, this project has a potential for improvement of €XXX,XXX in additional revenue.

### 1.2.2. Project Scope

Within the prime supply center of the company, four production plants are installed with different types of technology. For the case of AH the product portfolio is classified into four technologies that correspond to pipettes, tablets, liquids and injection molding (also referred as collars). The more relevant technology to this day is pipettes, which sales constitute around 40% of the total business. Hence, the scope of this thesis was narrowed to such technology.

As stated in the previous section, the supply center is currently not providing the required service to satisfy sales orders (timing and quantity). Orders are continuously postponed, triggering intense discussion with business about lost opportunities. Through semi-structured interviews a cause-effect diagram was constructed, where a set of problems that influence the low service level were identified (see Figure 15 in APPENDIX I). From that group of problems the

project was focused on the realm of planning and control processes in capacitated resources named as machine or workforce. Thus the main focus of the project was on the Supply Chain Planning department and its activities.

The provided solution was based on data from the pipettes technology, but with the mind set of being able to extend it to the rest of the technologies or for similar industrial processes.

### *1.2.3. Research Method*

The methodology used to conduct this project was based on the regulative cycle (Figure 4), with the intention to solve a specific problem in practice. This regulative cycle is a solving process guided by design rules that enables research to develop prescriptive knowledge in the form of field tested and grounded solution concepts through a learning cycle. The key elements of this method are its iterative and exploratory nature to collect information and knowledge and to select the method or tactic to perform analysis, until a satisfactory solution is materialized.

The research methodology is composed of six phases, integrated into the reflective cycle from Van Aken et al. (2007). The two first phases of the regulative cycle took part at the very beginning of the project, where the problem and scope of the problem were discussed along with the company. The *diagnosis* and analysis took place through extensive data collection of planning parameters such as safety stock policies, quality control, production planning and workforce planning. This phase helped us to construct an As-Is scenario of the entire system. After the As-Is scenario was created and bottlenecks were identified through quantitative analysis, a *design* of a planning and control structure took place. *Implementation* was out of the scope of this project, however a proof of concept was delivered.

After the conclusion of the project, reflection about the results, the design and the usefulness of the solution provided took place.

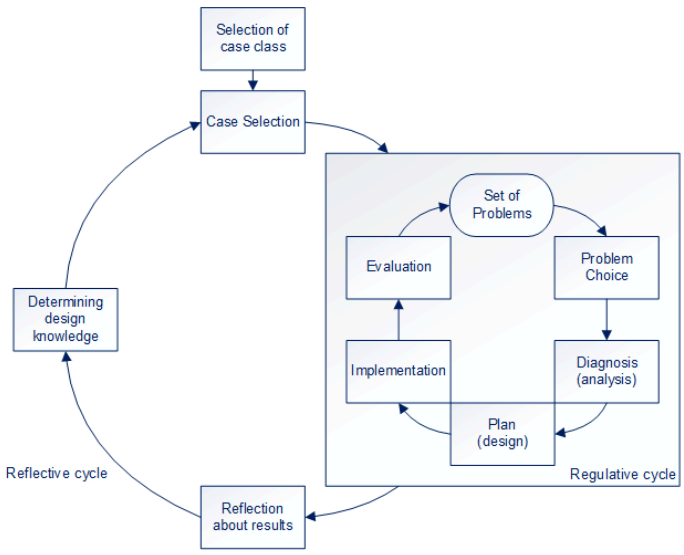


Figure 4. Reflective cycle (Van Aken et al. 2007)

### *1.2.4. Thesis Outline*

The report is structured as follows: in section 2 we provide the literature studied to give the theoretical framework of this research project in a real case problem. In section 3 the *diagnosis* and analysis of the relevant business functions is presented. In section 4 the new *design* of the operations and control structure is described, along with the numerical results of the solution. Section 5 explains the conclusions of this project and section 6 gives insight on the designed solution and its applicability to generalized situations. Finally section 7 gives insight into further research areas into the same case study or similar to the same kind of industrial process.

# 2. Literature Review

During the development of this project, four relevant fields in the academic literature were studied. Based on the initial interviews conducted in the company and the defined scope, these topics were identified as relevant to provide a concrete solution to the problem since the design and management of these processes determine to which extent the supply chain meets required performance objectives. The first field of study was production planning strategies, which considers the capacity available in production facilities and the coordination to release production orders in an efficient way. Queuing theory, presented as an evaluation model for a given set of decisions in manufacturing systems and operational problems. Inventory control, for the management of the storage policies for the final products. Lastly, the design of logistic control systems was studied in order to analyze supply chain problems and to structure a proper solution of such complex systems and fulfill the functional requirements in an organization.

## 2.1. Production Planning Strategies

In process industries, where the pharmaceutical sector is positioned, production systems can be classified as continuous and batching. Furthermore, the structural elements of multi-item, multi-stage, multi-resource and sequence-dependent set-up times also drive the type of solution to be formulated (Kallrath, 2002). The literature under this subject is extensive and solutions to the production planning problem are formulated considering some of the structural elements previously mentioned, and a deterministic or stochastic resemblance to the environment. In this section we will mention some of the more relevant problems.

Production planning encounters two main constraints when determining the production quantity. The first one is the available capacity in the production facility and the second one is the coordination to release production orders in an efficient way. Under these characteristics, block planning has gained considerable attention for determining production orders. A block is the representation of production orders released in a pre-defined sequence. The production size per item in the block is variable in time and is allowed to take place once per cycle ($T$) with finite length ($L$), which limits the time available to complete the production cycle. The production of blocks is repeated in a cyclical manner through the planning horizon. Günther et al. (2006) presented an implementation of block planning under continuous representation of time, based on a mixed-integer linear programming formulation (MILP). The MILP can be formulated with different objectives as: minimization of total costs per setup and inventory holding, minimize unfilled demand, minimization of makespan or maximize profit of the products sold. Nevertheless, there is no general objective function that can converge in an optimal solution for all the objectives. Therefore priorities and specific objective functions have to be defined. An important variable to be considered is the stochastic behavior of demand in process industries. In block planning this is managed by the minimization of makespan, i.e. the time after which the complete set of products in a block is completed. Then a buffer in time is created after the completion of a block, unproductive setup times are decreased and flexibility to react to demand changes is increased in this way.

The second branch of research studied was the Economic-lot scheduling problem (ELSP) and its stochastic version named as Stochastic Economic-lot scheduling problem (SELSP). The aim is to determine the lot size in a cyclical scheduling policy for several products in a single machine at the lowest cost (Rogers, 1958). Since then, several analytical solutions with specific assumptions have been developed, but still ELSP is considered a NP-hard problem (Chan et al., 2013). Therefore, the employment of heuristic approaches to find close-to-optimal solutions has been studied (Huang and Yao, 2008; Raza and Akgunduz, 2008; Brander and Segerstedt, 2009). Since ELSP is a deterministic model representation, it can only be applied under ideal situations (Gallego, 1990), hence the stochastic version of the problem is considered as well. In this type of problem, production capacity is dynamically distributed among products in order to react to stochastic demands, processing and setup times. The production sequence can be dynamic or fixed, in combination with a dynamic or fixed cycle length. Moreover, the lot-sizing policy can be calculated as a *global* policy, where the size of the lot for each product depends on the state of the system, i.e., state of the machine and mix of items with different processing times and yield in the manufacturing resources. Alternatively it can be calculated as a *local* policy, where the lot-size depends only on the stock level of the product (Winands et al., 2010).

A third production planning strategy that is relevant to mention is the capacitated lot sizing problem (CLSP). In this case, timing and lot sizes are calculated for several products that share a single capacity constrained resource. Cost and demand can vary over a finite horizon and it does not include job sequencing, as in the case of SELSP. Therefore sequencing can be left to detailed scheduling shop floor control systems. CLSP are classified based on the solution method that can be: exact methods, specialized heuristics and mathematical programming-based heuristics. Within the last classification, the procedure that relies upon a Lagrangian relaxation for the capacity constraint is commonly used (Trigeiro et al., 1989). The solution provided by mathematical programming heuristics is usually better in quality and it provides lower bounds on the optimal solution cost (Karimi et al., 2003). By means of a Lagrangian multiplier, the problem is decomposed into a set of uncapacitated single product lot sizing problems. The lower bound of the problem can be calculated by a simple Economic Production Quantity (EPQ) problem, which leads to optimal production quantities for the constrained resource and for every single product allocated to each machine.

The last branch of research studied in this topic was the stochastic capacitated lot sizing problem (SCLSP). As in the SELSP it is the stochastic version of the CLSP. Demand is considered as a random variable with a given probability distribution. The approach of this problem is with the analysis of queuing systems that are able to include the stochastic behavior of the demand by means of the arrival process. Furthermore, the service discipline of the model determines the amount of orders that can be produced in one visit per queue. Smits et al. (2004) presented an efficient approximate algorithm in the development of the first two moments of the waiting time with accurate results especially for high loads. The objective is to determine the time it takes to fulfill the replenishment orders in the queue. The type of interarrival distribution is modified, showing no impact in the results, nevertheless traffic intensity and squared coefficients of variations in the service time do affect the model. Winands et al. (2009) analyzed a two polling system, one with a high priority product in an exhaustive service, and a low-priority

product gated to a k-limited service or production run. The latter is limited to serve a k number of products or until the queue is empty, whichever occurs first. The results from the authors present a reduction in time and cost (holding and backlogging costs) using a k-limited service in a make-to-stock production setting, especially in the cases with high demand rates and short setup times.

## *2.2. Queuing Theory*

The second topic studied for this project was queuing theory in order to account for more stochastic characteristics of manufacturing systems. We know that production systems are subject to variability in every step of the process. Variability can be defined as anything that causes the system to depart from a predictable behavior. The ability to measure, understand and manage variability it is critical for effective manufacturing management (Hopp and Spearman, 2001). Sources of variability can be setups, machine failures, product differentiation, or operator unavailability. The coefficient of variation is a key measure of variability, and can be classified in low, moderate and high (Table 1).

| Variability Class | Coefficient of Variation | Typical Situation |
|---|---|---|
| Low (LV) | $c < 0.75$ | Process times without outages |
| Moderate (MV) | $0.75 \leq c < 1.33$ | Process times with short adjustments (e.g., setups) |
| High (HV) | $c \geq 1.33$ | Process times with long outages (e.g., failures) |

Table 1. Classes of Variability (Hopp and Spearman, 2001)

Queuing theory is defined as the science of waiting and is able to capture the variability in manufacturing processes and to characterize it into descriptive parameters as waiting time, utilization, work in process, throughput and cycle time. Due to this parameterization ability, queuing theory is more appropriate when several what-if situations need to be analyzed, or when insight is required about relation between variables (Gautman, 2008) like batch size, waiting time or utilization. Queuing systems make use of Kendall's Classification and by the notation A/B/m the arrival process (*A*), service process (*B*) and number of machines (*m*), are specified (See Table 17 in APPENDIX 1 for extended fields in the Kendall Notation).

The Queuing Network Analyzer is a heuristic that helps to approximate congestion measures for a network of queues. The advantage of this heuristic is that external arrival process need not to be Poisson and service time does not need to be exponentially distributed. Rather, the heuristic approximately characterize the arrival process and the service time distribution with a variability parameter (Whitt, 1983). The nodes are analyzed as a GI/G/m, open network, no capacity constraints, single server and First-Come, First-Served discipline. The superposition operation is applied in the arrival processes, and is based on the hybrid approximation method. According to Albin (1984) this method performs better with a 3% of error in the expected number of the queue, in comparison with a 20-30% from other approximations of the arrival process (Whitt, 1982).

## 2.3. Inventory Control

Because demand is seldom deterministic and processes are corrupted by means of variability, safety stock levels and control systems should be designed in order to cope with such uncertainties. Control policies in regard to inventory management should address 3 questions, (1) how often the inventory status should be determined, (2) when the replenishment order should be placed, (3) how large should this order should be (Silver et al., 1998). The most common control policies are depicted in Table 2, along with a recommended application according to the item´s importance in terms of dollar sales volume.

| Item Classification | Continuous Review | Periodic Review |
|---|---|---|
| A items | (s,S) | (R,s,S), (R,s,Q) |
| B items | (s,Q) | (R,S) |
| C items | (s,Q) | (R,S) |

Table 2. Rules of thumb for selecting inventory policy (Silver et al., 1998).

Whenever the ordered quantity is fixed (*Q*) or variable to an order-up-to-level (*S*), shortage and surplus of stock should be minimized through specific cost and service objectives. For the calculation of safety stocks based on a service level, two methods are the most commonly used (Silver et al., 1998). The first one account for the probability of no stock out per replenishment cycle (*P1*) and the second one is the amount of demand satisfied from the shelf, also called fill rate (*P2*).

Another important parameter that should be considered when calculating reorder point or order-up-to-level, is the variability during a period of time. Generally this period of time can be decomposed into the replenishment lead time and the time it takes to ship the product from the manufacturing site to a stocking point. Bagchi et al. (1986) proved with numerical examples and a case study, that variability during lead time should be considered when calculating safety stocks, in order to fulfill the service required. This is mainly important when there are long transportation lead times, like shipments overseas. In the case of replenishment lead time, it should be such that the manufacturing site is able to react and provide with the required amount of product. Smits (2003) states that this replenishment lead time should be considered as an endogenous variable. An endogenous variable is a variable that is influenced by the planning model by means of tactical decisions as changes in the distribution network or in the production schedule, i.e., highly utilized machines have longer waiting time. Therefore, it should be possible for the manufacturing site to control this lead time and provide a more accurate value of this variable.

## 2.4. Design of Control Systems

The last topic covered in this literature review is referred to the design process of the logistics control system. Design is defined as the creation of synthesized solutions in the form of products, processes or systems that satisfy needs between functional requirements and the design parameters of the physical environment (Suh, 1990). In literature we can find numerous

methods and techniques for production decisions making, but little attention has been given to the design process itself. Bertrand et al. (1990) presented design questions as a framework in the design process based on principles regarding goods flows control and production unit controls; the distinction between detailed item-oriented control, aggregate control and capacity-oriented control. In the realm of goods flows control the Supply Chain Operation Planning model (SCOP) was studied. In this model the planning of operations is integrated by control functions and parameters setting that regulate the amount of work accepted by the supply chain (de Kok and Fransoo, 2003). These control functions are in charge of the coordination over time of operations that consume materials and resource capacity. Taking into account these aspects in the design of a production control structure and the literature described in section 2.1, 2.2 and 2.3, we established the foundation to provide a complete and comprehensive solution to the defined problem.

# 3. System Diagnosis

This section contains information about the *diagnosis* and *analysis* of the most relevant systems in the Supply Center. These systems were identified as causes that influence our current problem (see Cause-Effect Diagram in APPENDIX I). This analysis was divided into different sections. The first part describes the phases of the manufacturing process so the reader can understand the structure of the goods flow. Next, we outline the supply chain planning process and the decision functions within this department. Thereafter, the business functions of quality control and workforce planning provide information beyond the scope of the activities related to the supply chain department but that still are relevant for the overall system. Then, an overview of the information systems that supports the planning and production operation is described and finally a detailed evaluation of the actual state of the manufacturing system is given at the end.

## 3.1. Manufacturing Process

The Supply Center comprises four production plants, but most of the pipettes´ manufacturing process takes place in plant number 2. The production process consists of three phases. It starts with the production of the solution, also referred as formulation and is located in plant 1, then the solution is carried to the next production unit (PU) called filling, located in plant 2 and as final step pipettes are packed into blisters and/or pouches that goes into folding boxes, also located in plant 2 (Figure 5).

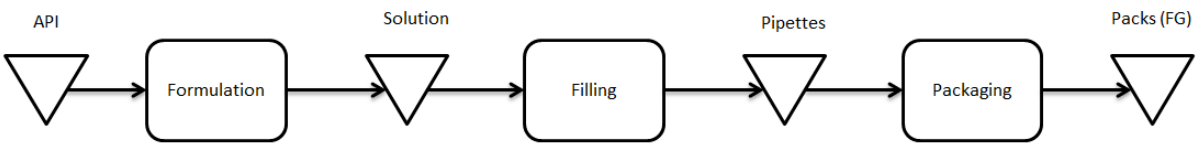


Figure 5. Pipettes' production process

### 3.1.1. Formulation

The formulation process takes place in three tanks that are used mostly for pipettes´ solution. The principal raw material is the Active Pharmaceutical Ingredient (API), which is stored at the local warehouse. Most of the API´s purchases are centralized in headquarter to have the advantage of economies of scale. The capacity of the tanks are: 100 lts., 5,000 lts, and 10,000 lts. After the solution is processed, it is stored in small tank pallets of 500 liters. It is important to mention that this is the most expensive part of the process due to the API's cost; therefore storage after the formulation is kept as low as possible.

### 3.1.2. Filling

The next phase is the filling process where seven production lines are fed by small moving tank pallets of 500 liters from the formulation phase. The filling quantities can be 0.23 ml, 0.3 ml, 0.35 ml, 0.4 ml, 0.5 ml, 0.7 ml, 0.8 ml and 1 ml, which correspond to the classification of small pipettes. The rest of the sizes are 1.6 ml, 2.5 ml, 3.2 ml, 4 ml and 5ml, and belongs to the

classification of large pipettes. Four of the seven production lines can produce small pipettes; two are kept to fill in big pipettes and one produces a mix of small and big pipettes. From the technical point of view, most of the lines can produce all the sizes but this is constrained by the available tooling to be used by each production line. The materials used in this step are the solution, tubes and the labels for the tubes. After the pipettes have been filled these are transported to the warehouse in bags.

### 3.1.3. Packaging

For the last part of the process pipettes are packed in seven production lines into three different packaging configurations: a blister packed inside a folding box, a blister inside a pouch that finally goes into a folding box, or only a pouch packed inside a folding box. Furthermore, the number of pipettes inside a blister or pouch can be 1, 2, 3, 4 or 6. Nevertheless, not all the machines can pack the different configurations of size, number of pipettes and type of packaging material. The materials employed in this step are folding box, insert, display, foil and outbox. After this phase is completed, the finished goods are transported to the warehouse where they are kept until the Logistics department starts to process the order for its shipment.

In all phases, production is released in batches by means of a *process order*. The process is characterized by long setup and cleaning times, therefore a predefined production sequence exists that aims to minimize the time of changeover from one product to other. Before starting a process order a setup is performed, which can include change of tooling and software adjustments in the machine; then at the end of each production order cleaning is performed, which accounts for removing all packaging material and cleaning of the solution in the case of the formulation and filling production unit. Both setup and cleaning time, are incurred in every change of product and therefore in this project are managed as one setup time made up by the sum of both. Due to different manufacturing conditions, the batch sizes are different for each phase, as well as setup time and process time.

## 3.2. Planning Process

### 3.2.1. Forecast and Release of Orders

Two systems are in place that support the production and distribution planning of the Supply Center. The timeline of the interaction of activities and systems is represented in Figure 6. The first system is called SAP Advanced Planner and Optimizer (APO), which provides the toolset to plan supply chain processes in strategic, tactical and operational planning levels (SAP AG, 2000). First, forecast and sales orders from all the different customers are consolidated on a monthly basis. Both have to be in APO in the last working day of each month. The new orders correspond to the 3rd month and forecast from the 4th month onwards, until 3 years of planning horizon is reached. Shipments for new orders are consolidated per customer and released once per month; therefore deliveries take place in the third month too. This scheme implies 3 to 4 months of lead time to fulfill sales orders, depending whether the shipping bucket corresponds to the beginning or end of month three.

Then, during the first week of the month the Supply Network Planning (SNP) heuristic in APO determines a short to medium term plan to fulfill this demand. SNP heuristic considers stock at the customer side if it is available for calculation of the net demand and the resulting orders. If inventory information is not available then orders are created automatically based on the forecast. This last case is for those customers that are not affiliates of the company. After the new orders are created and adjustments in the frozen period have been approved, these orders are released and sent to the execution system (SAP R/3) at the end of the first week of every month.

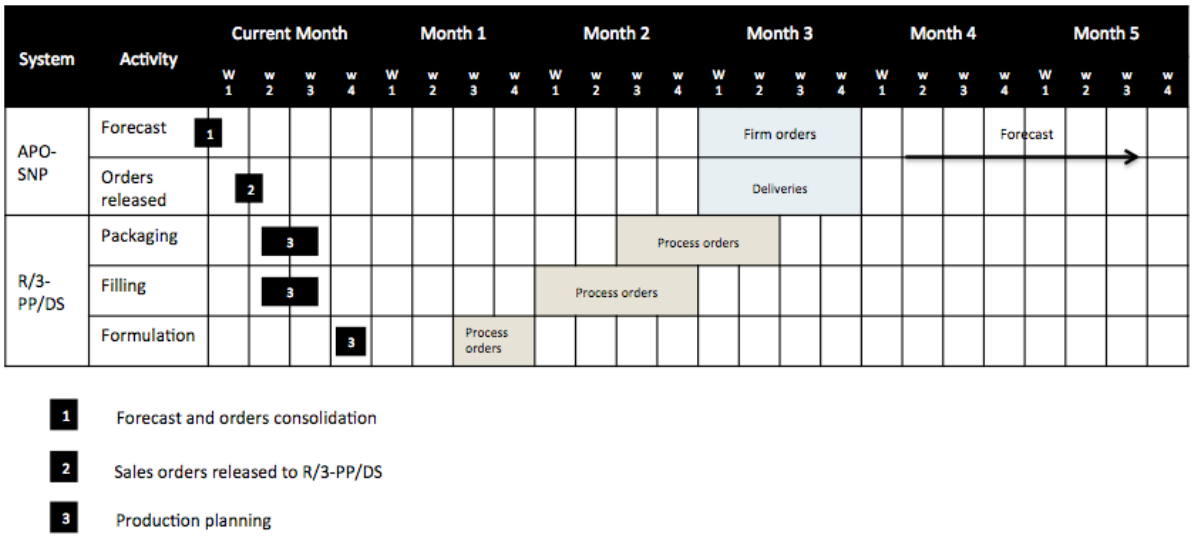


Figure 6. Planning timeline

### *3.2.2. Production planning*

In R/3, Production Planning and Detailed Scheduling runs and availability of resources and components is checked. The creation of process orders for the different phases (packaging and filling) takes place during the second and third week of the month, while formulation planning takes place in the forth week due to shorter production cycle time. Packaging and filling processes are scheduled following the production wheel concept were the sequence of production is fixed and with the objective to minimize setup times. In the third and fourth row of Figure 6, it can be seen the cycle length, which is around one month. During this cycle, products are allowed to be produced only once per cycle. Nevertheless, changes in the sales order constantly triggers the alteration of the production cycle, causing more changes than planned and less productive time. The length of production per item in the cycle is determined based on period lot-sizing procedures and the least unit cost heuristic. Both procedures will be explained in more detail in section 4.1.1. The number of products that are planned is about 409 for the filling phase and about 690 for packaging.

For the case of formulation the cycle takes from one to two weeks since the number of solutions produced is less than in the following phases of the process (about 13 solutions). The planning frequency is weekly and is done for the following third and fourth week. With this shorter

planning frequency it is possible to release more accurate process orders since the planning horizon is shorter and has less variability.

In the last week of the month, a complete production plan is ready. The plan is reviewed during this week along with the production department to check capacity constraints (machine hours, workforce hours, maintenances or breakdown status). Besides new sales orders are planned, adjustments during the frozen period are also evaluated and performed if capacity, materials and workforce are available.

## *3.3. Organization and Decision Functions*

From an organizational point of view, the structure of the Supply Chain department is composed by four groups (see Organization chart in APPENDIX V). The Logistics group is in charge of the activities within the warehouse; they perform the pick and pack of the orders to be delivered and supply material to the production plants. The Export and Transport group plans and executes the activities to ensure the proper transport mode to deliver the finish products to the customers. Finally, the Pipeline group is in charge of all the production planning and demand activities. At the same time this group is divided into two, according to the type of product under their control. The product group of pipettes is under the jurisdiction of the Pipeline Manager Liquida.

Once the general structure of the department was identified, a decision function diagram was mapped specifically for the group that accounts for the planning, scheduling and controlling of the pipettes´ production process (Figure 7). In this diagram we can identify four main aspects, hierarchy, time, dependencies and the role that performs each function performs. The hierarchy consists of three levels: Strategic Planning, Tactical Planning and Operational Planning. The time aspect is represented in the sequence in which each activity is performed and the frequency of it in a certain time period (weekly, monthly or yearly). Arrows coming in and out the functions depict the dependency. Moreover, in the left side of the diagram we can identify the specific role within the organization that is in charge of performing each function.

The Supply & Demand manager is responsible for the demand consolidation, the replenishment of the warehouses in each of the countries (Vendor-managed inventory model for affiliate customers) and the fulfillment of confirmed orders in time, quantity and quality. The Production Leader performs the Master Planning, which includes machine and workforce capacity planning activities and the follow-up for the delivery of confirmed orders on time. Lastly, the Production Planner is responsible for the Materials Planning and the Detailed Scheduling. The main activities performed by the planners are sequencing, unit assignment, release of production, order tracking and the release of purchase orders.

If we compare the decision functions depicted in Figure 7 with the planning timeline described in Figure 6 we notice that the decision taken in Demand & Supply planning makes reference to action 1 in the planning timeline and it is where the planning cycle starts. The Master Planning function takes place during the first week of the month and after action 1. Based on the outcome of the Master Planning, action 2 is the next in time to be executed and is under the

control of the Order acceptance and Supply Plan function. Lastly, Production Planning and Materials Planning functions take place during week two, three and four and are illustrated as action 3. With these two figures we make clear the relationship of decision and the space in time when each of them take place.

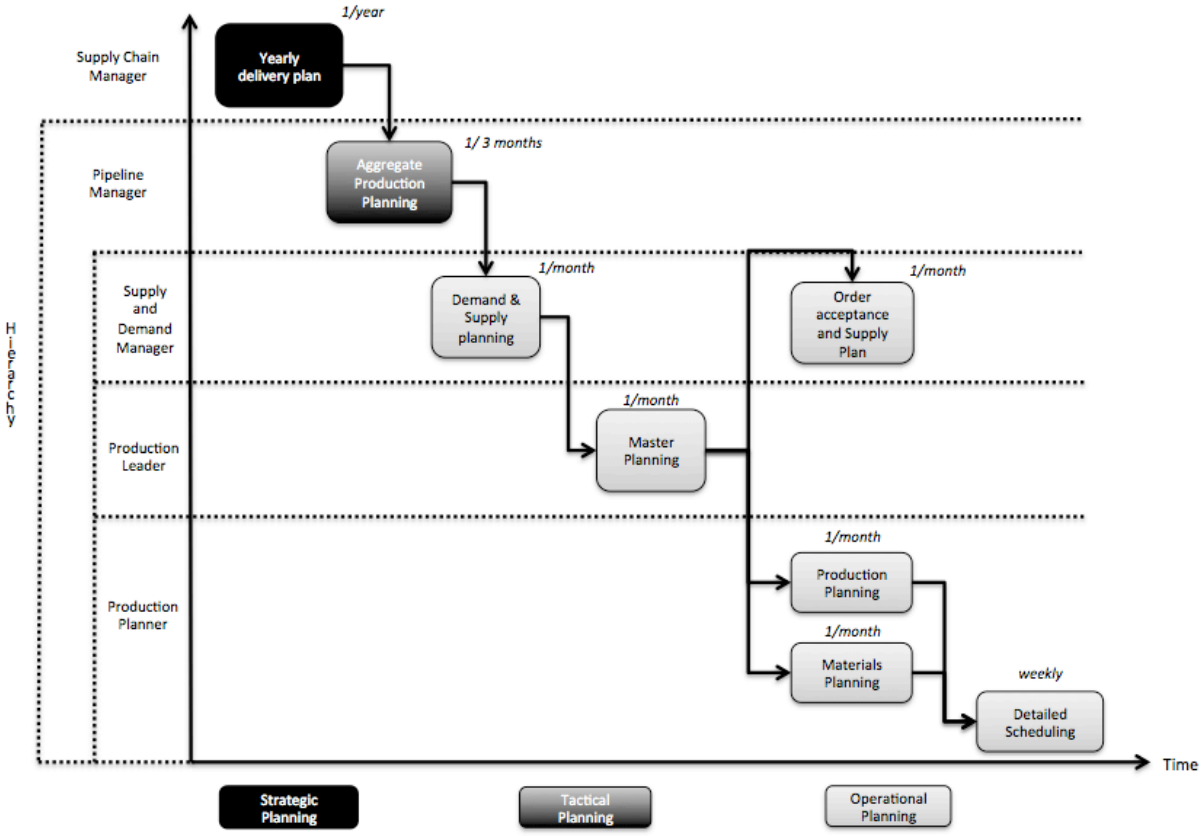


Figure 7. Decision Function Diagram

It is important to mention that currently the organization is going through a re-structuration process. Some activities and roles that were executed at the headquarters are now part of the Supply Center´s activities. This transformation process started in April and will be completed by the end of December of this year.

Regardless the well-structured and defined activities in the organization, some gaps were identified in the control structure. This gaps concern the determination of tactical parameters as a control structure of the planning system. As it was mentioned in section 2.4, in the SCOP decision functions De Kok and Fransoo (2003) highlight the integration of control parameters for the planning of operations in order to get a reliable performance of the system.

Specifically in this case we identified the parameters of lot size and safety stock with a lack of the inclusion of systems characteristics. The first characteristic violated is the resource capacity, which is not considered when calculating the lot sizes. The lot sizing policies are defined as tactical parameters and are a control parameter that influences the output of Master Planning, Production Planning and Materials Planning functions. The second tactical parameter under criticism is the safety stock. Currently this tactical parameter is established based on an

agreement between the Supply and Demand Managers and the affiliate customer. This parameter influences the Supply Planning function directly and all the following functions depicted in Figure 7 as a cascade effect.

## *3.4. Quality control*

In our Cause-Effect diagram, quality problems were mentioned as a motive for the low performance of the supply system. In this section we describe and investigate the impact of this business function.

Quality requirements are high; therefore through the production process several quality tests are performed. These tests can be divided in 3 levels as follows:

a) Materials test (*QC1*) – When materials are received in the warehouse, the quality of them is tested against required standards. The average lead time of this test is 10 days.
b) Production test (*QC2*) – After every production phase, a quality test of the products is performed. The test after formulation and filling takes around 7 days for each process; and at the packaging phase it takes in average 2 days to get the results.
c) Process test (*QC3*) – When a new product is going to be introduced, the stability of the formulation is tested and the production parameters to maintain the process in statistical control are established so the new product can meet the quality standards.

The materials and formulation tests are executed in a sequential manner, while the tests for filling and packaging are executed in parallel. This means that the semi product can be used for production of the final product, even if quality has not confirmed it fulfills the required standards. Nevertheless, the final product cannot be released until all quality tests approve it.

To prove if quality can be considered as a constraint that could hinder the delivery time, data from rejected and blocked items from 2013 was collected. The amount of blocked items during that year was 1.55% in the filling phase and 0.44% in packaging, in comparison with the total produced volume. The two main causes of blocked materials were *Residues in the tank pallet* and *Defective pipettes (see Figure 16 in APPENDIX III),* which after a second inspection where released due to its conformity to standards. The blocked items from the packaging phase were reworked manually, thus no extra capacity was needed in the packaging machines. After the inspection from the quality department only 0.005% of the items were actually rejected, therefor we can conclude that quality of items in the different phases, is not an issue in the process. Moreover, the lead time for the quality tests in each phase is not considered a delay in the process. As it can be seen in Figure 6, the production cycle of every stage is planned to take place at least with 2 weeks of difference and in some cases it takes place one month in advance, which is more than the seven days that it takes to release a batch in filling or formulation. OK

## *3.5. Workforce Planning*

Besides the manufacturing capacity, operator capacity is an important factor as well. Availability of operators for a specific production unit is restricted by skilledness and by various kinds of

absenteeism. In periods of high utilization and high demand variability, workforce planning is a key element. Moreover, through the conducted interviews it was identified as a cause of having limited capacity to operate the production lines (see Cause-Effect Diagram in APPENDIX I).

The workforce planning works in a weekly rolling scenario. Every Tuesday the new plan with available workers, workers on holidays and personnel absent for the following 4 weeks is delivered. An estimation of the plan for the second and third month is included in that plan as well. Furthermore, because the production lines are different, specialized training is needed to operate them. However, not all operators are able to perform operations belonging to filling or packaging; most of them are tied to a specific production unit.

To prove if workforce is a bottleneck in the system, information from 18 weeks period was gathered in order to measure workers ´availability (Figure 8). The legend *Required* represents the number of workers needed for the production plan and it is calculated by SAP based on standard hours. The legend *Available* exhibits the real number of workers during the week and the gap between these two lines is due to *Sickness* or people *In vacation*. For the concept of *Sickness* it is very clear that the behavior and trend is stable with an average value of 5% every week (see Figure 17 in APPENDIX IV). On the other hand, *In vacation* has peaks during the planned period, but this information is known in advance, in comparison to *Sickness/Absence* that is stochastic.

While it appears that the available personnel were not sufficient to realize the production plan, because the *Available* line is below the *Required* line, these figures alone do not make a clear statement about a correlation between low throughput and available workforce. What is possible to conclude is that there is no buffer between the number of workers requested and the number of workers available, so in case it is necessary to increase production it would be very difficult to react. An *inflation factor* can be used in order to create a buffer, and it can be calculated based on the historical data and trend on *Sickness*/Absence.

Furthermore, increasing the degree of cross-training among workers can help to create more flexibility and cope with changes in the production plan, so workers can be reallocated to those production lines where they are needed.

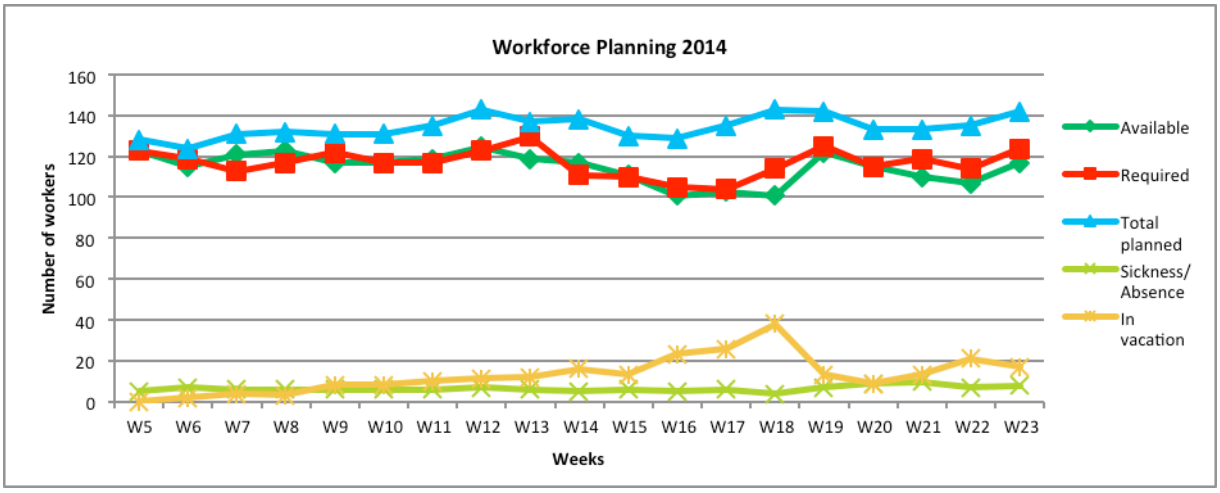


Figure 8. Workforce Plan

## 3.6. Information systems

As explained in section 3.2.1, the two systems in place are SAP APO and R/3-PP/DS (ERP). The Supply Center does not use the integration of transactional data in APO. The SNP heuristic, which calculates the future requirements, runs on a weekly basis. Nevertheless, this information is transferred to the ERP system (for the Supply Center) on a monthly basis. Then production orders, purchase orders, and reservations are transferred from the ERP system to APO on a monthly basis as well. The implications of this mismatch in update frequencies (weekly vs. monthly) are that the plant doesn´t receive updates on the upcoming requirements until a month after. And from the sales point of view, the feedback about product availability is not immediate as well. Nevertheless the supply and demand managers constantly monitor the stock at the customer side via VMI and production planners communicate any delay or problem with the plan when needed.

ERP systems and Advanced planning systems provides the functions of integrating and track enormous quantities of data, but the planning modules are based on simplified models. These simplifications of reality like the assumption of infinite capacity, constant deterministic demand, simple product or no product interaction and fixed lead times do not account for the critical characteristics of the operation. Therefore, there is a need for prescriptive models, that could capture the basic relationships governing a manufacturing system and that can provide with sufficient information for a better decision-making.

## 3.7. State of the Manufacturing System

For the evaluation of the manufacturing system, it was decided to decouple the system into two groups defined by type of process. These groups or subsystems are called production units (PU) and consist of filling and packaging. For each of them, the Net Capacity and the performance measures of Utilization, Throughput and Overall Equipment Effectiveness, will be provided.

The formulation process was left out of the scope of this analysis since in early stages of the project it was not highlighted as a problem. Moreover, the short production lead time and frequent planning schedule make us conclude that this is not a bottleneck in the system.

### 3.7.1. Capacity

The analysis of capacity starts with the calculation of the *gross capacity,* which is defined as the amount of time a facility is open and available for equipment operation. In principle, it is possible to operate the formulation tanks, filling and packaging lines three shifts and five days per week, or even to extend the working days to seven days a week. However, the initial state of most of the production lines is evaluated with and scenario of five working days. Further, due to low demand of the products assigned to two specific lines, one or two shifts a week is sufficient to meet the requirements. Under this scenario are lines 855 in the filling PU, 863 in the packaging PU and the three tanks in the formulation phase. Lastly, public holidays are not considered as working days either.

From the *gross capacity* we subtract a category of time called *planned shutdown*, which includes breaks and scheduled maintenance. The standard time for each break between shifts is of 30 minutes. For the case of scheduled maintenance, it differs from each PU as follows:

1. Formulation: planned maintenance takes place every three months and has a duration of one shift, resulting in four maintenances per year.
2. Filling: in this phase the maintenance is scheduled every quarter and it has a duration of 7 shifts, which means 21 shifts a year. Filling machine 750 is located in plant 1, therefore the maintenance planning is different and is performed every quarter; the duration is of 4 shifts, and therefore 16 shifts are spent in maintenance per year.
3. Packaging: there are two types of maintenance scheduled among the year in this phase defined as *big* and a *small* maintenance. Each of them takes place twice per year and interspersed each other so they do not overlap in the same period. The duration of the *small* maintenance is of 1 shift for all the machines. The *big* maintenance takes 7 shifts for the old machines (861, 863, 865, 867 and 868), and 15 shifts for the new machines (856 and 869). In total, the group of old machines uses 16 shifts in maintenance a year while the new machines require 32 shifts.

During the analysis, some major planned downtime activities were identified which are not part of the standard maintenance plan. One example is the maintenance of the ventilation system in the filling PU. Moreover, one of the production lines in packaging was planned to be removed by July of this year, nevertheless this plan changed recently. These special events were considered to perform the diagnosis of the manufacturing system.

After subtracting all the identified planned downtime activities, the remaining time is called *net capacity* and is also considered as the upper limit on the throughput of a production process

### 3.7.2. Utilization

Once we have calculated the net capacity, we continue with the calculation of the time a machine is actually used divided by the net capacity. The time a machine will be used is determined by two factors, the size of the demand ($D_i$) and the lot size ($Q_i$). The lot size will determine the number of orders released in a period of time and along with it the number of setups. Small lot sizes lead to frequent setups and this degrades the capacity. Equation 3-1 determines the utilization ($U$) of a resource $k$, subject to a net capacity ($C_k$). The effective process time is determined by the time spent in setup ($ST_i$) of every order of size $Q_i$ and the natural process time ($PT_i$) it takes to process that order.

$$U_k = \sum_{i=1}^{n} \frac{D_i}{Q_i C_k}(ST_i - Q_i PT_i) \tag{3-1}$$

To calculate the natural process time, or just process time, the total dependent and independent requirements for 2014 were retrieved from SAP, as well as the process times per item-machine since different products are processed at different speeds in different machines. To calculate the effective process time, the time to perform a setup per item-machine and the lot sizing policy

were obtained. The lot sizing policy in place was the determining factor for the number of orders that were intended to be produced with the current demand for a year.

From this analysis, the filling PU shows 2 lines over the 100% of utilization (see Table 3). This is actually possible because the current lot sizing policies in SAP does not take into account the capacity of the resource where the item is allocated, and secondly it can be that the demand for the items allocated to those lines is greater that the net capacity even if lot sizes are optimized. Moreover, line 850, 851 and 852 are close to the 100% and if we recall from the Law of Utilization, if a station increases utilization without making any other changes, average WIP and cycle time will increase in a highly nonlinear fashion (Hopp and Spearman, 2001). Finally, line 855 can be perceived to be close to the 100% as well, but we have to remember that for this line we performed the analysis with the assumption of working one shift five days a week. If the line is foreseen to be above the 100% it is possible to increase the number of shifts. From those lines that are over a 100% of utilization, it is possible to reallocate some of the products where there is an alternative routing available. Mostly, the groups made by pipette´s size that are depicted in Table 3 are the second alternatives were some capacity could be used.

| PU | Resource | Pipette´s Size | Net Capacity 2014 (hrs) | Process time for 2014 orders (hrs) | Effective process time 2014 | Utilization |
|---|---|---|---|---|---|---|
| Filling | 750 | 1ml, 2.5 ml & 4 ml (S,B) | 5.442 | 3.237 | 3.957 | 73% |
| | 853 | 2.5 ml (B) | 5.039 | 5.640 | 6.247 | 124% |
| | 850 | 1 ml (S) | 5.518 | 4.473 | 5.173 | 94% |
| | 851 | | 5.518 | 4.624 | 5.269 | 96% |
| | 854 | | 5.039 | 5.060 | 5.866 | 116% |
| | 852 | 4 ml (B) | 5.518 | 4.943 | 5.236 | 95% |
| | 855 | | 1.254 | 945 | 1.157 | 92% |

Table 3. Utilization PU Filling

In Table 4 we can see the analysis for the packaging PU. Here we find two lines over 100% of capacity and two with a 95% capacity utilization. The grouping of products in this phase is more difficult due to the different combinations of packaging materials, size of the pipette and number of pipettes in each pack. In general, it can be classified as small (S) or big (B) pipettes that are packed only in a pouch (Single Pouch), S or B that goes into a pouch and then in a folding box (Pouch), S or B that are packed into a blister and then goes into a folding box (FB) and S or B that are packed into a blister made of aluminum and then goes into a folding box (Alu). Because of this, an aggregate analysis is more difficult and less accurate; therefore it is mandatory to consider the special characteristics of item-machine.

| PU | Resource | Type of Packaging | Net Capacity 2014 (hrs) | Process time for 2014 orders (hrs) | Effective process time 2014 | Utilization |
|---|---|---|---|---|---|---|
| Packaging | 856 | Single pouch | 5.434 | 3.371 | 4.096 | 75% |
| | 861 | S, B / Pouch | 5.600 | 4.861 | 5.950 | 106% |
| | 868 | S, B/ Pouch | 5.328 | 4.103 | 5.036 | 95% |
| | 863 | S / FB | 1.770 | 934 | 1.500 | 85% |
| | 869 | S, B / FB | 4.811 | 3.189 | 5.116 | 106% |
| | 867 | S, B / Alu | 5.328 | 3.795 | 5.071 | 95% |
| | 865 | B / Pouch, Alu | 5.556 | 173 | 226 | 4% |

Table 4. Utilization PU Packaging

We can conclude from the evaluation of the utilization that the filling PU is the phase with higher utilized resources. Nevertheless, since close to zero inventories is kept between the PUs, late production in the filling phase caused by not having enough time to produce, will cause a delay in packaging. Moreover, the high utilization in filling influences starvation in the packaging phase.

### *3.7.3. Throughput*

The second performance measure used in the diagnosis was the throughput, which it is defined as the average output of a production process per unit of time.

From Table 5 and Table 6 we can see the quantity of milliliters produced per hour during 2013. These values will be used as base line to compare the output of the designed solution and its impact in these performance measures.

From the filling PU we can identify that the three production units with lower throughput were also identified as having high utilization (*U). Moreover, the items that are produced in these lines are the ones with the highest demand, or highest rate of arrivals, in comparison with the others.

| PU | Resource | Pipette´s size | Net Capacity 2013 (hrs) | Milliliters produces in 2013 | Throughput 2013 (ml/hr) |
|---|---|---|---|---|---|
| Filling | 750 | 1ml, 2.5 ml & 4 ml (S, B) | 4.788 | 29.337.754 | 6.127 |
| | 853 | 2.5 ml (B) | 4.902 | 48.594.190 | 9.913 *U |
| | 850 | 1 ml (S) | 4.499 | 14.123.684 | 3.139 *U |
| | 851 | | 4.727 | 14.506.211 | 3.069 *U |
| | 854 | | 5.411 | 16.529.885 | 3.055 *U |
| | 852 | 4 ml (B) | 4.248 | 67.723.196 | 15.942 *U |
| | 855 | | 1.634 | 22.247.168 | 13.615 |

Table 5. Throughput 2013 Filling PU

From the packaging PU the lines that share the small and big sizes are the ones that present the lower throughput. This can be explained by the fact that the setup that takes more time is the

one that adjusts the size of the pipette. More time is needed to change the tooling and less time is spent in packaging the items. Also these lines were identified as highly utilized (U*), therefore we can state these as the bottleneck in this production unit.

| PU | Resource | Type of packaging | Net Capacity 2013 (hrs) | Milliliters produces in 2013 | Throughput 2013 (ml/hr) |
|---|---|---|---|---|---|
| Packaging | 856 | Single pouch | 935 | 14.565.155 | 15.578 |
| | 861 | S, B / Pouch | 4.560 | 16.692.489 | 3.661 *U |
| | 868 | S, B/ Pouch | 5.176 | 40.070.312 | 7.742 *U |
| | 863 | S / FB | 2.523 | 4.714.423 | 1.869 |
| | 869 | S, B / FB | 5.426 | 54.465.022 | 10.038 |
| | 867 | S, B / Alu | 4.879 | 11.948.367 | 2.449 *U |
| | 865 | B / Pouch, Alu | 5.176 | 64.440.005 | 12.450 |

Table 6. Throughput 2013 Packaging PU

Generally, the recommended actions to improve throughput are to reduce blocking or starving of bottlenecks in the system by creating buffers with inventory near the bottlenecks, reducing the variability or reducing the utilization of the resource. The second group of options is related to increasing capacity by means of increasing operating time, increase reliability, reduction of yield loss or adding equipment.

From this performance measure we can conclude that in the filling PU the lines for small pipettes are the ones with lower throughput. In the packaging PU, the production lines that share the sizes of small and big have a lower throughput. This is mainly caused by the time that takes to change the tooling from one item of small size to an item of big size. Therefore, time that could be used for production is spent on setups.

### *3.7.4. Overall Equipment Effectiveness*

The last manufacturing performance measure used to evaluate the manufacturing system was the Overall Equipment Effectiveness (OEE). OEE is a best practice to monitor and measure the effectiveness of a manufacturing process. Making use of OEE can give a good estimation of productivity losses as breakdowns, setups and production rejects. It is frequently used in Total Productive Maintenance and Lean Manufacturing programs as a way to provide an overall framework of how effective the resources are (Vorne Industries, 2012).

This measure is made up three components: availability, performance and quality (Figure 9). Availability is defined as the operating time left after down time losses are considered like breakdowns and setups. Performance takes into account the factors that can cause the process to operate at less than maximum possible speed; these causes are called speed losses and can include substandard materials and operator inefficiency. Finally, quality considers the produced pieces that do not meet quality standards and the remaining time is called fully productive time.

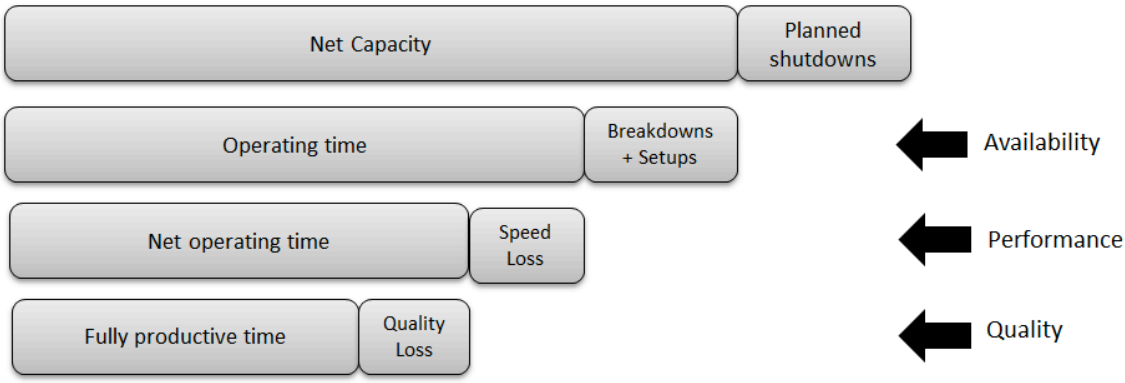


Figure 9. Overall Equipment Effectiveness Structure

In practice, OEE is calculated as the product of its three components:

*OEE = Availability x Performance x Quality*

The results from both PU are illustrated in Table 7 and are compared to World class goals for each factor. As we can see, the component with the worst performance in both cases is availability and therefore we continued our analysis into that segment. The components of performance and quality are out of the scope of this project.

| OEE Factor | World Class | Filling PU | Packaging PU |
|---|---|---|---|
| **Availability** | 90.0% | 80% | 70% |
| **Performance** | 95.0% | 100%[1] | 90% |
| **Quality** | 99.9% | 98.4% | 99.5% |
| **OEE** | 85% | 80% | 60% |

Table 7. OEE Results

As stated before, the losses that are measured by the component of availability are breakdowns and setups. When the project started there was not enough information about breakdown recording in the system in order to perform a quantitative analysis, therefore only setups were possible to track. Is our understanding that the supply center began at the end of last year with the implementation of a system that records the breakdowns. Therefore it is recommended that this type of loss is included in further analysis.

In the case of the filling production lines, Figure 10 depicts the time spent in cleaning and setup. In average 20% of the net capacity is spent in these two activities.

[1] The measure of Performance is calculated based on the ideal run rate per item, and as ideal run rate we considered the standard values in SAP, it can be that this standard is to high (with a buffer) and therefore the final value is 100%.

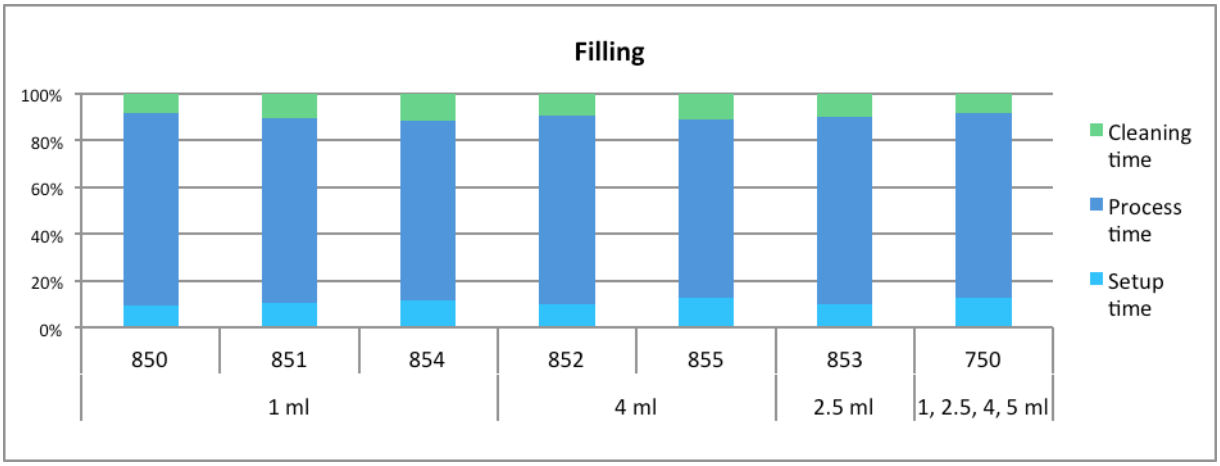


Figure 10. OEE Availability Filling PU

On the other hand, Figure 11 shows that in the packaging lines in average 29% of the net capacity is spent in performing setup activities.

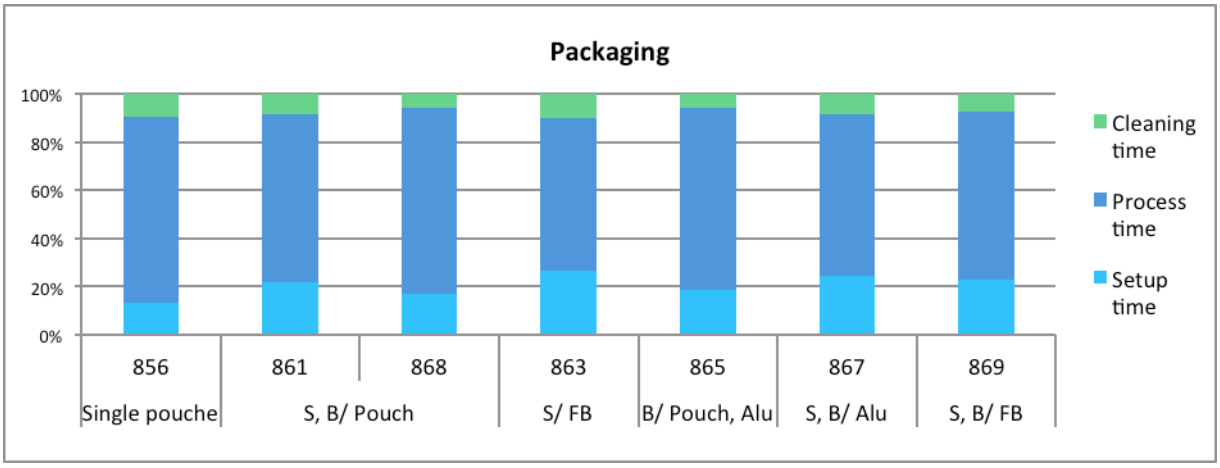


Figure 11. OEE Availability Packaging PU

From the OEE analysis we can conclude that availability is the concept with the worst performance. In principle this is not surprising since one of the characteristics of the pharmaceutical industry is that the manufacturing process is followed by large setups. Nevertheless, it is important to have a measure and track it in order to look for ways to improve the performance and to identify any deviation that could harm the throughput in a timely manner. With the cognition of the downtime spent in setups we were able to confirm that there was room for improvement. Furthermore, we have to recognize that if downtimes are included in the calculation of availability, this component will deteriorate.

## *3.8. Conclusion Diagnosis Phase*

In this section we described the different systems that were analyzed. The approach to manage a real life problem was through the decomposition into business functions and the analysis of these business function using relevant concepts and tools. From this analysis bottlenecks and opportunity areas were identified. The decision function diagram along with the analysis of the

different business functions as supply and production planning, quality, workforce planning, and the manufacturing system, help us to identify the interfaces between the functions as well.

With this chapter we close the *diagnosis* phase. From it we can conclude several points summarized as follows:

- Quality Control

This system does not represent a problem due to the low percentage of rejections in both production units. Moreover, the lead time for the quality tests in each phase is not considered a delay in the process either.

- Workforce planning

There is no buffer between the number of workers requested and the number of workers available. In case it is necessary to increase production it would be very difficult to react to such request.

- Control Parameters

The control interfaces were not appropriate for the system since two types of constraints were not considered. The first constraint that was violated is a *hard constraint type*, which is the number of machine hours available. The lot sizing parameters are set without the consideration of the capacity of the production lines, causing the system to constantly plan over the available capacity.

The second constraint that is not completely supported by the current control structure is a constraint of *soft type*, which is the service level. At present, the level of safety stocks is mostly the same in number of days for the portfolio of a customer, and is more an agreement between the customer and the Supply & Demand managers, based on the performance of their forecast accuracy and the service level.

- Manufacturing System

The filling lines with small pipettes are considered as bottlenecks because of the high utilization and low throughput. For the packaging lines, the ones that share the sizes of small and big are highly utilized and have a lower throughput.

Because the production process is sequential, we can argue that the low performance in the PU filling influence starvation or late deliveries in packaging since low inventory is kept between these two.

The OEE helped us providing more direction into the most important productivity losses. The component in the OEE with the lowest performance was availability, due to large setup times. Therefore our efforts to improve the system were focused into that direction.

# 4. Design of Operations and Control System

In the previous section we explained the major control problems and bottlenecks in the manufacturing system. In this section we present the design of an operation and control system for such environment. Because of the way in which this operations and control system was designed and parameterized, it can be easily implemented in similar environments from process industries with multi-items, multiple machines and with limited capacity.

Explicitly, this thesis provides insight into the design of a control system that can address the following hypotheses:

*Hypothesis 1: The implementation of a heuristic for setting tactical parameters as lot sizes, will maximize the output at the technology selected.*

*Hypothesis 1.a: Optimization of lot sizes per production line with the consideration of capacity, will lead to effective capacity utilization.*

*Hypothesis 2: Calculation of safety stocks based on lead time, demand variability and requested service level, will provide the necessary buffer to satisfy customers demand.*

To be able to answer these questions, two models were created. In section 4.1.1 we present the first model that addresses hypothesis 1.a and in conjunction with a heuristic, responds to hypothesis 1 (explained in section 4.1). The second model is explained in section 4.2 and provides the mathematical model to calculate safety stock levels. Both models are tools for the calculation of tactical parameters, which are lot sizes and safety stocks.

The performance of the heuristic is evaluated in terms of manufacturing performance measures and total relevant costs, which include holding cost and setup cost. The manufacturing performance measures are calculated using queuing theory; hence the mathematical model used to provide approximations is described in section 4.1.2

## 4.1. Allocation and Lot size calculation

Based on the diagnosis phase, we were able to identify that the calculation of lot sizes was not part of the former activities in the control structure. The parameters that are used do not consider the *hard* constraint of resource capacity and these are not updated if items are reallocated to another resource for a long run time period, if demand changes or if the number of items that share a resource increases. These flaws are addressed with a five steps heuristic in combination with an optimization model. This procedure does not require lengthy computations, but still gives a feasible and optimized solution for a multi-item, single resource problem. Additionally, it can be seen as a tool to create and test what-if scenarios in the medium to long term plan. Next, the steps of the heuristic will be explained.

***Input Data***

The required data to perform the following steps is the following:

1. Primary routing per item.
2. Based on the primary routing, process time and setup time.
3. Standard price per item
4. Ordering cost per item-resource
5. Demand in units per year
6. Current lot sizing policy
7. Variation in arrival process per item
8. Variation in process time per item-resource
9. Variation in setup time per item-resource

If items have a second or third resource where production can take place, gather data of point two, four, eight and nine for these additional resources. This information will be used to support step 2.

Once the parameters are fed into the model we can initialize the heuristic. Figure 12 illustrates the 5 steps to be followed and will be described next.

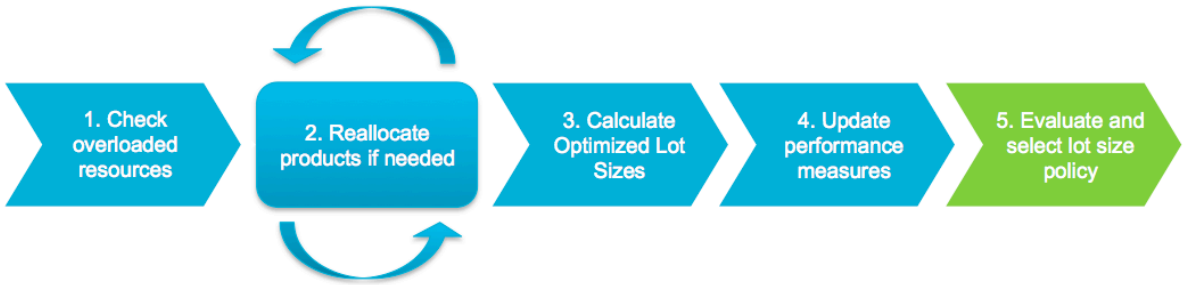


Figure 12. 5 Steps Heuristic

***Step 1. Check for overloaded resources***

In multi-item, multiple-resources facilities it is very common to find different routings available to process an item, this alternative options are determined mainly by physical constraints as machine tooling. Nevertheless, to consider all the possible alternatives and provide an efficient solution is complex. Hence the heuristic is initiated with the first available processing option per item. With that primary allocation of items to resources, the model calculates the utilization by means of equation 3-1 and production lines where capacity is not enough to fulfill the demand can be identified.

***Step 2. Reallocate items***

Once the production lines where the net capacity is not enough to fulfill the demand are identified, we look into the secondary alternative. A group of items is taken from the overloaded resource and are reallocated to the second resource. If the resource is under 100% of the utilization, then continue to step 3, otherwise perform this step until utilization is under 100%.

From the Conservation of Material Law we can say that the capacity of a line must be at least as large as the arrival rate to the system (Hopp and Spearman, 2001), therefore the first two steps

from the heuristic look to fulfill this law by reallocating products and with the consideration of a medium term planning (one year). If the arrival rate to a resource is higher than its capacity, then the organization should look into different plans as influencing the demand arrivals, or increasing the capacity by increasing the number of working days to the weekends.

***Step 3. Optimization of Lot sizes***

With the last allocation of products, the Lot sizing model calculates the optimal lot sizes per item and resource, taking into account all the multiple items allocated to the same resource. This model is described in detail in section 4.1.1.
Since the demand is assumed to be stationary and stochastic, the optimized lot size quantities are translated into optimized replenishment frequencies ($RF_i$) that can follow the forecast pattern.

***Step 4. Update manufacturing performance measures***

Once the replenishment frequencies are calculated, queuing theory is used to give approximations of the manufacturing performance measures like WIP, cycle time and throughput. The mathematical model is explained in detail in section 4.1.2.

Since one of the input parameters is the current lot size policy used in SAP, the model is able to provide a comparison and the user can evaluate the results and the performance of the proposed solution.

***Step 5. Select lot size policy***

Once the results are evaluated a new lot size policy can be determined for each item per resource. The solution can be easily implemented in the ERP system due to the extensive available options in Period Lot-Sizing Procedures (SAP).

### *4.1.1. Lot-size optimization model*

In this section we will explain in more detail the mathematical model that supports the calculation of the tactical parameter of lot sizes and it complements the heuristic in the first part of this section.

As explained in section 2.1, in the literature we can find several procedures to determine production quantities. Different procedures are applied according to the circumstances or requirements of the business. Currently, three lot sizing procedures are mainly used in both production units. The Lot-for-Lot Order quantity, Period Lot-Sizing Procedure and the Least Unit Cost.

The Lot-for-Lot approach (L4L) also known as base-stock level, orders the exact shortage quantity, which means the required quantity minus available stock, for each time period. This procedure has the advantage of having the least holding costs, nevertheless it is not recommended when ordering or setup costs are significant (Silver et al., 1998). In the Period Lot-

Sizing Procedure, several forecasted requirements within a time period are combined into one lot. The periods are generally defined as one, two, three and six months, for both production units. Finally, the Leas Unit Cost is a heuristic that accumulates requirements until the cost per unit reach a minimum level. The considered costs are equal to the sum of the ordering cost and storage costs. (SAP, 2014)

None of the previous described procedures take into account a capacity constraint. In the current situation, where multiple products are produced on a single resource and with high level of demand, profit maximization is achieved when available capacity is allocated properly under the consideration of distributed capacity among the mix of items and the optimization of capacity utilized in setup times (Fransoo et al., 1995). Therefore, an optimization procedure is proposed in order to include the upper limit on the throughput of each production line.

***Lot Size optimization in capacitated environments***

From our literature review, the analysis of the system and its characteristics, we propose the solution to a lot sizing problem by means of the Economic Production Quantity (EPQ) with the application of an availability rate for every product per unit time. Since we are facing a multi-item and multiple resources problem, the process rates vary for each combination item-resource. Therefore the optimization is proposed to be done at a resource level, so the dynamic of the system can be captured. The coordination among products' replenishments will allow reducing setup cost, during the productive time. The assumptions for this model are the following (Silver et al., 1998):

1. Demand is deterministic and constant over time.
2. The replenishment quantity needs to be an integer number of units.
3. A production run incurs a fixed setup cost, which is independent of the size of the lot.
4. The unit variable cost does not depend on the replenishment quantity.
5. The cost factors do not change substantially with time.
6. No shortages are allowed.
7. The replenishment quantity is delivered at a specific rate.

The objective of the problem is to find the optimal production quantities for each product *i* at a minimum cost and within the available productive time. The objective function of this problem is named as the total relevant cost (TRC) and is expressed as:

$$\text{Min } TRC_k = \sum_{i=1}^{n} A_i \left(\frac{D_i}{Q_i}\right) + \frac{v_{ir} Q_i}{2}\left(1 - \frac{D_i}{\mu_{ik}}\right) \qquad (4\text{-}1)$$

Subject to:

$$\sum_{i=1}^{N} D_i PT_{ik} + \frac{D_i}{Q_i} ST_{ik} \leq C_k \tag{4-2}$$

Where

| Symbol | Description |
|---|---|
| i ϵ N | Item index |
| k ϵ K | Resource index |
| $TRC_k$ | Total relevant cost in resource *k*, in euros per year |
| $D_i$ | Demand rate of item *i,* in units per year |
| $A_i$ | Setup cost for item *i,* in euros |
| $v_i$ | Unit variable cost of item *i,* in euros per units |
| r | Carrying charge of an item kept in inventory |
| $P_i$ | Production rate of resource *k* for item *i,* in units per year |
| $PT_{ik}$ | Average production time of item *i* in resource *k,* in hours per unit |
| $ST_{ik}$ | Average setup time of item *i* in resource *k,* in hours |
| $C_k$ | Net capacity of resource *k*, in hours per year |

And with the decision variable;

$Q_i$: Production order quantity or lot size of item *i*, in units.

In Schouten (2013), a Lagrange multiplier is introduced (λ). This method will allow us to minimize the function, subject to the constraint in equation 4-2. The expression for the Langrage multiplier is given in the next equation:

$$\lambda_k = \frac{\left[\left(\frac{Q_k v_i}{(Q_k - D_i PT_i)}\right)^2 \left(\frac{v_i r}{2}\left(1 - \frac{D_i}{P_i}\right)\right)\right] - A_i D_i}{D_i ST_i} \tag{4-3}$$

This equation is strictly dependent on the upper limit of $C_k$ of a production line. Combining equation 4-1 and 4-3 we can reformulate the problem as follows:

$$minTRC_k(Q_i, \lambda_k) = \sum_{i=1}^{n} A_i \left(\frac{D_i}{Q_i}\right) + \frac{v_i r Q_i}{2}\left(1 - \frac{D_i}{P_i}\right) - \lambda_k \left(\sum_{i=1}^{n}\left(D_i PT_i + \frac{D_i}{Q_i} ST_i\right) - C_k\right) \tag{4-4}$$

Since, $\frac{d^2 TRC_k(Q_i, \lambda_k)}{dQ_i^2} > 0$, we can find the optimal value of every replenishment quantity $Q_i$ with the first derivative of equation 4-4, giving as a result the following equation:

$$Q_i = \sqrt{\frac{A_i D_i - \lambda_k D_i ST_i}{\frac{v_i r}{2}\left(1-\frac{D_i}{P_i}\right)}} \tag{4-5}$$

With this expression we can solve the $EPQ_i$ problem for all products *i* by means of lambda.

***Replenishment Frequency***

In the previous section we proposed a modified EPQ model considering a capacity constrain. Nevertheless, this model assumes a deterministic demand rate. In this section we relax this assumption by letting the average demand rate to vary over time through an optimized replenishment frequency, instead of fixing a lot size quantity. In empirical studies, this approach has a better cost performance when variation in demand is significant (Brown, 1978).

We start from the assumption that $\frac{D_i}{Q_i} = \frac{W}{RF_i}$ , where *W* represents a time unit and $RF_i$ represents

the optimal replenishment frequency within this time period. In this case, the time units is defined as 50 weeks and $RF_i$ represents the number of weeks for item *i* to be produced. This equivalence holds for the actual problem only if the same time period is used for $D_i$ and *W*.

Replacing the latest equivalence into equation 4-4 we get:

$$minTRC_N(RF_i, \lambda_k) = \sum_{i=1}^{N} A_i\left(\frac{W}{RF_i}\right) + \frac{v_i r D_i RF_i}{2W}\left(1 - \frac{D_i}{P_i}\right) - \lambda_k\left(\sum_{i=1}^{N}\left(D_i PT_i + \frac{W}{RF_i} ST_i\right) - C_k\right) \tag{4-6}$$

This relation implies that optimized lot size quantities leads to optimized replenishment frequencies.

Lastly, we can convert the $RF_i$ into the equivalent lot size quantity with $RF_i = \frac{Q_i W}{D_i}$. By computing

$RF_i$ we can obtain the optimized replenishment frequencies.

Once the $RF_i$ are calculated, it is necessary to determine a maximum replenishment frequency due to the expiration time of the products, which varies from product to product.

It is important to remark that the reduction of replenishment frequencies affects the distribution of net capacity, therefore less capacity is available for production and more time is spent in setups. This lot size optimization model then takes into account the interaction among multi-items in a single resource with limited capacity.

### *4.1.2. Queueing Model*

In this section we discuss the effects on cycle time, throughput and work in process, based on the proposed replenishment frequencies. The purpose is to have a complete description of the

manufacturing process performance and the corresponding laws of physics, which integrate randomness. The expected result is a robust policy that can support a better decision-making process.

Reduction of variability can be achieved through variability pooling and by means of batch size. Process times of batches are less variable than process times of individual parts (Hopp & Spearman, 2001), and only one setup is needed to perform the whole set of products in the batch. On the other hand, transfer batches propagate variability from high variable upstream workstation to downstream workstations. Therefore, queuing theory can be used as a support for tactical as well as operational decisions and controls.

We make use of queuing theory to approximate the effects on cycle time and work in process in order to evaluate if we can make a better use of installed capacity. This model facilitates the analysis to adjust capacity through What-If scenarios in case the performance measures are unacceptable or are infeasible, like resources being used beyond available capacity. This What-If analysis can go from just off-loading heavily loaded resources and reallocation of products to other resources; to the implementation of capacity expansion. The manufacturing system´s characteristics are under the influence of the lot sizes and are as follows:

1. An arrival process of multiple items in batches.
2. Random interarrival times.
3. Single machine with random process times and setup times.
4. There is no limit to the number of items that can be in the system.
5. Items are selected for service according to first-come, first-serve discipline

A system with general process and arrival times is applied (GI/G/1), in view of time distributions that are nonexponential. The performance measures will be estimated by means of a two-moment approximation, which result in a good estimation for systems with moderate variability ($c_a$ and $c_e$ lower than 1) and with a utilization of resources lower than 95% (Hopp and Spearman, 2001).

The problem of single resource and multi-item subject to batch sizes is decomposed in two steps. The first step is to determine the processing times for every item individually. Then, an aggregate value of $t_{ak}$ and $t_{ek}$ is calculated, through the superposition of the arrivals and processing of batch-items that are allocated to resource $k$ (Whitt, 1983).The arrival process is calculated by means of the hybrid approximation for the superposition process at resource $k$ from the different items (Whitt , 1983).

The used notation is as follows:

| Symbol | Description |
|---|---|
| i | Product index |
| K | Resource index |
| $U_k$ | Utilization of resource *k* |
| $Q_i$ | Batch size of item *i* in resource *k* |
| $r_{ai}$ | Rate of arrivals of item *i* |
| $r_{aQi}$ | Rate of arrivals per batch of item *i* |
| $D_i$ | Demand rate of item *i,* in units per year |
| $C_k$ | Total available productive time of resource *k*, in hours per year |
| $r_{ak}$ | Aggregate batch arrival rate at resource *k* |
| $t_{ai}$ | Mean time between arrivals of item *i* |
| $t_{aQi}$, $c_{aQi}^2$ | Mean and SCV of time between arrivals of batches of item *i* |
| $t_{ak}$, $c_{ak}^2$ | Aggregate mean and SCV of time between arrivals of batches at resource *k* |
| $PT_{ik}$, $c_{PTik}^2$ | Mean and SCV of processing time of item *i* at resource *k* |
| $ST_{ik}$, $c_{STik}^2$ | Mean and SCV of setup time of item *i* at resource *k* |
| $t_{ek}$, $c_{ek}^2$ | Aggregate Mean and SCV of effective processing time at resource *k* |

*Step 1. Values at item level*

Average setup times ($ST_{ik}$) when changing to item *i* and the processing time ($PT_{ik}$) per item *i* in resource *k* are obtained and are part of the master data in the ERP system. The variation of these two concepts is calculated based on historical information from the last year. The mean time between arrivals of item *i* equals $t_{ai} = \frac{time\ between\ batches}{Q_i}$. And the rate of arrivals per unit of item *i* ($r_{ai}$) is equal to $D_i / C_k$. The variation of the average time between arrivals of batches ($c_{ai}^2$) is calculated using historical information from last year as well.

*Step 2. Values at resource level*

To calculate the arrival process of multi-items in a single resource we apply the hybrid procedure from Whitt (1983), therefore the following expression was used:

$$c_{ak}^2 = w_k \sum_{i=1}^{N} \frac{r_{ai}}{r_{ak}} c_{ai}^2 + 1 - w_k \tag{4-7}$$

Where

$$r_{ak} = \sum_{i=1}^{N} r_{ai} \tag{4-8}$$

Then a weighting function is used

$$w_k = [1 + 4(1 - u_k)^2(v_k - 1)]^{-1} \tag{4-9}$$

Where

$$v_k = \left[\sum_{i=1}^{N} \left(\frac{r_{ai}}{r_{ak}}\right)^2\right]^{-1} \tag{4-10}$$

To calculate the effective processing time per resource, we make use of the following expressions:

$$t_{ek} = \sum_{i=1}^{N} \pi_i(Q_i PT_i + ST_i) \tag{4-11}$$

$$\pi_i = \frac{r_{ai}/Q_i}{\sum_{i=1}^{N} r_{ai}/Q_i} \tag{4-12}$$

$$\sigma_{ek}^2 = \sum_{i=1}^{N} \pi_i\left(Q_i c_{PTi}^2 PT_i^2 + ST_i^2 c_{STi}^2\right) + \left[\sum_{i=1}^{N} \pi_i(Q_i PT_i + ST_i)^2 - t_{ek}\right] \tag{4-13}$$

$$c_{ek}^2 = \frac{\sigma_{ek}^2}{t_{ek}^2} \tag{4-14}$$

With this information, we can compute the cycle time. What we define as cycle time is the sum of queue time, setup time and process time. Thus it can be summarized as the average time from release of a job at the beginning of the PU until it reaches the end of that phase.

The average cycle time can be computed making use of Kingman´s equation, or VUT equation. Which addresses the dimensions of variability (*V*), utilization (*U*) and time (*T*) as follows:

$$CT_k = \left(\frac{c_{ak}^2 + c_{ek}^2}{2}\right)\left(\frac{u_k}{1 - u_k}\right) t_{ek} \tag{4-15}$$

The greater the variability in effective process times ($c_{ek}^2$) and in the arrivals ($c_{ak}^2$), the greater the average queue.

The second manufacturing performance measure computed was the throughput. Where $Q_i$ can represent the current lot size or the optimized proposed by our model.

$$TH_k = \frac{\sum_{i=1}^{N} U_i}{\sum_{i=1}^{N} D_i PT_{ik} + \frac{U_i}{Q_{ik}} ST_{ik}} \quad (4\text{-}16)$$

Finally, making use of Little´s Law we can establish the relationship among cycle time throughput and work in process for any production station:

$$WIP_k = TH_k \times CT_k$$

Recalling from the Law of Utilization, *If a station increases utilization without making any other changes, average WIP and cycle time will increase in a highly nonlinear fashion* (Hopp and Spearman, 2001) we conclude that, when utilization ($U_k$) is over 100% the model cannot calculate the WIP, CT and TH.

### *4.1.3. Results Lot Size Optimization Model*

The approach to solve a multi-item, multi-resource with capacity constrains problem is based on the application of a 5 steps heuristic, jointly with an optimization model. The manufacturing system was decoupled in filling and packaging and each production line was analyzed separately. Then lot sizes were optimized taking into account the allocated items per resource and the different process time, setup times, holding cost and setup cost. In comparison with the actual lot sizing policies, this approach is able to include the *hard* constraint of resource capacity and spread the available capacity among the items, based on a cost function as well. Therefore the most relevant information is included in the calculation, which is demand, cost and capacity.

In this section we present the results after following the 5 steps heuristic in the filling PU.

***Step 1. Check for overloaded resources***

The heuristic starts with the most recent allocation of items to resources. The input data specified in section 4.1 is required by the tool to compute the manufacturing performance measures. From this step we identify two production lines over a 100% of utilization and four close to 100% (Table 8).

| | Filling | | 750 | 850 | 851 | 852 | 853 | 854 | 855 |
|---|---|---|---|---|---|---|---|---|---|
| Current Lot size policy | NC | Net Capacity (hrs) | 5.442 | 5.518 | 5.518 | 5.518 | 5.039 | 5.039 | 1.254 |
| | C | Used Capacity (hrs) | 3.957 | 5.173 | 5.269 | 5.236 | 6.247 | 5.866 | 1.157 |
| | U | Utilization | 73% | 94% | 96% | 95% | 124% | 116% | 92%[2] |
| | WIP | Average work in process (parts) | 213.896 | 3.278.565 | 4.227.200 | 4.430.534 | N.A. | N.A. | 1.563.285 |
| | CT | Average cycle time (days) | 2 | 29 | 37 | 45 | N.A. | N.A. | 16 |
| | TH | Average output (parts/hr) | 5.021 | 4.880 | 5.009 | 4.323 | N.A. | N.A. | 4.200 |

Table 8. Manufacturing Performance Measures at Initial State at Filling PU

Measuring cycle time can be a complex task in an environment with multi-items, different process times, setup times and yield. Therefore, queue theory is used to get approximations and at the end being able to evaluate the As-Is and To-Be state of the designed solution. This step can be considered as the As-Is state.

If utilization is over a 100% the tool is not able to compute the manufacturing performance measures, as can be seen in line 853 and 854.

***Step 2. Reallocate items***

With the complete list of available routings, the second alternative with the lowest utilization is used to reallocate a set of items *i*. This step is performed until the utilization is under a 100% of utilization.

After several iterations, it was possible to allocate items to resources and achieve utilization under 100% (Table 9). This step is a manual process; therefore further refinement would be possible but is outside the scope of this project.

| | Filling PU | | 750 | 850 | 851 | 852 | 853 | 854 | 855 |
|---|---|---|---|---|---|---|---|---|---|
| Current Lot size policy | NC | Net Capacity (hrs) | 5.442 | 5.518 | 5.518 | 5.518 | 5.039 | 5.039 | 1.254 |
| | C | Used Capacity (hrs) | 5.437 | 5.410 | 5.269 | 5.236 | 4.936 | 4.980 | 1.157 |
| | U | Utilization | 100% | 98% | 96% | 95% | 98% | 99% | 92% |

Table 9. Utilization after Reallocation at Filling PU

***Step 3. Optimization of Lot sizes***

With the last allocation of items to resources, the tool computes the optimized lot sizes per item. Table 10 shows that with the optimization procedure explained in section 4.1.1 it is possible to

[2] The initial state of this production line was considering a working schedule of one shift five days a week. If utilization is foreseen to be over 100%, it is possible to consider increasing the number of working shifts.

reduce the time spent in setups, with the consideration of holding and setup cost, therefore the distribution of lot sizes is based on the values of cost, capacity and demand.

From the set of resources at the filling PU the results show that it is possible to release time from setups in all the cases. This "free time" can be used as a buffer to cope with demand and production uncertainties and be more flexible.

| | Filling | | 750 | 850 | 851 | 852 | 853 | 854 | 855 |
|---|---|---|---|---|---|---|---|---|---|
| Opt Lot Sizes | NC | Net Capacity (hrs) | 5.442 | 5.518 | 5.518 | 5.518 | 5.039 | 5.039 | 1.254 |
| | C | Used Capacity (hrs) | 5.144 | 4.959 | 4.922 | 5.073 | 4.731 | 4.646 | 1.046 |
| | U | Utilization | 95% | 90% | 89% | 92% | 94% | 92% | 83% |
| | Reduced setup time (hrs) | | 293 | 452 | 348 | 163 | 206 | 334 | 111 |

Table 10. Utilization with Optimized Lot Sizes at Filling PU

***Step 4. Update manufacturing performance measures***

Along with the optimized lot sizes, the tool is able to compute the following manufacturing performance measures: work in process, cycle time and throughput.

Table 11 depicts the relationship established by the Kingman´s equation that states if utilization decreases, cycle time decreases as well. Moreover, by means of the reduction in setup times, the manufacturing performance measure of throughput is increased since the same number of items can be produced in less time.

| | Filling | | 750 | 850 | 851 | 852 | 853 | 854 | 855 |
|---|---|---|---|---|---|---|---|---|---|
| Opt Lot Sizes | NC | Net Capacity (hrs) | 5.442 | 5.518 | 5.518 | 5.518 | 5.039 | 5.039 | 1.254 |
| | C | Used Capacity (hrs) | 5.144 | 4.959 | 4.922 | 5.073 | 4.731 | 4.646 | 1.046 |
| | U | Utilization | 95% | 90% | 89% | 92% | 94% | 92% | 83% |
| | WIP | Average work in process (parts) | 3.529.226 | 3.538.323 | 2.982.039 | 3.473.652 | 5.971.971 | 3.873.095 | 1.335.347 |
| | CT | Average cycle time (days) | 29 | 30 | 24 | 34 | 56 | 33 | 13 |
| | TH | Average output (parts/hr) | 5.344 | 5.239 | 5.363 | 4.462 | 4.695 | 5.180 | 4.644 |

Table 11. Manufacturing Performance Measures with Optimized Lot Sizes at Filling PU

Finally, as explained in section 2.2, one of the sources of variability in manufacturing systems are setups. With the optimization of lot sizes we decreased the number of setups and therefore the coefficient of variation of effective process time was decreased as well. Figure 13 depicts this effect on line 851 from the filling PU.

| | |
|---|---|
| SCV Effective process time current Lot size policy (Ce^2) | 1,10 |

| | |
|---|---|
| SCV Effective process time Model (Ce^2) | 0,72 |

Figure 13. SCV Effective Process Time

***Step 5. Select lot size policy***

Once the To-Be state has been evaluated, the new lot sizes per product are selected. Table 12 presents the numerical results of the released time in setup expressed as number of shifts and percentage of the net capacity per resource.

| Filling PU | 750 | 850 | 851 | 852 | 853 | 854 | 855 |
|---|---|---|---|---|---|---|---|
| Reduced setup time (hrs) | 293 | 452 | 348 | 163 | 206 | 334 | 111 |
| Reduced setup time % | 5% | 8% | 6% | 3% | 4% | 7% | 9% |
| Released time (shifts) | 39 | 59 | 46 | 21 | 27 | 44 | 15 |

Table 12. Reduced setup time at Filling PU

If we recall from section 3.7.4, the component Availability has the worst performance in the OEE calculation. With this reduction in time spent in setups, Figure 14 depicts how OEE will be influenced in a positive way as well.

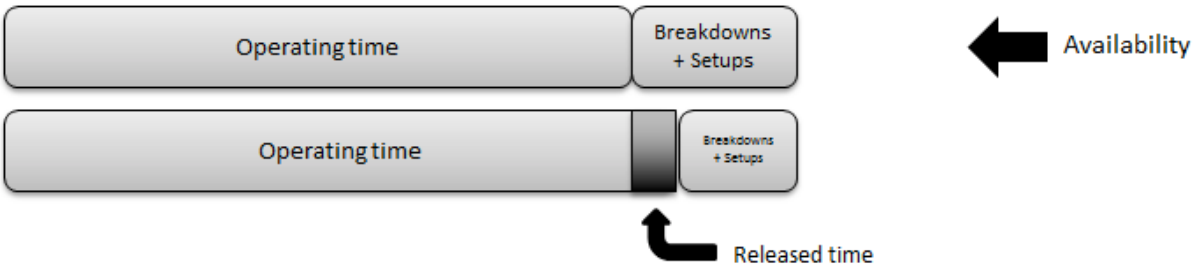


Figure 14. Impact on OEE

It is important to mention that since the products have an expiration date a maximum replenishment frequency should be established per item as well, since this value varies from item to item.

The same steps were applied for the packaging PU and positive results were encountered as well. The detailed information can be found in APPENDIX V.

What we can conclude from the result obtained is that it is possible to optimize the lot sizes per item-resource with the consideration of a *hard* constraint of machine capacity; demand per item and holding and setup costs. Time spent in setups was released and this represents an

opportunity for additional output and thus revenue. Considering the lost sales during the last year, this would represent an increase of €XXX,XXX in revenue.

Moreover, we have evaluated the impact of such solution in a set of manufacturing performance measures influenced by the effect of variability, to provide managers with relevant information for a better decision-making. Finally, this can also be considered as a procedure based on quantitative analysis to determine the tactical parameters of lot sizes.

## *4.2. Inventory Model*

When calculating the tactical parameter of safety stocks, uncertainty of forecast from each item should be considered. The Year To Date (YTD) forecast accuracy performance measure for the company is of 65.9%, which clearly represent this uncertainty. Some items in the portfolio of a customer can have a variation in demand of more that its own demand in one review period, and others present smaller fluctuations, thus their behavior is different.

In the case of the transit time from the supply center to the customer's warehouse, it can be of 2 days for the close locations in Germany, or more than 30 days like for Australia, Colombia or Mexico. And the variation of this lead time also depends on the type of transport mode. Nevertheless, the number of days of stock is mostly of two months for all customers.

The current inventory policy used by the company is based on an agreement between affiliate customers and the supply and demand managers. The agreement takes into account the previous performance of forecast accuracy and service level. The decision rules are not clear and there is no threshold for setting a tactical parameter such as safety stock. Generally, all the items in the portfolio of a customer have the same value of safety stock expressed on days and are evaluated once per year. Therefore the inventory policy is not chosen in a correct manner since it is not adjusted to the characteristics of every item-customer.

The proposed inventory model is of the (R,S) type. The problem is formulated in such a way that it takes into account the uncertainty and distribution of the demand during a period of duration *L* and a predefined service level. Moreover, *R* expresses the basic review period, which is the time between two consecutive moments when we monitor the stock level. In our case, R is derived from the optimized replenishment quantities in section 4.1.1. These replenishment frequencies represent the moments in time when stock is built up and is expressed in number of weeks. Finally, variable *S* is defined as the order-up-to-level, so orders are placed in order to raise the inventory position to *S.*

A key parameter in this model is the time period over which protection is required (*L*). This time period is composed by the total production time and a transit time. Both time periods are added and are represented as *L*, which is also expressed in number of weeks. In the actual situation, the safety stock does not take into account both components, therefore it is very common to have urgent orders from customers in the middle of the production cycle and that in order to provide a service, are expedited and have an impact into the rest of the products already scheduled. This

finally affects the deliveries of the rest of the products in the queue, causing a low on time order delivery.

In order to calculate this period of time *L* first we extracted the transport lead time for each customer. Generally there is only one transport mode per customer, but there are cases were orders can be expedited and are shipped by air. In this case we used the primary transport mode to deliver to each customer and we assumed orders cannot be expedited because it is also desired to reduce these events due to a high cost impact. The lead times in this model are based on historical information from last year of this primary transport mode, and are taken from the Transport Module of the ERP system.

Finally the production time takes into account the time that an item takes to be processed from the beginning of the manufacturing phases till the packaging phase. This time comes from our analysis in the queueing model from section 4.1.2.

**The assumptions for this model are the following:**

1. Demand is assumed to have a Gamma distribution.
2. Demand is an independent random variable
3. Lead time is an independent an random variable
4. Subsequent orders cannot over take each other.

The notation used is as follows:

| Symbol | Description |
|---|---|
| $X_t$ | Actual demand of period *t* |
| $\hat{x}_{t-3,t}$ | Forecast of period *t*, made on period *t-3* |
| R | Review period |
| N | Number of periods |
| $\sigma_1$ | Standard deviation of demand over a unit period |
| $\sigma_L$ | Standard deviation of lead time |
| E(L) | Expected lead time |
| E(D) | Expected demand in units in a unit time period |
| k | Safety factor |

The safety stock is calculated based on the next expression, where *k* is named as the safety factor derived from the required service level. $\sigma_L$ is defined as the standard deviation of the demand during a lead time *L*.

$$SS = k\sigma_L \tag{4-17}$$

The required service level and the distribution of the demand during a period L determine the value of *k*. The demand distribution is assumed to be Gamma since in many cases this turns out to be realistic (de Kok, 2002). And the $CV_{R+L}$ of demand over the review and lead time period in most of the items turns out to be above the threshold of 0.5 were the Gamma distribution is recommended to be used. With such a high value of the coefficient of variation a normal distribution would lead to a probability of negative demands. Finally, the value of the safety factor can be calculated with the Goal Seek ability of EXCEL™ with a gamma distribution and targeting to meet a specific value of service level.

To calculate the standard deviation of demand per period we make use of equation 4-18. In this case we make use of $\hat{x}_{t-3,t}$ which is the forecast provided three months prior to the actual demand of period *t* since this is the forecast version that is used to generate the new sales orders.

$$\sigma_1 = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(x_t - \hat{x}_{t-3,t})^2} \tag{4-18}$$

For the computation of the standard deviation in lead time we took the historical information of one year and only for the primary transport mode. With this we have the last parameter $\sigma_L$ to complete the order-up-to-level policy. All the described parameters are translated into weeks so everything is expressed in the same unit of time.

The expression in 4-19 calculates the order-up-to-level, where the first part accounts for the expected demand during lead time *L*; and the second term recalls from equation 4-17 as the safety stock value, or re-order level.

$$S = E[D(0, R + L)] + k\sigma(D(0, R + L)) \tag{4-19}$$

The value of *S* then is determined by the total length of time from when the inventory is reviewed, until the order arrives to the customer (R+L), and the variation of demand and lead time.

### *4.2.1. Results Inventory Model*

The calculation of new safety stocks based on the variability of demand during a period of lead time *L* gave as a result an appropriate distribution of stock among the items based on their forecast behavior and production frequency. Items that had large variation in forecast have a bigger value of *S*. In this section we provide several scenarios where the variables of standard deviation of demand, service level, standard deviation of lead time and the lead time it self were tested. We made use of the Excel spread sheet “Discrete time inventory models batch mode”

(de Kok, 2014) to compute the order-up-to-level and the average inventory prior to receive an order and after receiving it.

***Scenario 1. Standard deviation of demand***

Table 13 provides an example of the influence of variability of demand in the size of *S,* were the second item is covered with more stock, since its variability in a period of time *R* is more than its demand in the same period of time. A problem that we encounter in this situation is that the variability in forecast has a positive value; the forecast bias is between 5 and 10% globally. This means that the forecast provided by the customers is generally inflated.

It is commonly seen in practice that the forecast provided is corrupted with an additional "safety factor" as a way to ensure that the received product will be enough in case of shortages from the supply center. Moreover, since the affiliate customers don't have the control for setting the inventory level in the system, this measure of creating an extra buffer in the forecast can be a way to provide them with more product than they actually need. This behavior should be avoided since it is one of the ways to generate the bullwhip effect in the supply chain.

| Item | R | E[D] | $\sigma$(D) | E[L] | $\sigma$(L) | Q | $P_2$ | s | E[X] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.99 | 16710 | 6715 |
| 2 | 8 | 1000 | 1200 | 6 | 0 | 0 | 0.99 | 23513 | 13518 |

Table 13. Order-up-to-level with High Variability in Forecast

***Scenario 2. Service Level***

In a second case we evaluate the effect of the service level. Table 14 shows how the order-up-to-level is decreasing in function of a predefined service level of type P2, which is the fraction of customer demand satisfied directly from the shelf. This service measure is used because it expresses service level the same way in which the company measures it. Then the quantity of stock is aligned with the required performance measure of service.

| Item | R | E[D] | $\sigma$(D) | E[L] | $\sigma$(L) | Q | $P_2$ | s | E[X] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.99 | 16710 | 6715 |
| 2 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.95 | 14893 | 4918 |
| 3 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.90 | 13897 | 3947 |
| 4 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.85 | 13205 | 3280 |
| 5 | 8 | 1000 | 500 | 6 | 0 | 0 | 0.80 | 12638 | 2738 |

Table 14. Order-up-to-level with different Service Level

***Scenario 3. Standard deviation of lead time***

Table 15 represents the influence of the variability of the lead time. As it was expected, higher variability in lead time leads to higher values of *S* and higher average inventory.

| Item | R | E[D] | δ(D) | E[L] | δ(L) | Q | $P_2$ | s | E[X] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 8 | 1000 | 500 | 6 | 0.01 | 0 | 0.99 | 16689 | 6694 |
| 2 | 8 | 1000 | 500 | 6 | 0.1 | 0 | 0.99 | 16694 | 6699 |
| 3 | 8 | 1000 | 500 | 6 | 0.5 | 0 | 0.99 | 16826 | 6831 |
| 4 | 8 | 1000 | 500 | 6 | 1 | 0 | 0.99 | 17222 | 7227 |

Table 15. Order-up-to-level and Standard deviation in Lead Time

***Scenario 4. Lead time***

The last scenario that was tested was the lead time (Table 16). As we expressed in section 4.2, the value of *L* has a big impact in the calculation of the order-up-to-level. Higher lead times will require more inventory to cope with the uncertainty in demand.

In this case study, when we were defining the value of *L*, the biggest portion of it was attributed to production time. Due to the fact that the supply center produce with the policy of keeping as less inventory as possible between production units, the production time is considered from the formulation phase until the product is finally packed. If it is desired to reduce the production time, then there should be a stocking point between the production units and then the production time can start from that stocking point till the last phase.

| Item | R | E[D] | σ(D) | E[L] | σ(L) | Q | $P_2$ | s | E[X] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 8 | 1000 | 500 | 1 | 0.01 | 0 | 0.99 | 16689 | 6694 |
| 2 | 8 | 1000 | 500 | 2 | 0.01 | 0 | 0.99 | 17811 | 6816 |
| 3 | 8 | 1000 | 500 | 3 | 0.01 | 0 | 0.99 | 18930 | 6935 |

Table 16. Order-up-to-level and Lead Time

***Product Classification***

As it was explained in section 2.3, different inventory policies apply to different product types. A policy of the type (R,S) is suggested to be applied to B products. In this case we decided to use such model for all products since it represent a simplified method with reasonable values of stock for our system. With this model we were able to combine the optimized replenishment frequencies in the production site, the fact that the supply center does not hold inventory of finish products and the lead time for the customers to receive the product.

Some of the product for one of the customers is depicted in Table 17. From these results, the order-up-to-level for A and B products were considered more reasonable in terms of volume. For all the items a careful analysis should be completed in order to avoid extreme cases like in item 15 where the order-up-to-level is equivalent to fourteen months of demand due to a high standard deviation of demand. For C items it can be recommended to establish a minimum quantity to be ordered, due to the low volume in such items. The definition of minimum order quantities is a control measure that is already in place in the company.

| Item | R | E[D] | σ(D) | E[L] | σ(L) | Q | $P_2$ | s | E[X] | Product type |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 6132 | 2858 | 6 | 0.194 | 0 | 0.98 | 120573 | 47050 | A |
| 2 | 14 | 7035 | 1690 | 6 | 0.194 | 0 | 0.98 | 143254 | 51872 | A |
| 3 | 16 | 3061 | 705 | 6 | 0.194 | 0 | 0.98 | 68154 | 25330 | A |
| 4 | 10 | 6268 | 1937 | 6 | 0.194 | 0 | 0.98 | 105402 | 36522 | A |
| 5 | 8 | 2582 | 737 | 6 | 0.194 | 0 | 0.98 | 38123 | 12329 | A |
| 6 | 6 | 10390 | 1927 | 6 | 0.194 | 0 | 0.98 | 128694 | 35292 | A |
| 7 | 16 | 1954 | 836 | 12 | 0.194 | 0 | 0.98 | 57977 | 18908 | B |
| 8 | 14 | 4240 | 2147 | 6 | 0.194 | 0 | 0.98 | 92766 | 37685 | B |
| 9 | 16 | 2180 | 926 | 9 | 0.194 | 0 | 0.98 | 57730 | 20692 | B |
| 10 | 18 | 1661 | 913 | 6 | 0.194 | 0 | 0.98 | 43349 | 18450 | C |
| 11 | 10 | 42 | 115 | 8 | 0.194 | 0 | 0.98 | 1992 | 1453 | C |
| 12 | 16 | 31 | 99 | 6 | 0.194 | 0 | 0.98 | 1809 | 1374 | C |
| 13 | 14 | 37 | 91 | 6 | 0.194 | 0 | 0.98 | 1622 | 1137 | C |
| 14 | 18 | 12 | 37 | 6 | 0.194 | 0 | 0.98 | 703 | 524 | C |
| 15 | 16 | 31 | 97 | 6 | 0.194 | 0 | 0.98 | 1775 | 1340 | C |
| 16 | 12 | 31 | 69 | 9 | 0.194 | 0 | 0.98 | 1318 | 851 | C |
| 17 | 14 | 1923 | 1053 | 8 | 0.194 | 0 | 0.98 | 46776 | 17952 | C |
| 18 | 18 | 22 | 14 | 8 | 0.194 | 0 | 0.98 | 647 | 268 | C |
| 19 | 18 | 175 | 75 | 8 | 0.194 | 0 | 0.98 | 4794 | 1821 | C |
| 20 | 18 | 736 | 210 | 8 | 0.194 | 0 | 0.98 | 19543 | 7030 | C |

Table 17. Order-up-to-level and Product Classification

***Measuring Service Level***

The objective of creating inventory is to provide with the adequate buffer to cover the demand uncertainty and finally be able to provide the required service level. Therefore a key variable is how the service level is calculated. A P1 service level, that is the probability of no stock just before the arrival of an order, will provide a different result than if we measure a P2 service level, which is defined as the fraction of demand satisfied directly from the shelf. This in fact makes a difference since for the same value of *S,* P1 reflects a lower service level, which means that more stock will be allocated when it is not necessary. To exemplify this effect we made use of the Excel spread sheet "Classical Inventory Models" (de Kok, 2002). We considered the case of the first item in Table 17 and we can show that for an order-up-to-level of 120,573 units a service level of the type P2 reaches a 98% but a P1 type has a value of 80% (Table 18).

| Analysis | |
|---|---|
| $P_1$ | 80% |
| $P_2$ | 98% |
| $E[X(t+½)^+]$ | 47050 |
| E[Q] | 73584 |

Table 18. P1 and P2 Service Level

Additionally, a simulation from this Excel spread sheet was used to illustrate the behavior of the model and the physical inventory of the same item through the time. In Figure 15 we can see how every 12 weeks the red line increases to a value of 120,573 that is the order-up-to-level S. The blue line represents how the physical inventory at the customer site will behave. And the doted line is the average inventory E[X(t+½)+], with an average value of 47,050 units.

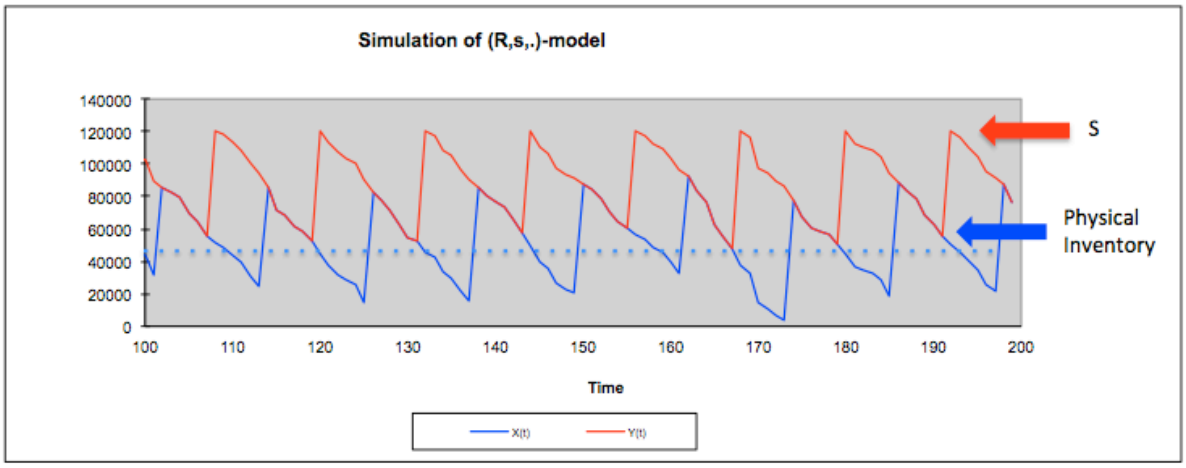


Figure 15. Order-up-to-level simulation

Concluding, the results from the inventory model are recommended for A and B products were the investment in stock is more advisable due to the profit generated from them. Moreover, this items presented a relatively a more stable behavior in the fluctuations of demand and the value of S is well assigned to this variation during the review period and lead time. If the company has interest in reducing the inventory at the customer site and still delivers a high service level as 99%, it is advisable to reduce the production cycle or reduce the transit time.

## *4.3. New Supply Chain Control Structure*

The following functional requirements and conditions were formulated for the new control structure:

1. The total capacity utilization per year must be under 100%.
2. Holding and setup costs should be minimized to the extent that requirement one is meet.
3. Keep cycle time per production unit under 30 days.
4. Provide a safety stock policy subject to a predefined service level.

The basis for the fulfillment of the previous requirements is the calculation of the tactical parameters of lot sizes and safety stock levels. These tactical parameters are part of the decision function diagram explained in section 3.3, specifically in the functions of demand planning and master planning.

Making use of the IDEF[3] modeling method, we position the tactical parameters in the decisions function diagram. Specifically, these parameters perform the control role in the Supply Management function, Master Planning and Production Planning (Figure 16).

The frequency to calculate both parameters is at least twice per year, but in the case of the lot sizes it is recommended to use the proposed tool every quarter to perform medium term analysis and evaluate if changes are necessary, either in lot sizes or to increase capacity. Frequency places an important role in every control system. The provided models are tools that support management for a more effective production and inventory planning. The decisions taken after the analysis of the result is obtained are ways to anticipate to any unforeseen change in the demand behavior. If this aggregate planning analysis is not performed on time, the ability to react to such changes is very hard and costly.

From the organizational perspective, the role that should be in charge of doing such calculations and what-if scenarios is recommended to be someone who is knowledgeable in the operation. For the safety stock calculation the role of supply and demand management is recommended, and for the calculation of lot sizes the production leader is appropriate. Both roles should communicate the outcome of such parameters in order to ensure the alignment of the operation with the strategic objectives of the company.

[3] See APPENDIX VI for semantics of the modeling technique.

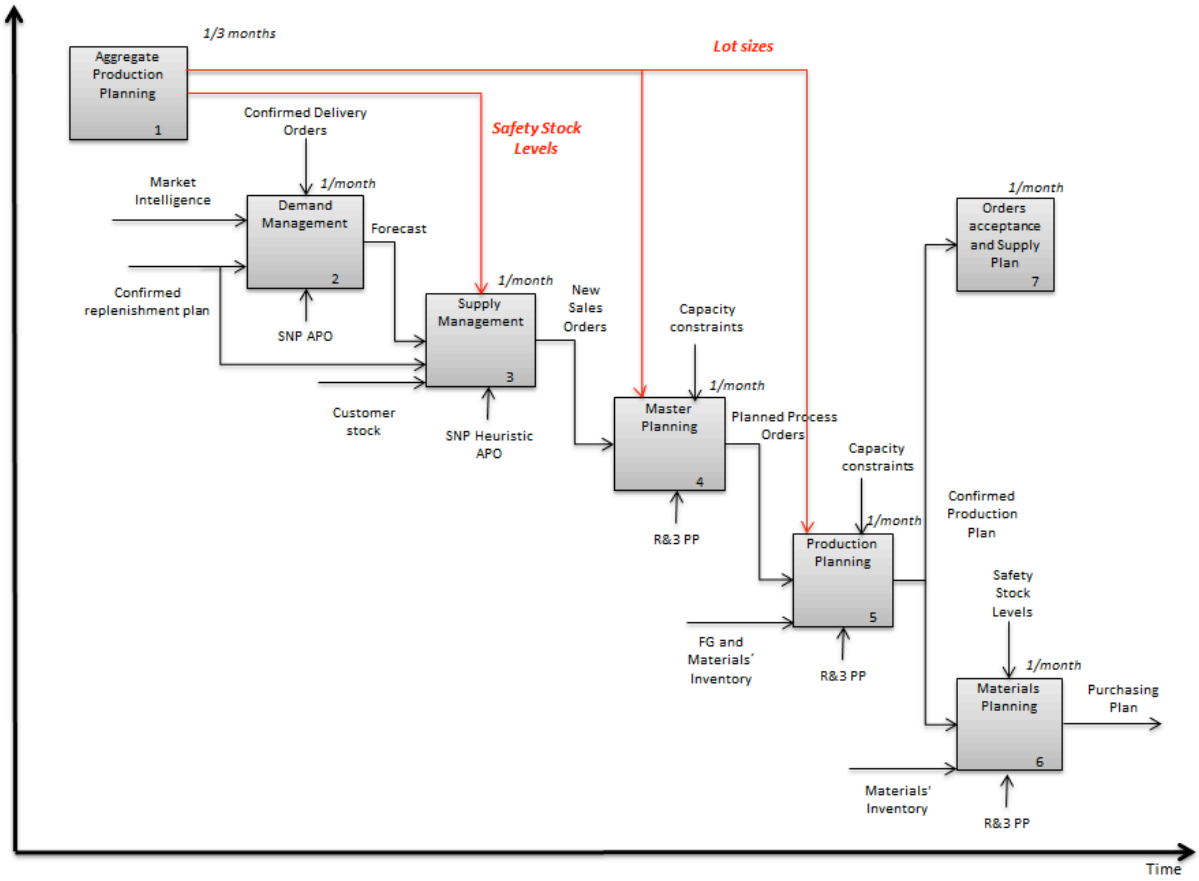


Figure 16. New Supply Chain Control Structure

# 5. Conclusions

The problems encountered by the Supply Center with the delivery reliability are caused by the decision procedures used in the actual situation. The major deficiency in the existing process is by not taking into account the capacity constraint and interaction of items at resource level. Furthermore, the behavior in the short run in coping with potential shortages with an already limited available capacity has created a "fire fighting" effect. This leads to high utilization of resources, low production efficiency, long cycle times and poor delivery performance.

A control structure that is supported by the calculation of tactical parameters was the result of this thesis project. In this report we have explained how the control structure was characterized in terms of functional requirements that address the major characteristics of the system.

Moreover, this thesis provides insight into the design of a control structure that can address the following hypotheses:

***Hypothesis 1: The implementation of a heuristic for setting tactical parameters will maximize the output at the technology selected.***

The proposed heuristic has shown to improve the As-Is state of the system. The information used as input considers a period of time longer than the actual procedure for the allocation of items; therefore it is possible to detect potential bottlenecks in a medium to long term plan. Additionally, with the implementation of a lot size optimization procedure it was possible to release time to increase production for the cases were it was foreseen not to be able to fulfill the demand, maximizing the throughput of the resources.

Finally, with the application of queuing theory it was possible to give approximations for the manufacturing performance measures of work in process, throughput and cycle times. With the calculation of such measures, we provide information about the impact of the proposed lot sizes from the model. Once again, these measures support this hypothesis showing reduction in the cycle time, work in process and increase in throughput. As a whole, information that is relevant for a better decision making is provided.

***Hypothesis 1.a: Optimization of lot sizes per production line with the consideration of capacity, will lead to effective capacity utilization.***

The optimization of lot sizes of multi-items in a single resource has shown that it is possible to decrease the time spent in setups. The model takes into account the individual characteristics of a set of items allocated to a resource and by means of a minimization cost function and a capacity constraint the replenishment frequencies are spread among the items.

The increment of replenishment frequencies in situations where demand level is high and capacity is limited, is driven by short term interests which focus on the realization of high service level. Nevertheless, long term interests are harmed (total throughput and profit) and constant delays are present or demand is not fulfilled. According to Fransoo (1992), if maximization of long-term profit is a firm's objective, therefore it can be hypothesized that keeping

replenishment and cycle time stable is a sufficient condition for maximizing profit in a highly utilized single-machine production system with large setup times.

***Hypothesis 2: Calculation of safety stocks based on lead time, demand variability and requested service level, will provide the necessary buffer to satisfy customers demand.***

Through statistical planning of safety stocks we can leverage the capabilities of the company to allocate inventory were it is necessary. Items with higher variability in forecast, lead time and high expected service level, are assigned with more inventory. An order-up-to-level policy (R,S) was proposed and the results presented a more reasonable outcome in items of type A and B in terms of inventory investment. For C items it was recommended to keep the policy of a minimum required quantity since most of these items have a very low demand.

Moreover, these tactical parameters were positioned in a new decision function diagram that depicts the influence of them in the supply chain structure. As it was stated previously, the organization is going through a re-structuration process so it is a perfect time to define the roles that should be responsible for setting such parameters in a regular basis. These are not one-time parameters and should be adjusted to the new reality of the system.

The methodology developed has been carefully documented based on data from the pipettes technology of the company but it can be applied routinely to other product categories in the same company or in the pharmaceutical industry, where lot sizes and safety stocks have to be reconsidered. It is of our knowledge that pipettes is not the only technology with such capacity and service level problems and the tactical parameters are not defined either, therefore this solution can be extended to the other areas as well.

# 6. Reflection

In real life production systems, the design of a solution can be a complex task due to the existence of many dimensions, different resource types, processes and the many interdependencies among them (Bertrand, A Note on the Design of Logistics Control Systems). A solving process guided by design rules enabled us to approach such a complex real life problem in an organized an effective way.

The contribution of this thesis project relies on the generation of a generic operation planning and control structure for a pharmaceutical company. The problem was partitioned in modules to gain insight into the operation, constraints and flaws. The modules in which the problem was partitioned were quality, workforce, production and supply planning and manufacturing systems. This structured problem solving technique can give a guideline for similar environments where the organization has critical constraints regarding workforce as well as machine capacity and where the products are required to meet high quality standards.

Furthermore, the solution provided was supported with modeling tools for the calculation of tactical parameters. The mathematical models make use of simple but effective techniques as the EPQ problem, queuing theory and inventory models for one item in one location. Applying this simple methods to a case study in the process industry characterized by multiple items, multiple resources and limited capacity; provides validity of such solutions in such an environment.

Since we are dealing with a system that is by nature dynamic, the usefulness of this models can be seen also as a support for better decision making when the system changes, like increment in demand or increment of products in the portfolio. However, the frequency at which these analyses are conducted plays a very important role because it determines the ability to be able to anticipate potential changes in the system and its environment.

# 7. Further Research

From a theoretical perspective there are many options for additional research. From the optimization of lot sizes we were able to reduce the time spent in setups and also the variation in the effective process time. Since the manufacturing system is sequential, the variability in the upstream station propagates this effect to the next station. The proposed model decouples this system and is not able to evaluate the effects of changing the lot sizes from one station to the other, therefore the model can be improved if both process are analyzed at once.

The inventory model was analyzed as a one product, one location. Considering that most of the customers are affiliates of the company, further research in multi-echelon inventory would be of interest to know where it is more convenient to position inventory in terms of cost and service. Currently the supply center plans with a policy of keeping the inventory between production units as low as possible, however this causes a long total production time and the affiliate customers have to have more inventory at their site. It would be of interest to evaluate the possibility of keeping some inventory between the production phases and determine if this could improve the customer service and generate a higher return on investment in the company as a whole.

Finally, the Overall Equipment effectiveness has been proven to be an easy way to identify productivity loses; nevertheless it is also a deterministic metric. Zammori et al. (2011) presented an approximated procedure to take into account the stochastic nature of the OEE, based on the application of the Central Limit Theorem and that has been tested in real cases. Making use of the OEE with stochastic parameters will give a more realistic measure about the state of the manufacturing system.

# *Bibliography*


Albin, S. (1984). Approximating a Point Process by a Renewal Process, II: Superposition Arrival Processes to Queues. *Operations Research*, 1133.

Bagchi, U., Hayya, J., & Chu, C.-H. (1986). The Effect of Lead-Time Variability: The Case of Independent Demand. *Journal of Operations Management*, 159-177.

Bertrand, J. (n.d.). A Note on the Design of Logistics Control Systems. *Lecture Notes*. Eindhoven University of Technology.

Brander, P., & Segerstedt, A. (2009). Economic lot scheduling problems incorporating a cost of using the production facility. *International Journal of Production Research*, 3611-3624.

Brown, R. (1978). *Materials Management Systems.* John Wiley & Sons Inc.

Chan, H., Chung, S., & Lim, M. (2013). Recent research trend of economic-lot scheduling problems. *Journal of Manufacturing Technology Management*, 465-482.

de Kok, A. (2002). *Analysis of one product/one location inventory control models.* Eindhoven: Eindhoven University of Technology.

de Kok, A. (2002). Classical Inventory Models.

de Kok, A. (2014). Discrete time inventory models batch mode v2.

Draft Federal Information Processing Standards Publication. (1993). *Integration Definition for Function Modeling (IDEF0).* National Institute of Standards and Technology.

Fransoo, J. (1992). Demand management and production. *International Journal of Operations & Production Management*, 187-196.

Fransoo, J., Sridharan, V., & Bertrand, J. (1995). A hierarchical approach for capacity coordination in multiple products single-machine production systems with stationary stochastic demands. *European Journal of Operational Research*, 57-72.

Gallego, G. (1990). Scheduling the production of several items with random demands in a single facility. *Management Science*, 1579-1592.

Gautman, N. (2008). Queueing Theory. In *Operations Research and Management Science Handbook.* Taylor & Francis Group.

Günther, H., Grunow, M., & Neuhaus, U. (2006). Realizing block planning concepts in make-and-pack production using MILP modelling and SAP APO(c). *International Journal of Production Research*, 3711-3726.

Harvard University. (2009). *Lagrange Multipliers.* Retrieved June 2014, from http://www.math.harvard.edu/archive/21a_spring_09/PDF/11-08-Lagrange-Multipliers.pdf

Hopp, W., & Spearman, M. (2001). *Factory Physics.* New York: Irwin/McGraw-Hill.

Huang, J., & Yao, M. (2006). An improved heuristic for solving the economic lot scheduling problem in flow shops under porwer-of-two policy. *Journal of the Chinese Institute of Industrial Engineers*, 127-140.

Kallrath, J. (2002). Planning and scheduling in process industry. *OR Spectrum*, 219-250.

Karimi, B., Fatemi Ghomi, S., & Wilson, J. (2003). The capacitated lot sizing problem: a review of models and algorithms. *The International Journal of Management Science*, 365-378.

Raza, S., & Akgunduz, A. (2008). A comparative study of heuristic algorithms on economic lot scheduling problem. *Journal of Heuristics*, 94-109.

Rogers, J. (1958). A computational approach to the lot scheduling problem. *Management Science*, 264-284.

SAP. (2014). *SAP Help Portal*. Retrieved 06 2014, from SAP Business Suite: http://help.sap.com/saphelp_erp60_sp/helpdata/en/f4/7d289444af11d182b40000e829fbfe/content.htm?frameset=/en/f4/7d28ae44af11d182b40000e829fbfe/frameset.htm&current_toc=/en/60/33b8371a2c9912e10000009b38f889/plain.htm&node_id=30

SAP AG. (2000). *SAP Advanced Planner and Optimizer (SAP APO)*. Retrieved February 25, 2014, from SAP Library: http://help.sap.com/saphelp_apo/helpdata/en/92/dd013872af2946e10000009b38f8cf/frameset.htm

SAP. (n.d.). *Material Requirements Planning (PP-MRP)*. Retrieved May 2014, from Period Lot-Sizing Procedures: http://help.sap.com/saphelp_46c/helpdata/en/f4/7d282c44af11d182b40000e829fbfe/content.htm?frameset=/en/fe/819b9f643b11d3b4e40004ac160649/frameset.htm&current_toc=/en/f4/7d3f9344af11d182b40000e829fbfe/plain.htm&node_id=62&show_children=false

Satyam, K., & Krishnamurthy, A. (2011). Performance analysis of CONWIP systems with batch size constraints. *Annals of Operations Research*, 85-114.

Shouten, W. (2013). *Synchronization of supply chain planning processes: Design of a production wheel at an outsourced company.* Eindhoven: TUE. School of Industrial Engineering.

Silver, E., Pyke, D., & Peterson, R. (1998). *Inventory Management and Production Planning and Scheduling.* New Jersey: John Wiley Sons.

Smits, S. (2003). *Tactical design of production- distribution networks: safety stocks, shipment consolidation and production planning.* Eindhoven: Eindhoven University of Technology.

Tan, T. (2013). Modeling and Analysis of Manufacturing Systems. *Lecture Notes*. Eindhoven University of Technology.

Trigeiro, W., Thomas, L., & McClain, J. (1989). Capacitated Lot Sizing with Setup Times*. *Management Science*, 353.

van Aken, J. E., Berends, H., & van der Bij, H. (2007). *Problem Solving in Organizations.* New York: Cambridge University Press.

van Drongelen, I. K. (2001). The iterative theory-building process: rationale, principles and evaluation. *Management Decision*, 503-512.

Vandaele, N., Van Nieuwenhuyse, I., Claerhout, D., & Cremmery, R. (2008). Load-Based POLCA: An Integrated Material Control System for Multiproduct, Multimachine Job Shops. *Manufacturing & Service Operations Management*, 181-197.

Vorne Industries. (2012). *Fast Track OEE for Production People on the Move.* Retrieved May 2014, from http://www.oee.com/

Whitt, W. (1982). Approximating a Point by a Renewal Process, I: Two Basic Methods. *Operations Research*, 125-147.

Whitt, W. (1983). The Queueing Network Analyzer. *The Bell System Technical Journal*, 2779-2815.

Whitt, W. (1983). The Queueing Network Analyzer. *The Bell System Technical Journal*, 2779-2815.

Winands, E., Adan, I., & van Houtum, G. (2010). The stochstic economic lot scheduling problem: A survey. *European Journal of Operational Research*, 1-9.

Zammori, F., Braglia, M., & Frosolini, M. (2011). Stochastic overall equipment effectiveness. *International Journal of Production Research*, 6469-6490.

# *APPENDIX I*

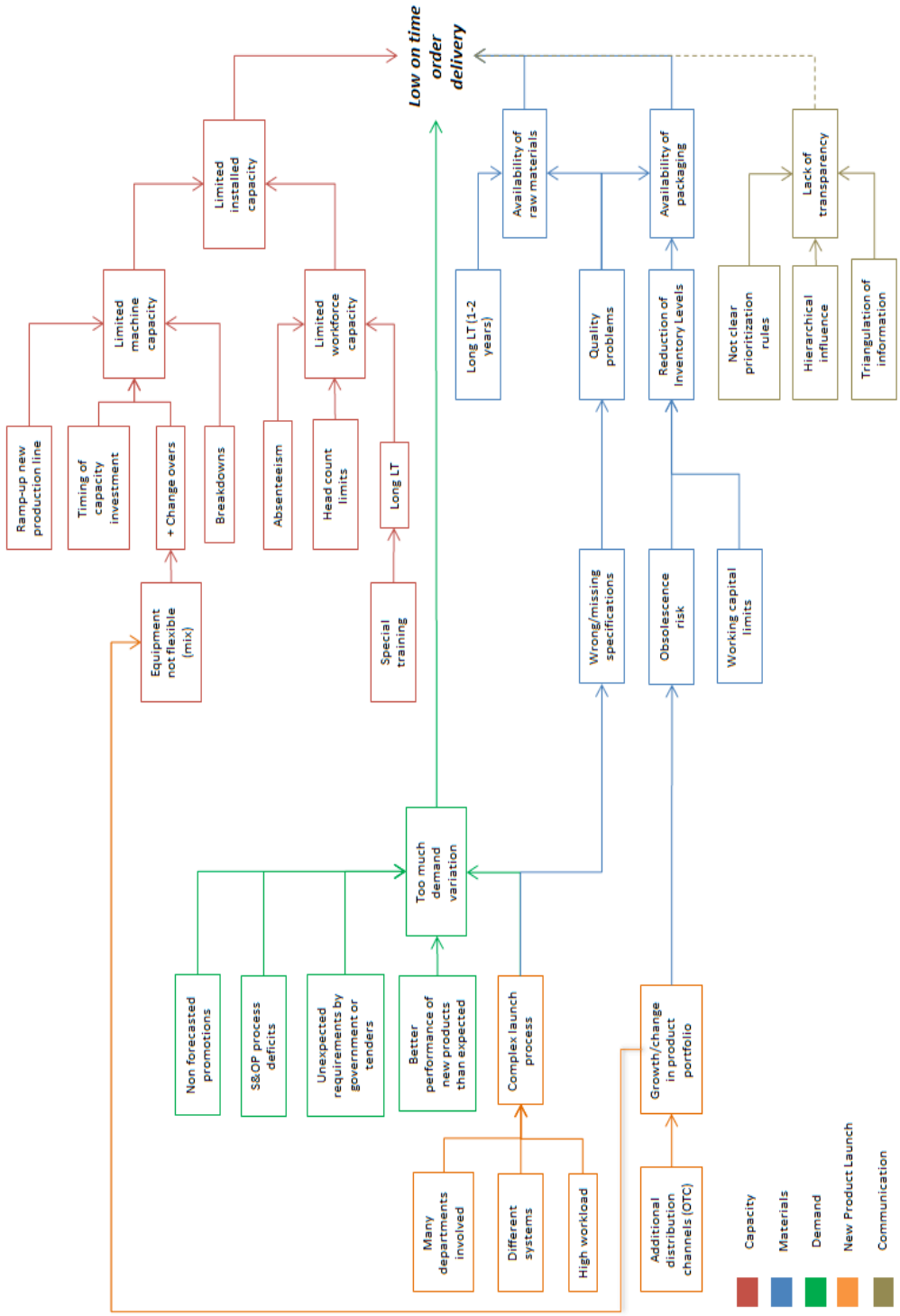


Figure 17. Cause-Effect diagram

# *APPENDIX II*

| Notation | |
|---|---|
| **Arrival Process** | M, G, $E_k$, H, PH, D, GI, etc. |
| **Service time distribution** | M, G, $E_k$, H, PH, D, GI, etc. |
| **Number of servers** | 1,2,…, ∞ |
| **Number of customers in the system** | 1,2,…, ∞. Default: ∞ |
| **Service discipline** | FCFS, LCFS, ROS, SPTF, etc. Default: FCFS |

Table 19. Fields in the Kendall Notation (Gautam, 2008)

# *APPENDIX III*

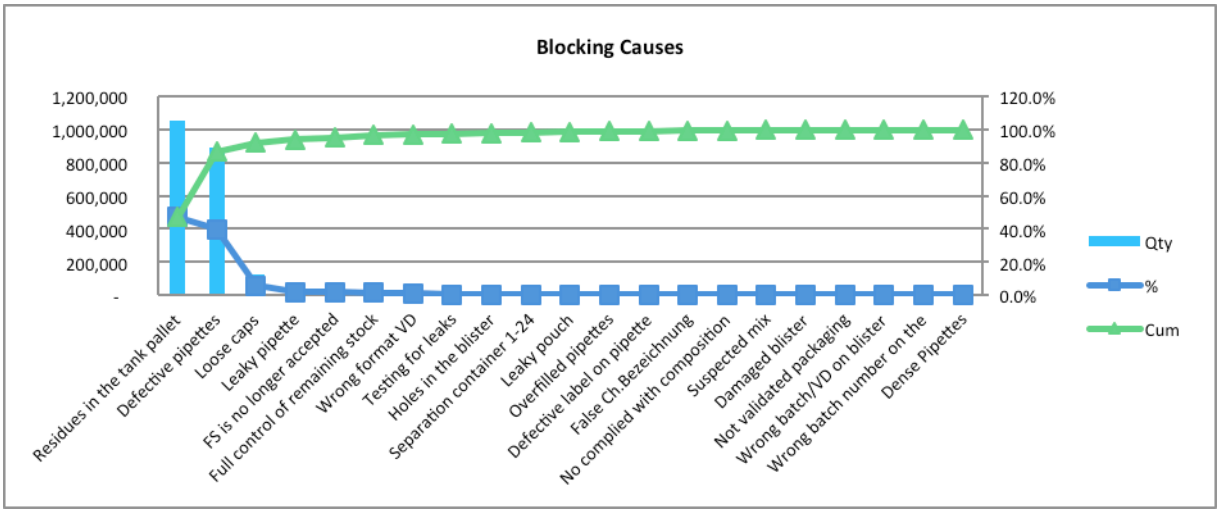


Figure 18. Quality Blocking Causes 2013

# *APPENDIX IV*

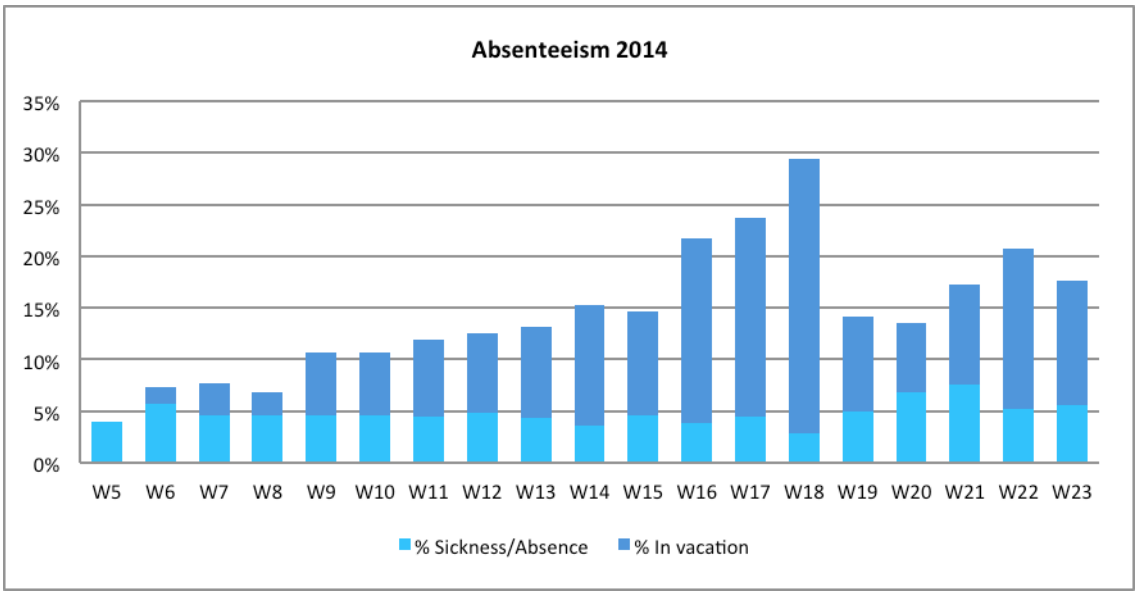


Figure 19. Absenteeism 18 weeks

# *APPENDIX V*

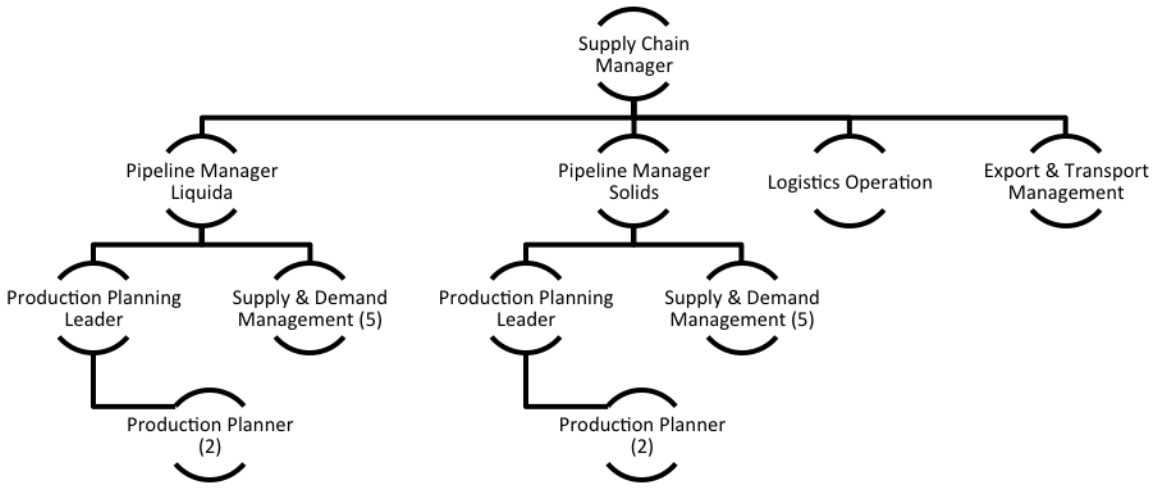


Figure 20. Organization chart of the Supply Chain Department

# *APPENDIX V*

Step 1. Check for overloaded resources

| | Packaging PU | | 856 | 861 | 863 | 865 | 867 | 868 | 869 |
|---|---|---|---|---|---|---|---|---|---|
| Current Lot size policy | NC | Net Capacity (hrs) | 5.434 | 5.600 | 1.770 | 5.556 | 5.328 | 5.328 | 4.811 |
| | C | Used Capacity (hrs) | 4.096 | 5.950 | 1.500 | 226 | 5.071 | 5.036 | 5.116 |
| | U | Utilization | 85% | 106% | 85% | 4% | 95% | 95% | 106% |
| | WIP | Average work in process (parts) | 257.389 | N.A. | 26.693 | 9.898 | 74.023 | 250.863 | N.A. |
| | CT | Average cycle time (days) | 4 | N.A. | 2 | 0 | 11 | 16 | N.A. |
| | TH | Average output (parts/hr) | 2.567 | N.A. | 734 | 1.019 | 307 | 707 | N.A. |

Table 20. Manufacturing Performance Measures at Initail State at Packaging PU

Step 2. Reallocate items

| | Packaging PU | | 856 | 861 | 863 | 865 | 867 | 868 | 869 |
|---|---|---|---|---|---|---|---|---|---|
| Current Lot size policy | NC | Net Capacity (hrs) | 5.434 | 5.600 | 1.770 | 5.556 | 5.328 | 5.328 | 4.811 |
| | C | Used Capacity (hrs) | 4.096 | 5.585 | 1.500 | 226 | 5.315 | 5.254 | 4.569 |
| | U | Utilization | 85% | 100% | 85% | 4% | 100% | 99% | 95% |

Table 21. Utilization After Reallocation at Packaging PU

Step 3. Optimization of Lot sizes

| | Packaging PU | | 856 | 861 | 863 | 865 | 867 | 868 | 869 |
|---|---|---|---|---|---|---|---|---|---|
| Opt Lot Sizes | NC | Net Capacity (hrs) | 5.434 | 5.600 | 1.770 | 5.556 | 5.328 | 5.328 | 4.811 |
| | C | Used Capacity (hrs) | 3.828 | 5.256 | 1.388 | 229 | 5.128 | 4.999 | 4.112 |
| | U | Utilization | 80% | 94% | 78% | 4% | 96% | 94% | 85% |

Table 22. Utilization with Optimized Lot Sizes at Packaging PU

Step 4. Update manufacturing performance measures

| | Packaging PU | | 856 | 861 | 863 | 865 | 867 | 868 | 869 |
|---|---|---|---|---|---|---|---|---|---|
| Opt Lot Sizes | NC | Net Capacity (hrs) | 5.434 | 5.600 | 1.770 | 5.556 | 5.328 | 5.328 | 4.811 |
| | C | Used Capacity (hrs) | 3.828 | 5.256 | 1.388 | 229 | 5.128 | 4.999 | 4.112 |
| | U | Utilization | 80% | 94% | 78% | 4% | 96% | 94% | 85% |
| | WIP | Average work in process (parts) | 275.459 | 192.239 | 22.989 | 9.793 | 141.799 | 297.194 | 36.551 |
| | CT | Average cycle time (days) | 4 | 11 | 1 | 0 | 17 | 17 | 2 |
| | TH | Average output (parts/hr) | 2.746 | 747 | 793 | 1.004 | 357 | 783 | 693 |

Table 23. Manufacturing Performance Measures with Optimized Lot Sizes at Packaging PU

Results 5 Steps Heuristic Packaging PU

| **Packaging PU** | **856** | **861** | **863** | **865** | **867** | **868** | **869** |
|---|---|---|---|---|---|---|---|
| **Reduced setup time (hrs)** | 268 | 329 | 111 | - | 187 | 255 | 457 |
| **Reduced setup time %** | 5% | 6% | 6% | 0% | 4% | 5% | 9% |
| **Release time (shifts)** | 35 | 43 | 15 | 0 | 25 | 34 | 60 |

Table 24. Reduced Setup time at Packaging PU

# *APPENDIX VI*

IDEF0 is an engineering technique for functional analysis, systems design and baselines for continuous improvements. The models provide a "blueprint" of functions and the interfaces among them (Draft Federal Information Processing Standards Publication, 1993).

Boxes represent the functions of the system and the relationship to other functions is depicted with arrows. The side of the box with which an arrow interfaces has a standard meaning as can be seen in Figure 21. Arrows coming form the left side are called *inputs*. Inputs are transformed or consumed by the function to produce outputs. Arrows coming from the top of the box are *controls*. Controls specify predefined condition of the function in order to have a correct output. Arrows going out on the right side are called *outputs*. Outputs are the data or objects produced as a result of a function. Arrows coming in from the bottom of the box are called *mechanism* and are considered as support to execute the function. (Draft Federal Information Processing Standards Publication, 1993).

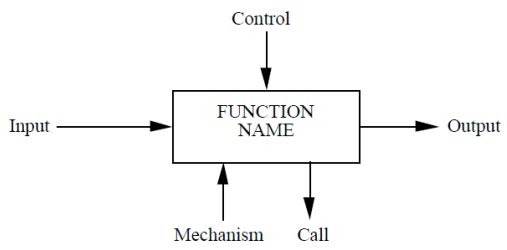


Figure 21. IDEF0 Arrows Positions and Roles