A CASE STUDY ON
“SUPPLY CHAIN MANAGEMENT”

Jorge Maia Gomes
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EXECUTIVE SUMMARY

Due to rapidly expanding business operations in global scale many companies have faced the management of the total network of their customer service and deliveries as the major challenge. As Forrester [20] and Burbidge [8] already on the 60’s showed the supply chains may be characterised by many dynamic phenomena like ‘bullwhip effect’ that in general are not discussed under business process re-engineering or production flow design.

Taking as base a make-to-order product, this work is a study of how the structure of the supply-chain and the performance of its players can impact on the customer response.

At the top of this study is the concept of supply-chain-management. Then, to apply that concept to the present case, it has been made a dynamic simulation of the total supply chain, in which techniques like factor analysis, time series analysis were used.

In the end, the simulation model could not reflect the real system, and due to time restrictions changes could not be executed. However, some recommendations are presented here to improve the validity of the model, so that it can be useful to test different structures in the chain and experiment different performances from the actors, in order to conclude about the main factors affecting the dynamics of the chain.
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1. INTRODUCTION

Brief Description Of The Theme

The value adding from a supplier to a customer can be measured through technical quality, price and cost, service availability, as well as delivery time and punctuality. Increased competition puts more pressure on cost, thus affecting the lead times and inventories. The reduction of lead times and inventories is getting more difficult to achieve because of increased market and customer variations as well as increased logistic distances. These challenges cannot be effectively met by isolating the improvements to specific organisational units, but instead depend critically on the relationships and interdependencies among the different actors (or organisational units) in the network. This means that besides improving their internal processes, companies must also take into consideration the complete supply chain. The supply chain for a given product or product group, can be described as the network of facilities and facilitators that perform functions like procurement of materials, transformation of these materials into intermediate and finished products, warehousing and the distribution of final products to customers.

These networks show various dynamic responses not only because of changes in the markets and competition, but also due to some of its internal characteristics, like:

- Different performance profiles of the supply chain actors, i.e. delivery time, delivery punctuality, defect rate, machine brake downs, absence rate, etc.
- Extended product, customer, and market variations;
- Existence of various organisational behavioural patterns;
- Existence of various loops and overlaps in the information and material flow, as well as decision making processes along the network;
- Number of actors and connections in the chain.

The dynamic behaviour of the network can not be demonstrated with traditional process and activity chain descriptions, specially when the lead times and time buffers are set into minimum. A possible way to analyse the network is to make computational simulation. Using simulation one can experiment different configurations of the system and see how they impact on the total performance.

Aims And Objectives

This work was aiming to model and simulate a ‘make-to-order’ supply chain, with the objectives to analyse the impact of lead-times, information flows, and suppliers’ performance on inventories and delivery punctuality.

Assumptions Of The Work
As a case in the study was used an engineering company having several geographically distributed production facilities, in both parts manufacturing and assembly, and a global sales and site assembly network. The work was focusing on the delivery of new products only.

Methodology

In order to understand the way the case company as a whole, i.e. as a system, operates, what are the basic reasons to its dynamic response, and how it could be improved, data was collected from its operational data bases, and through personal interviews. The data was analysed using various statistical methods, and a computer based continuous/discrete time based simulation model was constructed in order to carry out more in depth analysis. The results from the model were compared with the original data, analysed with statistically methods, and conclusions were drawn from the same.
2. THE CASE

2.1 THE CASE COMPANY

The case company makes engineering products in several locations. Each plant is specialised on its own product group, which are shipped to different sales offices for final assembly and delivery. Sales offices, supported by a number of local distributors are located all over the world, close to hundred countries. The number of products sold through the network is several thousands per annum.

The product portfolio consists of a number of base products, abt. 30 of them, which are sold to customers in hundreds of configurations. The basic configuration is done already in the production units in accordance with the options selected by the customer. The final assembly of the product brings in a higher variety of customer specific solutions and outfit, which makes this part of the supply chain to function like a project organisation.

The company used to have a traditional functional organisation with high autonomy on business unit level, i.e. production plants and sales offices. Each of them has a full responsibility and also control over their own purchases, resource allocation, and to some extent also product development. There are common suppliers only to some key components. Annually agreed transfer prices are used between production units and sales offices. Today the organisation is in a transition phase towards extended common co-ordination of several key areas, like R&D, sourcing, etc.

The business is characterised by high degree of customisation: in the sales offices it is said that every deal is different and unique as such. Still some time ago most of the plants used to operate on semi-annual planning periods, which caused high inventories, demand speculation from sales to production, as well as lack of market flexibility. The high variety of different products, certain market volatility, and more strict profit requirements do not give any space for using a make-to-stock system anymore. Instead, today 'make-to-order' type of operations are implement in every unit. Manufacturing, or to be more exact the assembly, does not start before the order has been received at the factory. Because the production of components follows make-to-stock policy with 'floating' buffers, the system is more likely to be an assembly-to-order one than a make-to-order one. However, some components are also made according to order, although they don't have any major impact on the system itself.

Presently, the total customer lead times are varying from one to several months. The total order administration time throughout the chain can be more than two months. The longest lead times from suppliers are up to two months, which together with rather weak average delivery punctuality (0.7 ...0.8) causes problems in manufacturing. One of the main sources for uncertainty and unpredictability in the system is the preparation of the final assembly site. Quite obviously this uncertainty has also been used as an excuse for delivery adjustments from factories leading to weaker final delivery performance.
2.2 PROBLEM SETTING

The biggest problem which the case company is facing is that the delivery process is rather inconsistent, and due to that conflicts between production plants and sales offices show up quite often.

Manufacturing inputs the responsibility of having delays in their deliveries to sales, arguing that they group their orders to send to the factory, leading the capacity to be under the needs. Sales point that the agreed lead times for production are never fulfilled. This implies that on one hand sales often asks for more products than actually is needed, and on the other hand manufacturing sometimes produces to stock in order to avoid disruptions, and based on forecasts that cannot be accurate when talking about a product that can be configured in several ways to the customers. This production to stock is done to reach manufacturing efficiency, and to balance the production, as well as to avoid possible lack of capacity.

The huge implications of these actions is the big growth of inventories along the chain without improving customer response so much, due to the fact that they can order products with such configuration that is not available either at sales' stocks or manufacturing ones.

This situation needs to be revised and this work is an attempt to go through the main processes and see what are the main actions which should be done to improve the overall efficiency of the delivery process and implicitly the customer response.
3. METHODOLOGY DESCRIPTION

In this chapter I shortly describe the concepts and methods used in this study. First I'll discuss the topic of “Supply Chain Management” and, in more details the supply chain management in assemble-to-order systems. In the second part the subject will be “Supply chain dynamics”, showing the importance of time compression to improve the performance of supply chains. The third part talks about the practices that, in theory, should take place to improve the behaviour of supply chains. The fourth part presents the way supply chains should be modelled and stresses the importance of “Time-based simulation” in this context. The fifth and last part of this chapter is about the modelling tools that could be used in this work. This is followed by the presentation of the reasons that lead to the choose of one of them.

3.1 INTRODUCTION TO “SUPPLY CHAIN MANAGEMENT”

One of the definitions of supply chain is presented by Christopher [11], who says it is “the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the final customer”.

Figure 1 shows an simplified example of a supply chain. On one hand, materials flow downstream, from raw material sources through a manufacturing level, that can be composed of intermediate products manufacturing and final product assembly. These products are then shipped to distribution centres or sales offices and from there to the final customers. On the other hand, we have the information flow going upstream, through the same ‘actors’ of the system.

![Diagram of supply chain](image)

*Figure 1 - Main material and information flows along one supply chain*

Supply Chain Management is a term which has been used extensively over the past fifteen years, particularly by those production and distribution organisations, that have implemented the logical principles of Lean Production, Total Quality Management an Just In Time production into the manufacturing and process world [21]. The term was essentially developed to get across a conceptual view, that business are connected both internally and externally, and that in order to control them in an efficient way one must put more attention on the flow of decisions or products through all the activities that are
encompassed by the ‘chain’ in order to satisfy the global customer and business need. In fact it is usual, that each function contributing to the management of the supply chain, develops processes and systems, that meet their individual needs, not necessarily in the best interest of the overall supply chain. Each function strives for its own excellence, and many achieve it, but this certainly does not create an optimised supply chain.

Although an efficient way of working within the boundaries of one organisational unit is desirable, generally the performance will not be the expected one, due to poorly performing external suppliers and customers in the supply chain. This means that supply chain management requires co-ordination with customers and suppliers, in order to avoid the problems resulting from, for example, unnecessary changes in orders from customers, or late deliveries or defected materials provided by the suppliers.

It is stressed that “Supply chain management” doesn’t mean the same as “Vertical Integration”, which usually implies the ownership of upstream suppliers and downstream customers. Nowadays, organisations are focusing on their ‘core business’, i.e. where they can have a competitive advantage, leaving the strategy, or the intention, of owning all the chain. However, the overall perspective should never be put aside as this work tries to demonstrate.

In order to decide the main actions, which should be made to improve the overall performance of the supply chain in what concerns to customer response (customer expectations) and costs, it is important to look in detail to the dynamics that are generated in supply chains.

Make-to-order systems present some distinct characteristics, respecting to supply chain management. Here, the traditional distribution systems, with warehousing of final products does not take place. Because of that, the challenge of choosing the best warehouse location is not, for example, considered here. The biggest challenge is to reduce the time to deliver a product, which has to be manufactured almost since the begging, only after the receiving of the order from the customer. This is the notion of decoupling point: the place where the demand is met, i.e., where the production starts based on real values for demand. The focus of supply chain management should be, in make-to-order systems, to reduce the lead time to customer and at the same time improve the flexibility of the processes.

3.2 SUPPLY CHAIN DYNAMICS

Observing the dynamics generated in a supply chain is the objective in this chapter and three major aspects are here considered relevant:

- Lead time and time lag;
- Lead time and forecast;
- Demand Amplification.

*Lead time and time lag*

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The biggest problem which supply chains face is the fact that customers require the product in a shorter time than that is needed to procure, manufacture and deliver it. This is even more noted in make-to-order supply chains, where manufacturing always takes place after receipt of the customer’s order. This results that forecast is needed to anticipate the production and the ordering of some components which integrate the final product. This is the case in make-to-order systems, because it is not possible to forecast the complete final product configuration, due to the high variety of different options the customer can ask for.

The components and parts, that have longer total lead time in purchasing and manufacturing than the customer order cycle is, need forecasting. Materials which have purchase lead times shorter than the manufacturing lead time may be called-off based on the requirement from the production schedule so as to arrive just in time for the assembly operation.

![Diagram of supply chain process]

**Figure 2 - The need for forecast**

*Lead time and forecasting error*

Associated with forecasting is always the uncertainty. One cannot see in advance what will happen in the future with 100% confidence. The further the forecast is taking place, the bigger will be the error inherit to it. This is shown in the picture below, where the curve represents the increasing uncertainty with increasing time lag. This was a description of Blackburn who called this curve as “trumpet of doom”, here in a slightly modified version by Makkonen [37] adapting it to principal business planning and operation cycles.
Figure 3 - Forecasting error with increasing time lag

This means that the longer the lead time, in manufacturing as well as in the entire supply chain, the more inaccurate will be the process of forecasting. And the consequence will be the creation of a vicious cycle where the trend will be always to increase the lead time, as it can be understood through the following description of this dynamics by Hoover [24]:

Long lead times breed inaccurate sales forecasts; inaccurate sales forecasts mean that production schedules and inventories do not match real demand. As a result, late changes have to be made in the factory and warehouse to try to prevent stockouts and missed opportunities. When manufacturing fails to respond at short notice, the sales organisation gets frustrated, exaggerates its orders to build in a safety margin, and introduces extra planning activities. Internal signals become still more distorted. Manufacturing is encouraged to extend lead times and introduce frozen planning periods for orders from the sales units. Frequent late changes to production schedules give rise to intensive fire-fighting, poorer quality, additional quality inspections and the building of yet more lead time into the process.

Figure 4 - Lead time dynamics
From the above situation, results that reducing overall lead time allows companies to reduce the uncertainty associated with forecasts and, consequently, reduce inventory costs, and increase service levels and responsiveness to changes in demand at the same time. Inventories are reduced because smaller order sizes are made and defects from poor quality are also reduced.

_Demand amplification_

Another major problem arising in supply chains is the “Bullwhip Effect” or “Demand Amplification”.

![Diagram of supply chain showing demand amplification](image)

*Figure 5 - The ‘Demand amplification’ effect in supply chains*

Lee [29] relates a case in Hewlett-Packard which describes completely this effect: “When HP executives examined the sales of one of its printers at a major reseller, they found that there were some fluctuations over time. However, when they examined the orders from the reseller, they observed much bigger swings. Also, they discovered that orders from the printer division to the company’s integrated circuit division had even greater fluctuations”. So, while the consumers consumed the final product at a steady
rate, the demand order variations in the supply chain were amplified as the focus moved up in the supply chain [figure 5]. The main reason for the appearance of this effect is that delayed reaction to demand change causes inventory imbalance in the local stocks. So the replenishment volumes not only support anticipated customer demand, but also the rebalancing of the local inventories.

The demand amplification as described above, can have serious cost implications. For instance the manufacturer may incur excess raw material costs due to unplanned purchases of supplies, additional manufacturing expenses created by excess capacity, inefficient utilisation and overtime and excess warehousing expenses. Trade estimates suggest that these activities can result in excess cost in the range between 12.5% and 25% (Kurt Salmon Associates, 1993).

Lee [29, 30] and Towill [47] point many factors contributing to amplification of the demand. Following, is the grouping of them:

- Each company (or organisation in the supply chain) places orders with an upstream organisation using some inventory monitoring. Demands come in, depleting inventory, but the company may not immediately place an order with its supplier. It often batches or accumulates demand before issuing an order, due to costs and time lost processing an order.

  Consider a company that orders once a month from its suppliers. The supplier faces a highly erratic stream of orders. There is a spike in demand at one time during the month, followed by no demands for the rest of the month. Of course, this variability is higher than the demands the company itself faces.

- Marketing take promotional and pricing decisions affecting the trends in demand. As an example, estimates indicate that 80 percent of the transactions between manufacturers and distributors in the grocery industry were made in a ‘forward buy’ arrangement in which items were bought in advance of requirements, usually because a manufacturer’s attractive offer. The result is that customers buy in quantities that do not reflect their immediate needs; they buy in bigger quantities and stock up for the future.

- About forecasts, one of the problems is what Lee [29] calls ‘Demand Forecast Updating’. Every company in the supply chain does product forecasting for its production scheduling, inventory control, capacity planning and material requirements planning. A manager who has to determine how much to order from a supplier, generally uses a simple method to do demand forecasting where future demands are continuously updated as the new daily demand data becomes available. The order the manager will send to the supplier reflects the amount he needs to replenish the stocks to meet the future requirements of demand, as well as the necessary safety stocks. Now, one site up the supply chain, the manager of the supplier gets the orders from the previous site and considers it his demand. If he also uses the same kind of method to update his forecasts and safety stocks, the orders he places to his supplier will have even bigger swings.

- Also related with forecasts, the only thing one can be sure is that they are wrong. In what concerns to the forecasting of final product’s demand, it can be many times almost correct, but when translating these forecasts to the Stock Keeping Unit level, errors will be certainly introduced, even more when the final product can have different configurations, as it occurs in make-to-order manufacturing.
• Yet another point related with forecasts is that as its accuracy decreases, behavioural factors come into equation. Plants start double-guessing on what the business volumes will be, sometimes overproducing, sometimes under producing, thus bringing extra uncertainty into the supply chain.

• Another factor that disrupts supply chains is the lack of accuracy in recording inventory levels. The computer says there are 100, and one cannot find more than 60 at the warehouse, although the planning has been based on the 100 being available.

• Rationing and shortage gaming: when product demand exceeds supply, a manufacturer often rations its product to customers. Usually, the manufacturer allocates the amount in proportion to the amount ordered. Knowing that the manufacturer will ration when the product is in short supply, customers exaggerate their real needs when they order. Later, when demand cools, orders will suddenly disappear and cancellations pour in. The effect of ‘gaming’ is that customers give the supplier little information on the product’s real demand.

3.3 ‘GOOD PRACTICES’ WHEN MANAGING SUPPLY CHAINS

Avoiding the problems described on the previous chapter is the goal of ‘Supply Chain Management’. It lays on three major points that managers should always have in mind, so that customer service can be improved:

• Reducing lead times;
• Reducing uncertainty;
• Increasing flexibility.

Lead time

Reducing lead times is a goal itself, but also it has implications in reducing the uncertainty (like it was explained before) and increasing flexibility.

Flexibility

Flexibility can be defined as the preparedness for changes. The implication of lead time in increasing flexibility is that with short lead time in manufacturing it is possible to schedule the production backward from the requested delivery date, leaving slack time in reserve for longer engineering and possible customer changes.

Christopher [11] argues that the main barrier to flexibility in manufacturing is the time taken to change; to change from one level of volume to another and to change from making one variant to another. Typically this is called ‘set-up time’. It will be apparent that if set-up times can be driven as close as possible to zero then flexible response to customer requirements presents no problem.

Flexibility can also be reached through standardisation:
- In a make-to-order production, there are multiple versions of a product. The final product is a result of a large amount of assemblies and sub-assemblies that are carried on through the manufacturing process. By delaying product differentiation, using the same modules in various versions, one delays as much as possible that moment when different product variants assume their unique identities, thereby gaining the greatest
possible flexibility to changing customer demands. Also, this causes high reductions in inventories due to the fact that less components are required to make all the products given that they share a large amount of parts. Another implication may be the reduction of suppliers (because there are less different components), which increases the previsibility of the process.

Uncertainty and information flow

The “Bullwhip Effect” explained before, appears mainly due to the lack of material and information synchronisation along the supply chain. To avoid this fact close relationships with both suppliers and customers are a request.

According to Stalk and Hout [43] supply chain ‘Product champions’ work with their suppliers simultaneously on the following three fronts:

- they work to provide each company in the chain with better and more timely information about orders, new products and special needs;
- they help members of the chain, including themselves, to shorten work cycles by removing the obstacles to compression that one company often unwittingly imposes on another;
- they synchronise lead times and capacities among the levels or among tiers of the supply chain so that more work can flow in a co-ordinated fashion up and down the chain.

Following the same idea, to counteract the ‘Bullwhip Effect’, Lee [29, 30] categorises the various initiatives on the underlying co-ordination mechanism, namely, information sharing, channel alignment and operational efficiency. With information sharing, demand information at a downstream site is transmitted upstream in a timely fashion. Channel alignment is the co-ordination of pricing, transportation, inventory planning, and ownership between upstream and downstream sites in a supply chain. Operational efficiency refers to activities that improve performance, such as reduced costs and lead times.

The advantages of information sharing can be seen in more than one factor that originates the ‘Demand Amplification Effect’:

- Avoiding multiple demand forecast updates: making demand data at a downstream site available to the upstream site results that both sites can update their forecasts with the same raw data. Also, the problems arising from guessing the business volumes will be eradicated, due to the fact the suppliers are in possession of the current demand data from theirs customers.
- Breaking order batches: one reason that order batches are large or order frequencies low is the relatively high cost of placing an order and replenishing it. New advances in information technology, like EDI (Electronic Data Interchange), can reduce the cost of the paperwork in generating an order, and as a consequence, customers can order more frequently.
- Eliminating gaming in shortage situations: ‘Gaming’ during shortages peaks when customers have little information on the manufacturers’ supply situation. The sharing of capacity and inventory helps to alleviate customers’ anxiety and, consequently, lessen their need to engage in gaming. One can think that when there
is a true shortage, the information sharing is insufficient to avoid the gaming, but it
does not have to be so, since knowing in advance the supplier lack of capacity in a
given moment, allows companies to find other solutions on time for their schedules.
This is also good for the supplier in the way that it will avoid anger from its
customers when disruptions in the supply chain suddenly show up.

3.4 SUPPLY CHAIN MODELLING AND SIMULATION

To present the actuality of supply chain modelling, some authors are referred here.
Starting by presenting the need for simulation and following with the presentation of
some works performed in this field, this chapter ends with the theoretical approach
which should be taken to model complex systems like supply chains.

A good explanation to the notions of modelling and simulation are given by Law and
Kelton [28] through the following: “The facility of process of interest is usually called a
system, and in order to study it scientifically one often has to make a set of assumptions
about how it works. These assumptions, which usually take the form of mathematical or
logical relationships, constitute a model that is used to try to gain some understanding
of how the corresponding system behaves. If the relationships that compose the model
are simple enough, it may be possible to use mathematical methods (such as algebra,
calculus, or probability theory) to obtain exact information on questions of interest; this
is called an analytic solution. However, most real-world systems are too complex to
allow realistic models to be evaluated analytically, and these models must be studied by
means of simulation. In a simulation one uses a computer to evaluate a model
numerically, and data are gathered in order to estimate the desired true characteristic
of the model.”

Complexity

The complexity pointed out before is present along supply chains and many authors
have described that fact:

• Davis [15] says that large manufacturing companies are ‘hostage of complexity’. He
  explains this referring that the nature of complexity is evident in a review of material
  flows for a complicated product. Multiple suppliers ship manufacturing sites with
  varying regularity. There, subassemblies and final products are made by complicated
  and somewhat uncertain processes. Products are then shipped to direct customers,
  OEM1 customers, and “internal OEM’s” (downstream manufacturing divisions of the
  same company treating the first factory’s “final” product as but one of their many
  component materials).

1. Original Equipment Manufacturing
• Massotte [38] follows the same tendency pointing that when considering a multi-product, multi-process production shop involving thousands of parts, associated with a particular management system, submitted to various inputs, one cannot calculate and predict what will happen in time, that is to say: what the WIP will be, or the location and the status of any parts. One is not able to determine future and the dynamic evolution of the production system, due to the volume of information which has to be handled and also to the uncertainty which plagues the system. Here the focus is the production system, but these concepts can be easily extrapolated to the whole supply chain, where there is even more complexity.

• Makkonen [37] argues that even a relatively small business can create complex networks, like Figure 7 demonstrates, showing the material flows between a medium size component manufacturer and its suppliers. And this is yet more evident when considering the whole supply chain where we have not only material flows, but also information flows.

![Image of a network diagram]

**Figure 6 - Complexity generated by information flows in a business network**

**Dynamic factors**

Modelling has been used as a tool within supply chain management for the last decades; but only in the last decade dynamic simulation has gained considerable attention and momentum. Swaminathan et al. [45] mention the use of modelling and simulation on the supply chain with different purposes, namely studies of the effects of various supply chain strategies on demand amplification and a study of the effect of sharing supplier available-to-promise information.

Davis [15] suggests an analytical model, describing HP supply chains. Its objective is the creation of a strategic decision support where the impact of uncertainty and performance of the actors along the chain could be seen, through the observation of the delivery performance. Here, the main variables used for analysis are the inventory levels and the customer response/customer service level of the supply chain.
Also Inger et. al. [25] follow a similar approach for understanding the dynamics of supply chains. They address the importance of time-based simulation in this context and propose a supply chain model where the key driver is the market demand and its statistical profile. Also, they support that, in the network, the design variables (medium to long term structural factors) are the customer service goals, number of echelons in the chain, structural lead times, point of decoupling (location where forecast meet real customer demand) and point of fulfilment (place where the delivery to customer is performed). As parameters for the simulation (the factors which are at the heart of the business processes) they designate review cycles, lead times, and forecasting methods.

Lin et. al. [34] have developed an object oriented model to simulate the order fulfilment process in a supply chain and find out about its performance. They base their model in a multi-agent system, where the main entities are suppliers, manufacturers and distributors. These are composed of agents (or activities), each one incorporating the decision making, information and material processing. Goals are incorporated into the decision making rules of the agents. They argue that the key drivers for a good process are the efficiency (cycle time), flexibility (minimisation of costs), robustness (strength to handle uncertainty), and adaptability (self-learning ability). The most important idea to take out from this modelling is that they see, and try to demonstrate, that the information infrastructure is the most critical issue for improving the system’s performance.

Experiment design

As the final purpose of this study is to simulate one supply chain, the description of the approach taken to make it, is now described in a general way. Assuming a supply chain as a complex system, it’s modelling rules do not differ from the ones taken in a common modelling work like, for example, a manufacturing system. In the picture below, the main steps usually considered to perform this kind of works are shown.
First of all, one has to formulate the problem. It involves the following procedures:

1. State definitively the study’s overall objectives and the specific issues to be addressed;
2. Boundary the system;
3. Specify measures of performance for conclude about simulation results;
4. Take a first idea about the system configurations to be studied; and
5. Decide on simulation software.

Next, the model definition. Here one has to be careful about the detail of the model, as it depends on the following:

1. Project objectives;
2. Performance measures;
3. Data availability;
4. Computer constraints; and
5. Opinions of system experts, i.e. functional specialists of the company.

The level of detail will impact mainly the choice of variables acting in the system. They will have to be chosen according to the points stressed before.

It is pointed out that the last point plays a special role in what concerns to the validity of the conceptual model. Most likely, the system experts will know by experience what are the principal factors affecting the system and their help may give credibility to the model in this phase.

If the model was considered valid, the next action is to collect the required data. Some aspects should be considered here:

1. Collect information on system operating procedures, having in mind that no single person or document is sufficient, or some people may have inaccurate information, and because of this one has to be sure that the true system experts are identified. Another point, is that operating procedures may not be formalised and the only way to deal with this, is to gain the confidence of the people involved in the system and try to make them give the most precise information about the operations.
2. Collect data to specify model parameters and define some requested probability distributions.
3. Collect data on the performance of the existing system to make the system evaluation later, when analysing the results, and also to have a clearer picture of the processes.

When translating the model into the computer program, selected in the beginning of the process, one may have to adapt somehow the model, due to programming restrictions. Also, the code can be wrong, not reflecting the model. These are the reasons why pilot runs need to be performed to see if the computer model is valid, when compared to the reality one wants to describe. Making the pilot runs and the validation requires the following:

1. To have system experts reviewing numerical results from preliminary simulation results for reasonableness.
2. to compare model and system measures for existing system
3. To use sensitivity analysis to determine what model factors have a significant impact on performance measures.

If the coded model is not valid, it can be due to false definition of the model, incomplete or wrong collection of data, or even to incorrect construction of the computer program. If the coded model is accepted, new configurations of the system can be simulated and results evaluated. In this phase, one should specify the length of each simulation and the number of independent runs, given that each one uses different random numbers to originate some statistical functions. This will allow to calculate the confidence intervals of the performance measures being taken to evaluate the system.
3.5 MODELLING TOOLS

When developing a simulation project, one has to decide either to use a discrete, continuous or combined approach to it. In a discrete simulation, the parameters of interest change instantaneously at separated points in time. With continuous simulation, the considered parameters suffer changes in a continuous way over time. The combined discrete/continuous simulation is a mix of the two previous types, where the variables change both continuously and discretely.

The approach to be used in a simulation depends on the problem characteristics, and some factors assume here particular relevance:

- Level of details: One has to be sure about what is the purpose of the modelling. As an example, in most cases the state of a light, on or off, would be modelled discretely. However, at a very small time scale, the status of a light might be modelled as being continuous.
- Usually it is easier to model systems discretely: Modelling a system using continuous approach requires mathematical expressions to describe the system’s processes, while modelling using a discrete approach allows statistical descriptions to be utilised rather than equations.
- Driving forces: On one hand, discrete event simulation is driven by random sampling of distributions describing times between arrivals to the system or times spent in a process. On the other hand, continuous simulation is deterministic (e.g. \( y = f(t) \)).

Like described in the previous chapter, one of the steps in a modelling work is to choose the support for the simulation, i.e., the simulation tool.

In accordance with the selected approach, there were several options of simulation tools. The most popular simulation software regard to the field of discrete simulation of rather detailed manufacturing processes, like for example, Arena, AutoMod, Taylor II, MicroSaint, Quest, or Winsim. Regarding to continuous simulation, the most used software is Simulink, which is used within Matlab.

In the modelling carried out in this project, there was the aim to combine the advantages of discrete event simulation with the continuous one. A simulation software called SIMNON 2.0 from SSPA (Sweden) was used because of its capability to integrate these two types of approaches.
4. DESCRIPTION OF THE WORK

4.1 BRIEF INTRODUCTION TO THE CASE

Due to limited time schedule and availability of data I will focus only on a small portion of the total network in this study. The study will cover one plant, one sales office, including their suppliers, and one major product in details. The units are selected in such a way that they give a good picture of the total operations.

Briefly, the steps taken, and explained in the next chapters, have been as follows:

- Describing the organisation structure;
- Describing the network structure;
- Getting knowledge about the product and its structure;
- Understanding of customers’ characteristics;
- Understanding sales’ office processes and problems;
- Understanding factory works and methods;
- Understanding suppliers’ characteristics;
- Designing the experimental model;
- Collecting data;
- Analysing true delivery performance;
- Building the model;
- Experimenting the model.

After, the achieved results are presented and discussed.

4.2 ORGANISATION DESCRIPTION

The ‘Case company’ presents a typical functional organisation as can be understood by the next picture. Each plant has its own products, which they deliver to different sales regions. The autonomy of each business unit, i.e. production plant and sales office is rather high. Due to this autonomy common co-ordination of activities important to the management of the total supply chain and network of operations has not been an easy task.
4.3 NETWORK DESCRIPTION

The entities in a supply chain are linked by information and material linkages, or either of them, and the information is used to ease the material flow. The picture below shows the main actors and their connections in the material flow of the case company.

Figure 9 - The ‘Case Study’ network
Although the above figure gives a good idea about the flows in the system, a more detailed description is needed to understand the dynamics that it can create, being that one of the major issues of this work.

### 4.3.1 Information Flow

The process starts when one of the sales organisations receives an order from a customer, which can follow two main principles: customers can put the order directly to the sales office or to the distributor. However, the order will always pass through the corresponding sales office before being sent to the factory. It means that when a distributor receives the order, he will send it to the sales office.

The next phase is to engineer the product. According to the requirements, engineers in the sales offices have the responsibility of checking the technical specification created by the salesman/distributor, as well as to check the availability of parts and resources for final delivery. Then, a delivery date is agreed with the customer, based on estimated site information and preliminary delivery schedule from the factory. The order is then sent to the factory, which confirms its receiving to the sales office.

![Figure 10 - Order information flow in the supply chain](image)

Furthermore, there are some feedback flows from Sales offices to customers and distributors, mainly to inform them about possible delays and also about questions regarding the configuration of the product.

Meanwhile, there is another information flow between the plant and its suppliers, which is typically performed due to replenishment needs, more than because of one single order being issued. The resource management on assembly site is flexible utilising a network of subcontractors in an adaptive way based on weekly/daily negotiations and adjustments.

Also, there are some supplies to be ordered from sales offices, concerning to materials needed for final assembly.

### 4.3.2 Material Flow

The material flow at the utmost upstream place in the chain is the delivery of raw materials and intermediate products to the manufacturing. Again, as it will be seen in more detail in the chapter describing the inventory control, this flow is not due to one single customer order, but is done on regular basis following plant specific rules.
At the plant, when the final product is ready, the delivery process starts. The product is sent to the assembly site. Finally, after final assembly and testing, the product is delivered to the customer and invoicing takes place.

![Diagram of product flow](image)

*Figure 11 - Final product flow in the supply chain*

### 4.4 PRODUCT STRUCTURE AND PRODUCT SIMPLIFICATION

The final product, after final assembly, consists of the basic unit and some options (components) chosen by the customer. One of the models (which can have different configurations) has been chosen for the simulation. This is so, because some level of abstraction is needed when dealing with this kind of modelling. Choosing one of the models only is justified due to the fact that the differences between them are mainly in lead times of production and not in different operations to be taken at the factory or different material suppliers. Later, when designing the simulation model, I will explain the way all the different products were taken into consideration.

The model which was chosen is one of the most frequently sold to the customers. This allows a good picture of the demand and evaluation of the customer. The basic unit is composed by various modules and small parts, like screws, bolts, nipples, etc. These small parts were considered as not having any impact either in the delivery performance or in the inventory costs, and because of that, the work carried out includes only the main modules of the basic unit.

Still, the product is not complete without the set of configurations which are chosen according to customer needs, as said before. These options are divided into less than 20 categories, each one having some (1 to 6) different versions. Most of these components are only needed to the phase of final assembly, although they make part of the production for a given order. It means that most of them are not assembled at the factory, they are part of the package that includes the final product and a set of kits for final assembly. The ‘most likely’ configuration of each category according to past sales statistics has been chosen. Some of the categories were not considered because of a very low usage, i.e. 1 to 4% of the cases. Some of these options are external and others internal supplies.
At the end, the final product used in the simulation was composed of 6 modules corresponding to the basic unit, and 9 modules regarding to the main required options.

This was a critical phase, because only with a simplified structure is possible to integrate the product and the main production flows. At the same time, the model gains some robustness in the way that it becomes less sensitive to small changes in the flows.

### 4.5 CUSTOMERS AND MARKET

The product is considered to be in a mature market, where the overall sales have been rather stable for some years, with exceptions of some regional volatility. The case company has a leading position in the markets, although its market share is not dominating over the other competitors. The customer base is very fragmented and varies strongly from one region to another, leading to different modes of operations even within the same sales organisation.

Anyhow, the pressures are high, given that competitors are currently practising very low prices to secure the market. Furthermore, another issue putting some pressure in this industry is the shortening of the product life cycle. Innovations are constantly arising and every competitor, in order to prevent the risk of loosing market share, has to follow the improvements made by the others.
Regarding to customers, they are becoming more and more hard to please. In the past they could quite easily accept a delivery times of several months, whereas nowadays they ask deliveries rather in some weeks and punctuality in days.

The selected sales office is from one of the most important market areas, and is considered to be the forerunner in many new applications.

4.6 THE SALES OFFICE

4.6.1 Main Processes

The market area covered by selected sales office is divided into sales territories, each one controlled by a salesman or a distributor. Some 80% of the sales is done through own sales force. However, even the remaining 20% of sales is controlled by the sales office and their technical people.

When an order comes in from the salesman/distributor to the sales office, it has to be checked and accepted before confirmation to the customer, if necessary with support from engineering and production. The time associated with this operation is, in about 75% of the cases, 1 - 2 days. This means that most of the orders pass through without further involvement from engineering department. For the rest 25% it takes from 2 days to 3 weeks (sometimes even 6-8 weeks) to prepare the final quotation. Before being issued to the plant, all the orders are controlled and confirmed by sale's technical support, production, procurement, and quality functions. The orders are sent daily to the factory, where a confirmation for the due date of delivery should be returned.

At the same time a preliminary schedule for final assembly with resource allocation is done. However, due to several reasons the predictability of this part of the delivery process is poor. It consists of to main factors, the first being the scheduled site readiness to final assembly, and the second the amount of work needed on the site. About 80% of the scheduled starting of the final assemblies fit into a +1 week accuracy window. For the rest the maximum variation can be -2 (early) to +4 (late) weeks. The work load can vary several hundreds of percentages, and can be justified just on the assembly site. Also at this stage, the materials needed to perform the final assembly are checked and ordered from the suppliers if missing from the stocks.

Having the assembly site ready, the product and the needed components in house, the final assembly takes place. In 50 to 60% of the cases, it is performed by using own resources, the rest is done by external subcontractors. In case of delays the sales office communicates it with the customer.

After delivering, the invoicing takes place and it is also under the sales office responsibility.

4.6.2 Main Problems

At least two reasons for the variation in the delivery punctuality from the sales office have been identified:
• On one hand the deliveries from the factory are not always in-time.
• On the other hand, the preparation of the assembly site presents high variation, originating some uncertainty in the scheduling of the final assembly. Furthermore, the preparation of the site is not under responsibility of the sales office, so it is not easy for them to control its delivery.

4.7 THE FACTORY

4.7.1 Type of Work

The product which is object of this study is a typical 'engineering industry' product, i.e. the main operations needed in the manufacturing are steel fabrication, machining and assembly.

Concerning to layouts, the factory presents a typical "process layout", having groups of similar machines/operations. However, as the trend is to start producing standard modules to incorporate in different products, there is the intention of changing this layout and use a "product layout", where the production process takes on the characteristics of a continuous flow operation, reducing drastically the work in process. But, this is only an efficient layout when the volumes are high and the products are similar.

Nowadays, however, the product mix is very high and that brings that grouping machines by function results in less machine idle time. Furthermore, process layouts are far more flexible than product layouts. Design changes in the product that requires changes in the sequence or type of operations can be more easily accommodated with process layout.

Besides, the components manufacturing, there is a part of the factory which is dedicated to the assembly. There are three assembly lines, each one used to produce a certain type of products.

4.7.2 Methods

4.7.2.1 Production Planning

The production planning is performed after the administration staff receives the order and confirms it to the respective sales office.

The product which is manufactured at the plant is mainly an assembly-to-order one. Mainly, because there are some special products with unique configuration that sometimes are made according to a make-to-order system. However, they represent a very small part of the production and so it has been considered as not impacting the activities at the factory.

In an assembly-to-order system the real demand originates the starting of the assembly operations, i.e., the real demand is met only when the assembly has to be performed.
This is the notion of decoupling point mentioned in the chapter dedicated to the introduction of "Supply Chain Management" (3.1).

But, in order to have availability of components and raw materials to start the assembly, those which have cycle time bigger than the customer cycle, cannot be ruled by real demand. They need to be produced through a make-to-stock system based on forecasts. Those components which have cycle time smaller than the customer cycle can be called-off based on real needs, meaning that the raw material from supplier will be the decoupling point in this case.

![Diagram showing parts manufacturing and external supplies to assembly](image)

Figure 13 - Production control

In this kind of system, the assembly is scheduled following the "available-to-promise" concept. This means that when one order comes in the factory, it is accomplished by a due date for delivery which should be met by the production. In the end the performance will be measured putting the real delivery date against the agreed due date with the sales office. This means that the delivery performance is here measured on an accuracy level of one day, although at the plant they are used to measure it on weekly basis. In the last one and a half years, the delivery performance at the factory has been around 60% in-time against 40% late deliveries measured on daily level, as it will be seen in more detail in the chapter 4.10.

As mentioned, the production scheduling is based on the due date agreed with the sales office. At the factory, for each order, a production termination date is defined. This is done counting about two weeks, backwards from the agreed due date. These two weeks are taken to packaging and to finish the production of some components that have to accomplish the product for final assembly. The production itself, or more exactly, the assembly is scheduled to start in about one week before the date in which the product should be ready.

4.7.2.2 Forecasting

The parts manufacturing is the main obstacle for forecasting. As mentioned, they are produced following make-to-stock rules which requests some idea about future demand. Also, the purchasing function has to know the future trend of demand to better deal with suppliers about lead times and quantity orders.
At the production field, the forecasts which are needed are very different from the ones used by the financial department, for example, where the important information is the overall sales activity. Here, the complexity is much higher since the request for forecasts is present at each Stock Keeping Unit (SKU).

The method which is in use, begins by considering the demand of the final product and a monthly forecast is executed for each different basic model, according to the following mathematical expression:

\[
C_1 \cdot \sum_{i=1}^{4} \text{month}_i \text{ sales} + C_2 \cdot \sum_{i=5}^{6} \text{month}_i \text{ sales} + C_3 \cdot \sum_{i=7}^{9} \text{month}_i \text{ sales} + C_4 \cdot \sum_{i=10}^{12} \text{month}_i \text{ sales}
\]

where \( C_i \)'s are the smoothing coefficients for the past 12 months, which are fixed but not shown here due to confidential reasons.

Then, the translation of this forecast to each SKU is done by a probability function present in the MRP system, that determines the extent in which each component is used in the final product.

\[4.7.2.3 \quad \text{Inventory Control}\]

The components which are internally manufactured and the parts coming from external suppliers are stored in buffers. They are controlled by a Q,R method, where Q is the lot size of each order and R is the reorder point. Here, the inventory level is assumed to be under continuous monitoring and when the stock level reaches the reorder point, a replenishment order for a fixed quantity is issued.

The quantity to be ordered is calculated by the Economic Order Quantity (EOQ) rule, which assumes constant demand, that in the present case is the monthly forecast explained before. In a simple system, the value for the reorder point is influenced by the demand rate, the replenishment lead time, and the safety stock.

However the assumptions of fixed demand rate and constant replenishment lead time are rarely justified in the real life operations. Random fluctuations in demand for individual products occur because of variations in the timing of customers’ purchasing behaviour. Likewise, the replenishment lead time often varies because of machine breakdowns, employee absenteeism, material shortages, etc.

Because of this situation, a weekly control is executed at the factory for each SKU. The intention is to absorb demand variations, by changing the reorder point in a systematic way. The following expression is the basis for this operation:

\[
\text{Balance} - \text{Orderlog} - \text{Reservation} - \text{Reorder Point} \quad \text{Average Usage} - \text{Lead Time} = 0
\]

where the involved parameters have the following meaning:

- Balance: is the total number of components available.
- Orderlog: is the number of components released for scheduled production.
Reservation: is the number of components that will be needed in orders queuing for assembly scheduling, during the considered time period.
- Reorder Point: is the variable calculated by this expression.
- Average Usage: is the usage of the component during the order lead time, calculated in proportion to its monthly forecast.
- Lead time: is the time needed, in average, to produce (or to order), a batch of the considered component.

4.8 SUPPLIERS

Considering the whole supply chain, there are two groups of suppliers, the ones supplying the factory with raw materials, components, and intermediate products, and the ones supplying the final assembly that is under sales office responsibility.

The number of principal suppliers to the final assembly is about 20. Mainly due to the fact, that there is a lot of time for planning since the order is received at the sales office until the product is delivered for final assembly, the suppliers of this phase do not present performance problems. In fact, it has been assured by sales office people that disruptions with parts coming from this suppliers are very rare and they consider this supply as not presenting any problem.

Quite different is the situation at the factory. Around 180 suppliers providing about 3000 distinct parts, show diverse profiles in lead times and quality and impact strongly the behaviour of production at the plant.

Although the policy regarding the relations and delivery terms with the suppliers is under chang, the practical results are still to be seen. Suppliers get information about the factory’s needs with a low frequency, resulting of the inventory system which is used at the plant. Only when the re-order point for a given SKU is reached, the supplier is contacted to provide the accorded batch size. It follows that the supplier has very little information about the real demand and its production planning becomes more difficult, causing problems with its delivery performance. This is one of the “Demand amplification” effects mentioned in the chapter 3.2.

4.9 DATA COLLECTION AND ANALYSIS

4.9.1 The Model and the Requested Data

Having in mind how the processes are executed, it is time to design the model and at the same time collect the needed data. When designing a model, one has to be sure about the goals of the experiment. The model to be executed in this work is supposed to have a tactical importance and not so much of operational or strategic ones. For example concerning to the strategic level, it is not the objective of the work to calculate the responsiveness of the chain if the factory moves its location, closer to the customers, decreasing this way the lead times for transportation. Also, it is not a goal of this work to optimise the internal efficiency of the plant through better allocation of resources, typically an operational issue.
The main actions to test will be around changes in the structure of the chain, or changes in the performance of the different actors and observe about the impact they have in the responsiveness to customer, meaning filling or not its expectations about agreed lead times. In the first phase it is important to have a wide scope and observe the main flow along the network.

**Figure 14 - Main actions in the supply chain**

From the above picture it stands out that the natural input for the run of the system is the customer demand profile. As Inger et al. [25] mention, it is the key driver of the supply chain. However, in this work it was considered also as key driver the agreed due date for delivery, which, in the end, will be confronted with the real delivery date to infer about the overall chain performance in terms of in-time/late deliveries.

Collecting data from a supply chain is not an easy task. In fact, because the typical supply chain comprises many organisations, data must come from many distinct locations. In the present case, however, there were only two main sources: the sales office and the factory.

The accuracy of the data plays a significant role in the modelling. Often, collected data paints a false image of an operation due to data errors, inconsistent collection procedures, and system incompatibilities. Indeed, as it will be explained later, there were some problems to connect data with origin in the sales office to the one coming from the plant, for example due to different coding of the orders.

Another important thing about data is that it has to be valid, says Davis [15]. Like it was mentioned, when talking about the product structure and its simplification, it would be unwieldy to include every stock-keeping unit in a model that is used for tactical purposes only. Thus, some parts were left out of the model completely (e.g. common nuts and bolts). Others may be aggregated and represented in the model as a single, "generic" component, like "mechanisms". However, the aggregation must be checked.
against expert opinion to see if they represent the situation fairly, still Davis [15] arguing.

After visiting the plant and the sales office, it has been grouped the requested data into some subjects. The data which was gathered to make the modelling is presented and explained under the next titles.

4.9.2 Deliveries

The main figures came from the sales office. Complete delivery data for that market from about one and a half years’ period was collected.

Because the deliveries of this market represent only a share of the factory’s deliveries, data on the factory orders was also gathered, in order to better model the production processes.

4.9.3 Order Management

This data is related to the one described previously. Here, one can follow the time differences between the steps taken in the order fulfilment process. Data coming from the sales office contains, for each order, number and types of products, order entry and confirmed due date, factory order and due date, real delivery date from factory, site ready date, and final delivery date.

The same kind of data was asked at the factory. For each order, there is the type of product, order entry at the factory date, order released to production date, due delivery date, and a dispatch date.

The main purpose was to connect this data with the one available at the sales office, to conclude about the time spent to process the order administration at the factory, and the transportation time, i.e., time from dispatching to receiving at Sales. In chapter 4.10, this data is subjected to analysis.

4.9.4 Product Structure

The data regarding to product structure was the one with more difficulties in its analysis, even though, only one of the several products was selected. In fact, the data available at the factory consisted of more than 7000 rows, in which the product was described through 5 structure levels, including all the possible options that could be part of it. Also, the components and raw materials were mentioned by codes, which was making it impossible to understand. Later on, data containing the codes and the respective names was accessed and the simplification could start, following the method described in chapter 4.4.

The result of the first simplification, consisting of selection of the main options from the 18 categories and the basic unit (Chapter 4.4), was a file containing about 2600 rows. Each one included the codes for up to the 5 levels, the incorporation factor, the batch size, the operation machine, and the batch lead time for the operation. This means that, if a part needed 4 operations, there would be 4 rows regarding to that component.
Furthermore, if this part was, as an example, from the level 4, and if the level 3 needed 2 operations, those 4 rows would be repeated in what concerns to the 4th level fields.

4.9.5 Sequence of Operations

One important part of the work has consisted in the description of the operations taken at the factory. From a very wide scope of the flows, where only the main chain relations were described, to a more detailed view of the processes at the plant was the goal when collecting the data regarding the sequence of operations.

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<td>87333333</td>
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</tbody>
</table>

Figure 15 - Originating the product sequences

Starting with the same raw data as used for the product structure and adding the information concerning the suppliers’ name and code for each supplied part or raw material, the flow description for all the 15 selected modules could be executed.

Firstly, the flow described for each module was containing all the components and materials needed for its production. Still, some simplification was to be made. In some modules, the total flow comprised many manufactured small parts which do not present stock problems, and the only impact they have in the system, is reducing the capacity of some operations. Their throughput time is short, so they usually do not have the dynamic effect of taking the capacity at a wrong time, either. All the small parts excluded from the flows were grouped and the capacity used by them calculated so that one could have the idea about the share of it available for the selected operations.

Another issue at this stage was to identify the points where the supplied parts come in the flow. The information available could not describe this in a perfect way. This because the structure of the firstly available data only allowed to know that a given part was needed to produce a given product, regarding to a certain level of the product...
structure. This can be better understood observing the example in the picture below, respecting to the production of an intermediate part:

![Diagram of production process](image)

*Figure 16 - Production of an intermediate part (1)*

This is in a certain degree different from the flow shown below, where some supplies are needed, not in the beginning of the process, but in an intermediate phase:

![Diagram of production process](image)

*Figure 17 - Production of an intermediate part (2)*

The importance of this is that some extra time is given to supply some parts which can be missing from time to time.

This job could not be executed without the help of people knowing perfectly well the processes. So, after drawing all the flows, mostly in an intuitive way, the confirmation of its validity was asked from the Production Planner at the factory. Some corrections had had to be made, but in the end the flows were ready to incorporate into the simulation model.

### 4.9.6 Capacity of Machines and Labour

Although there was a suspicion that problems at the factory were not caused by lack of capacity but due to the dynamics generated by the chain actors, when simulating the operations taken at the plant, capacities have to be taken into consideration. This because, it can be a restriction when suppliers miss to delivery components and the factory needs to recover the lost time or a big number of orders arrive to the factory at the same time. These could be examples of experiments taken in the simulation to be built.

Data containing information about capacity (in hours/day), and efficiency for each cell was made available.
The simulation model which was later developed, has a time step of one day. That is why it was necessary to convert the capacities of each cell (expressed in hours per day) to the number of units that could be made of one given component. The capacities would be expressed, now, in units of a component per day.

One other sort of data was needed. Information on the batches for each component, and the set-up and working times for each operation were required. With this data, one could calculate the time spent to make a batch of a given component. Nevertheless, this operation required some caution. As a matter a fact, the linearity of this conversion can only be reached if the set-up times for the machines are equal to zero. After its calculation, it has been concluded that its impact is almost null. The average set-up times are about 2.5% of the required time and with low variance among the different machines.

So, for each pair component/cell used, it was calculated the maximum capacity, which is:

\[
\text{Capacity [no. parts / day]} = \frac{\text{time available [hours / day]} \times \text{batch size [no. parts]}}{\text{time to produce 1 batch [hours]}}
\]

The restrictions coming into this maximum capacity were due to cell sharing in the production of different components and to the efficiency parameter of the cell.

4.9.7 Inventory Management

It has been mentioned, in the chapter regarding to the inventory control, that the method used to manage inventories (parts manufacturing and external supplies) is the deterministic model \((R,Q)\), with a re-order point and a replenishment quantity equal to the economic batch size.

The following data was sent from the factory, regarding to both external supplies and in-house manufactured parts:
- Batch sizes according to EOQ;
- Average Re-order points.

4.9.8 Suppliers

The suppliers are supposed to be one of the major focus of uncertainty on this supply chain. However, one can not generalise too much and put this suspicion on all of them. But, even here, the problem can be due to bad administration of the orders at the factory, more than because of suppliers themselves.

In this phase, the intention was to collect the information about suppliers’ performance, the recording of which is under change at the plant. Indeed, two different kind of records has been made available, the old and new schemes, that are described below.

The data respecting the old process contained, for each supplier in a given one year period, the information as follows:
- Number of deliveries;
- Number of in-time deliveries;
- Number of early deliveries;
- Average for early deliveries (days);
- Maximum for early deliveries (days);
- Minimum for early deliveries (days);
- Number of late deliveries;
- Average for late deliveries (days);
- Maximum for late deliveries (days);
- Minimum for late deliveries (days);

The new procedure for registering the supplier performance differs from the above in a way that the number of days is not recorded anymore. A period of time is defined to include the in-time deliveries. This period is between -2 days and +5 days from the agreed lead time with the supplier. This is a simpler procedure than the used before, but the information is not so good for statistical analysis. The advantage argued by people at the factory is that, this way, less errors are entered into the system. So, the new registers present the following fields, for each supplier in a given period:

- Number of orders;
- Number of items ordered;
- Number of deliveries;
- Number of items delivered;
- Number of early deliveries;
- Number of in-time deliveries;
- Number of late deliveries.

4.10 DELIVERY PERFORMANCE ANALYSIS

Before constructing the simulation model, one should have a clear picture of the chain performance, which in this work, is measured by the times and delays for the delivery. However, not only the overall lead time is important, since it does not show where the main problems along the supply chain are located. The total process was split into six main steps, concerning to the delivery of the final product, plus parallel process of the 'site preparation'.
The sequences covered by the data from sales office and production as in Figure 18 are explained more closely below:

1. **Order administration at the sales office**: This is the time taken in the processing of the order, since the customer fixes a contract until the order is sent to the factory. This time lag is used, among other things, to make the specifications of the product, as described in chapter 4.6.1. There were two dates corresponding to these two actions in the sales office data, the order receiving date, and the order sent to factory date.

2. **Order booking at the factory**: This is the time corresponding to the difference between the date when the order was sent to the factory from the sales office and the date when the order was processed at the factory. The importance of this step is to conclude about the reliability of the administration process, because according to factory the order may be waiting for booking maximum two days. Here, there is the need to consider the 'connected' data, since only there is available the two necessary dates - order sent to factory date and the order received at the factory date.

3. **Order planning and production**: This is the interval between the time when the order was released from the administration processes until the production should be ready. This time lag comprises about one week of real production and the rest is spent in planning due to capacity limits and materials availability. The measure of this interval has been based in the 'Factory data' which contains the two dates described before.

4. **Packaging and storage**: This interval is originated by the agreed due date for delivery from the factory. The main actions are packaging and storage, but also it can be considered a time buffer to complete the production, if delayed. So, the required dates are the end of production and delivery, which are present in the 'Factory data'.

5. **Transportation**: To measure the time used for transportation, the 'connected data' has to be considered. This because it is the difference between the date when the product left the factory, which is included in the 'Factory data', and the date when the product arrived to the sales office, that is part of the 'Sales office data'.

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6. **Final assembly**: The *final assembly* only takes place when the product is available and the site is ready. Thereby, it is the time interval between the final delivery and the latest delivery amidst the product and 'site ready' time. All these dates are available in the 'sales office data' and because of that, this one is considered to measure this time lag.

7. **Site preparation** time: theoretically, the 'site ready' time is defined at the same time as the customer puts an order for the product. This means that the time needed to make it available, is the difference between its registered ready date and the customer order date at the sales office.

As it is mentioned in the chapter regarding the collection of the order management data, this information comes from more than one source. From the sales records of about 700 events were received, and from the factory about 3000 recordings. It was possible to connect about 170 recordings from those two registers.

When calculating the times for the different steps, the data analysis should be taken with the largest amount of information as possible. Although all the steps could be measured from the connected data, only those necessary requesting it, were measured that way. The other the calculations have been made from the other data, which contain more information.

Beginning with the raw data described before, the performance analysis process passed through the conversion of the data to new units, due to confidential reasons, and also through a manipulation action to erase some values which were completely unrealistic, as can be seen in the following picture, where there are negative values (!) for one of the selected time steps:

![Figure 19 - Raw data for the 'Order administration at the S.O.' step](image)

To manipulate the data in a correct way, one has first to understand the processes and not look only to the data as numbers or values. They have meaning, and erasing some registers can have serious impact in the statistic measures taking place. Because of this, the first thing to do is try to find out the reasons that lead to the imprecision of some data.
It was concluded that three major sources were the basis for the presence of the inaccurate registers:

- First of all, the input errors: in some cases it was clear that the problems were simply due to input errors. For example, the presence of some future dates in the registers is an obvious indication of that.
- Secondly, the lack of updating the changes: sometimes, along the process changes in agreed dates and re-scheduling are made. If this corrections are not entered into the files, unreal information is going to be stay there.
- Thirdly, the lack of some dates: when calculating the time intervals, one has to be careful with the existence of some blank fields, which may lead to completely impossible values.

The picture below presents the results of the data manipulation process.

Figure 20 - Results of the data manipulation process
Although, the reasons for the problems with the data were mentioned before, now follows a detailed description about the way each time step was manipulated:

1. Order administration at the Sales Office:
   1.1 The presence of negative values lead to not consider 33 registers among the 700.
   1.2 High values were not excluded because they were not considered as errors. In fact, some actions taken at the sales office can originate them, like time for engineering or indecision by the customer about postponing his decision. The date of order is registered and then there is a time lag until the decision is confirmed and the order sent to the factory.

2. Order booking at the factory:
   2.1 There were 8 negative values for this interval, that were obviously excluded.
   2.2 Here again some high values were not erased and the reason is mainly one: sometimes, although the customer has not confirmed his deal, the dealers are quite sure about the final agreement and put its order in advance to the factory, but this is only registered there when the final deal becomes true.

3. Order planning and production:
   3.1 The negative values were 10 and not taken into consideration for this analysis.
   3.2 The high values which could be observed can be explained by deficient specification of the product, leading the order to go back to the sales office for better description. Also another reason can be again indecision by customers implying the stop of the planning process.

4. Packaging and storage:
   4.1 Six registers from the file containing about 3000 were deleted due to being negative values.

5. Transportation:
   5.1 One of the dates used for counting this interval was the Product delivery date, and there were 12 registers where it was missing. So, these were not considered in the analysis.
   5.2 There were 2 registers where it was obvious the mistake of data entering, and that was the wrong entering of the year. These were fixed and included in the calculations.
   5.3 Six errors regarding to extremely high values for transportation and 7 respecting to negative values were not considered.

6. Final assembly:
   6.1 In 77 records, there was missing the date of Product receiving at the Final Assembly place, and because of that could not be included in this calculation.
   6.2 256 of the registers did not include the final delivery date. Due to it, they were excluded from this analysis.

7. ‘Site ready’ time:
   7.1 In 278 registers, the date for the ‘assembly site’ readiness was missing, so, they could not be considered.
   7.2 It were detected 7 errors concerning to negative values for this time interval.
Although the data available was somehow poor for many of the described time steps, the analysis carried on, considering that the selected data was reliable.

The final results for the calculations of some statistics on each time step can be observed through the following histograms.

One thing that stands out from the above is that the ‘Site ready’ time, which is under the responsibility of the customer, presents high variation and that can be one of the causes for the uncertainty of the process. This can be one of the objectives of the simulation to be performed, i.e., to see if this really causes problems in the system.

With the knowledge about the different time intervals involved in the chain is possible to have better insights on the delivery performance. This can be defined in different ways, according to different perspectives of the delivery process.

Viewed from the factory perspective, it can be defined either as the difference between the due date requested by the sales office and the delivery from the factory, or the confirmed due time from factory and its delivery. These two measures have distinct meanings, in the way that the due date from sales office is the one which considers the requested customer service. In fact, the final due delivery date is translated to an intermediate phase according to the time necessary to make the final mounting and delivery. However, in many times, the factory agrees with the sales office another due date, the one it finds possible to make the delivery on time. Although, measuring the performance against this date should not be considered valid to express customer
service, it is a good reference to conclude about the factory response to the purposes itself has made.

Considering the total perspective, meaning the time for the complete ‘order fulfilment process’, there is only one measure to take. It is time interval between the final delivery date and the settled final due date with the customer. Respecting to customer service, this is the most important reference to take out from the system, given that the customer does not care about the processes taken to have the product available. Nevertheless, the references pointed out before, regarding to the factory response, are very useful when managing the supply chain, in the way that it enables one to observe possible reasons impacting on the final delivery performance.

---

**Figure 22 - Performance measures**

Considering the available data, only two of the above measures could be performed accurately: the factory delivery performance according to its confirmed due date (PM2) and the total supply chain delivery performance (PM3). More, the samples which are the basis for these calculations are not the same, but regard to the same period of time. In order to contemplate de higher amount of data as possible, PM2 and PM3 were calculated from the following registers, respectively:

- all the orders coming to the factory from all the sales offices.
- all the orders issued from the selected sales office to the selected factory.

The results shown below, measured with daily level accuracy, reflect the attempt in the final phase to recover some of the intermediate delays.
Figure 23 - Observed performances based on accuracy of one day

Because, as mentioned before, the customer is only interested in the final delivery, it is important to observe in more detail the meaning, or the impact, of late and in-time deliveries. An in-time delivery is taken by the customer as something he expects, and because of that he does not value it as an outstanding performance by the company. This is the opposite to what happens with late deliveries. Customers give high negative importance to the delayed time, and it results that it is completely different to deliver the product within a window of a few time units later than expected, and with a big difference between agreed and final delivery time.

What is tried to be demonstrated is that the percentage of late deliveries itself does not demonstrate the performance of the delivery process, it should be accomplished by its time profile.

So, other reference should be the average of the delays as well its variance. It can be seen from the picture below that the ‘Case Study Company’ presents an high variation among the late deliveries, and when compared to the early deliveries, a much bigger average.

Figure 24 - Time distributions of intime and late deliveries

Correlation analysis

In order to experiment different situations and conclude about the results in the simulation model, one has to have some idea about the main factors contributing to the
current delivery performance of the ‘Case Company’. The data analysis executed before allows one to have some insights on it, however, the hypothesis that can be formulated are not demonstrated with the previous analysis. One good way to test some of the hypothesis is using a correlation analysis, where two variables are compared to conclude about its dependence/independence.

The analysis that follows was made recurring to the Pearson correlation coefficient, which is defined as below:

\[
r_{xy} = \frac{\sum_{n=1}^{N} (x_n - \bar{x}) \cdot (y_n - \bar{y})}{\sqrt{\sum_{n=1}^{N} (x_n - \bar{x})^2 \cdot \sum_{n=1}^{N} (y_n - \bar{y})^2}}
\]

The Pearson correlation assumes that the two variables are pair-wise connected, and it determines the extent to which values of the two variables are "proportional" to each other. The value of correlation (i.e., correlation coefficient) does not depend on the specific measurement units used; for example, the correlation between height and weight will be identical regardless of whether inches and pounds, or centimetres and kilograms are used as measurement units. Proportional means linearly related; that is, the correlation is high if it can be "summarised" by a straight line.

The Pearson coefficient can take values between -1 and 1, depending on the level of dependency shown by the variables.

- \( r_{xy} = 1 \) when the linear relation between the variables is perfect and the line’s angular coefficient is positive;
- \( r_{xy} = -1 \) when the linear relation between the variables is perfect and the line’s angular coefficient is negative
- \( r_{xy} = 0 \) when there isn’t any linear relation between the variables.

Three hypothesis were tested in this phase, respecting to the factory performance (1) and to the total performance (2):

- **Number of products to deliver in a given due date is related with the sum of delays for that date (Factory performance).**
In this case, $r_{xy} = -0.509101$. The meaning of this is that these two variables are negatively related in a certain degree. The bigger the number of products to deliver, the bigger the time for late deliveries (delay as negative value).

This relation can be due to lack of parts from suppliers or capacity limitations when the demand high peaks, as the simulation to be performed tries to show.

- The factory performance impacts the final result of the delivery (Total performance).
Surprisingly, these two variables were found not to be in close connection. The Pearson coefficient was here \( r_{xy} = -0.096497 \). This can be explained through a behavioural reason: when getting the product from factory with a given delay, the sales office puts all the effort on this order, trying to avoid the propagation of this delay to the customer.

- **The time for availability of the site is related with the final performance (Total performance).**

![TOTAL_DELAY_vs_FINAL_ASSEMBLY_SITE_DELIV_TIME](image)

Figure 27 - Total delay vs ‘site ready’ time correlation

In this situation, \( r_{xy} = -0.173430 \). It means that site preparation time (or the ‘final assembly site’ delivery time) is likely not to impact the final delivery performance. However, the recording which was the basis for the calculation, was not containing all the registers regarding to the site delivery time, and that can be a reason not to believe in this result. Because of that, this situation will be tested in the simulation model to conclude about its veracity.

### 4.11 MODEL CONSTRUCTION

The model to be executed has, as final objective, the observation of the supply chain responsiveness to customer. This is measured by the capacity to respond in-time to customer requests, i.e. with the agreed date for the final delivery.

In this chapter, it is described the way the model was built and programmed in the selected simulation language, so that to reach the final objective mentioned above. First, a general description of the programme’s structure is presented. After this, it is presented the time step, variables and parameters which are used in the simulation code. The next part, is about the way the inputs were used to generate the dynamics in the system. Then, follows a more detailed description of the code capabilities and the way some distribution functions were obtained to describe some processes. The fifth part
presents an overview about the outputs that the simulation executed here can show. The results which were obtained are, then, presented and discussed.

4.11.1 Model Structure

Like in other studies on supply chain's simulation mentioned in chapter 3.4, this modelling work started by considering the manufacturing activities, and then adding the selected suppliers, the final assembly and the delivery process.

Because the aim is to model the current situation of the network, the initial part of the supply chain, concerning to order administration at the sales office, was considered rigid, i.e. the real data regarding to the times spent there with each order was taken into consideration. The input data, meaning the time when the order arrived at the factory, the due date to the factory and the final due date were, then, fixed by the real data which was available. However, for future experiments, new data can be created, based on the statistical profiles shown by these operations and described in the previous chapter.

After describing the whole model, the input data explanation will be considered again, thus in a more detailed way.

In order to create an easily manageable code, the main operations were split into different modules. So, the structure of the total model includes the following systems:

- 13 modules, each one referring to the production of one of the selected parts from the product structure simplification;
- 1 module regarding to the selected suppliers for assembly;
- 1 module concerning to the assembly, and also, site availability and final assembly;
- 1 module which makes the connections between the different systems;
- 1 module that has the function of reading the external data; and finally
- 1 module responsible for executing the simulation and presenting the results.

Parts manufacturing modules

The approach starts, as pointed out before, with the manufacturing operations. An example of a flow description for a selected internally manufactured main component (meaning used for assembly), is shown below:

![Figure 28 - Example of a component flow description](image_url)
For all the selected modules, a flow description like the above was executed. The blocks refer to the operations to be performed in the component’s production. The filled triangles report to a storage place, controlled by the processes explained in chapter 4.7.2 and the unfilled ones represent buffers, or better, work in process (WIP).

The flow representation shown above, differs somehow from the one presented in the chapter regarding the sequence of operations. There, when a cell was used more than once to produce a given component, the correspondent block was not repeated, instead more than one arrow would pass there. Here is different. Because each operation is represented by a block, when a cell is used twice or more, two or more blocks will be drawn. This was the structure chosen to built the programming code: each operation will be described by a block. Then if a given cell is used more than once, relations will be established between the corresponding blocks to determine the priorities.

Another relevant aspect to take out from the picture is the relation settled between the different levels of the product tree and its sequence of operations. It is important to note that each level has its own stock pile, which controls its own production.

The initiator of this process is, however, the 2nd level stock, which is the one present before the assembly. When the reorder point is reached a batch order is sent to the first operation of that level. It will produce according to the availability of external and internal supplied parts, regarding to the 3rd level of the product structure, and also to the capacity availability.

Suppliers for assembly module

The external supply for the assembly is composed by more than 100 different parts. However, only 29 components were considered critical, respecting to the suppliers performance and complexity of the product. This means that, here again, parts like bolts and nuts were not taken into consideration.

This module is comprised by 29 blocks, each one respecting to one given component. Further down in this chapter these type of blocks will be described in detail. The figure below represents the structure of this module, where again, the stock control for the parts is done by its utilisation in the assembly phase.
Assembly, site delivery and final assembly module

This can be considered as the main module of the simulation. This is where the main input comes in and the output is obtained.

The input comes straight to the begin the assembly operations, which will be executed according to the availability of the internally and externally supplied parts, as well as its capacity. Then there is a time lag, which in practice is almost invariant until the product is ready for the final assembly. However, this does not start before the site for it is ready.

Figure 29 - External supply for assembly module description

Figure 30 - Final module description
After the final assembly the final product is instantaneously delivered to the customer and the total performance evaluated, as mentioned, putting the final delivery time against the agreed time with customer.

4.11.2 Time, Parameters and Variables

The time step considered within the model was 1 day. Although for some processes it can be excessive, for some of them, like measuring the deliveries from suppliers, it is quite reasonable. Also, the objective of the simulation was to measure the delivery performance on a daily basis and that contributed to choose this time step, as well. The simulation code uses a set of parameters and variables to explain the functioning of the supply chain. It is important to mention here that the utilised simulation software, considers the variables, those which are defined from a state to another, i.e. from a time step to another. Those which only act in a given time period are considered as auxiliary.

Taking as a base the description of the model presented before, one can say that the main variable of the whole process is the number of final products delivered in a given time step. From here, and going backwards in the processes the main variables can be identified:

1. Before final assembly:
   - Number of sites ready for final assembly (boxM)
   - Number of products waiting final assembly (box1)

2. In the assembly (factory):
   - Number of products being assembled (p1)

2. In parts manufacturing, for each cell:
   - If final operation in each structure level production flow, the number of components in stock (boxi, i = block number)
   - If intermediate operation in each structure level production flow, the number of components in the buffer, i.e. the number of WIP (Work-In-Process) components (bufi, i = block number)
   - The cumulative number of components produced in a given time step (cumpi, i = block number)
   - The counter, determining if the cell is working or not (tb, i = block number)

4. About external supplied parts:
   - The number of components in stock (boxi, i = block number)
   - The time counter for the delivery time of a given a order (tb, i = block number)

Besides the presented variables, there is another one to consider in the suppliers blocks, but it has an auxiliary function to the code, and will be explained further down, under the chapter “Code Explanation”.

As mentioned, not only the variables define the processes taken along the supply chain, there is also a set of parameters which rule the operations in different ways. This simulation model includes the following:
• Incorporation factor of each component from level j in component of level j -1 (n_i, i = block number)
• Production capacity limits for a cell producing a given component, according to the expression defined in 4.10.6 (pm_i, i = block number)
• Disturbances, meaning the probability for break downs, absenteeism, etc. in the manufacturing cells, and probability for delays in the suppliers blocks. (pb_i, i = block number)
• Agreed delivery time with suppliers for a given part (tsup_i, i = block number)
• Maximum registered delay for a given supplier (tmax_i, i = block number)
• Average registered delay from a given supplier (tad_i, i = block number)
• Batch size for the internally produced and external bought components (b_box_i, i = block number - supplier blocks and last operation block for each internally manufactured component)
• Fixed reorder point for the internally produced and external bought components (l_box_i, i = block number - supplier blocks and last operation block for each internally manufactured component)

The way these variables and parameters were used within the code will be explained in section 4.12.5.

4.11.3 Input information

The input file contains two types of data, in what concerns to its utilisation in the simulation programme: on one hand we have data influencing processes and used to calculate the performance measures, and on the other hand, data which is used only to compare the real performance and the obtained one by the simulation.

The first group of data includes the following fields:

1. Number of products to start the assembly;
2. Number of products to start the assembly in a month time;
3. Forecasting coefficient;
4. Planned number of deliveries from the factory;
5. Number of ready Sites;
6. Planned number of final deliveries.

And the second group:

7. Number of products delivered in time from factory in real life;
8. Number of products delivered late from factory in real life.

It was already mentioned, that the first input coming in the system is the start for assembly (1). According to the availability of components and capacity it will start or not.

Because in real life there is a time lag of approximately one month since the order is released for production till the assembly starts, this was also considered in the model, putting as input for components manufacturing the production which will start after one month (2).
Using the same kind of method which is in practice at the factory to make forecasts, a coefficient (3) is generated externally and used to move the re-order point of external supplies.

The input for the system was based in the orders of the considered model of the product, from the period of one and a half years. Because this regards to all the orders coming from whole sales network, not all the data was available. These were the time when Site was ready (5), and the final agreed date with customer (6). Due to this fact, that data had to be generated in an 'artificial' way, meaning extrapolating values from the distribution curves obtained with the valid data.

From the real data, the value which can be taken to the Site time is the one corresponding to the interval between the order receiving at the Sales office and its readiness. However, in the simulation model, the time counter is located in between those two moments. This means that, for each order, the time to consider in the model is the gap between the assembly starting (which is available in the original data) and the site readiness (which is generated by the distribution curve obtained with the valid data). This is shown in the figure below, where the grey part of the Gantt map represents the time interval to consider.

![Figure 31 - Time for Site preparation](image)

To obtain a distribution function for the Site preparation time from the valid data, a statistical package called STATISTICA was used. From there resulted that the best fitting was reached with the 'Extreme' distribution, as the pictures below demonstrate.

![Figure 32 - Extreme distribution for the Site readiness time](image)

The extreme value (Type I) distribution (the term first used by Lieblein, 1953) has the probability density function:

\[
f(x) = \frac{1}{b} e^{-\left(\frac{x-a}{b}\right)} e^{-\left[-e^{-\left(\frac{x-a}{b}\right)}\right]}
\]

, where

\[ -\infty < x < \infty \]

a is the location parameter
b (> 0) is the scale parameter
e is Euler's constant

The cumulative distribution function for the Extreme Value distribution is:

\[ F(x) = e^{-(e^{-\frac{(x-a)}{b}})} \]

A random number was generated from the Uniform distribution and used as the value for \( F(x) \). This made possible to achieve a \( x \) value for each order representing the sum of the grey and white parts of the Gantt map shown before. Like mentioned before, to obtain the time interval to be used in the simulation model, for each order this time was subtracted by the real value present in the files for the assembly starting.

Similarly, the agreed final delivery date was originated through this type of process. The need for this time comes from the fact that the final performance of the chain has to be evaluated. Only with the final due date available, one can conclude about the results achieved for the final delivery.

In this case, the times follow the shape presented below.

![Figure 33 - Extreme distribution for the agreed final delivery time](image)

Here again, the best fitting was obtained with an 'Extreme' distribution but, obviously, with different coefficients from the previous case.

### 4.11.4 Code explanation

In this section, the most important features performed by the code are described. It will not cover all the different blocks, but only the most common ones and those having a fundamental role, like for example the assembly operations.

Before the code explanation itself, an overview about the different efficiency approaches taken with distinct kinds of blocks is presented.

#### 4.11.4.1 Efficiency Distributions

In section 4.12.2, a reference to the disturbances parameter \( (p_{bi}) \) was done. Within the simulation model, this parameter was used in three different ways, according to the type of block:

- Suppliers: Meaning the percentage of late deliveries
- Mainly labour cells: Meaning the absenteeism rate and human efficiency
Mainly machine dependent cells: Meaning the probability for breakdowns

**Suppliers**

In the case of suppliers, it has been assumed that when the deliveries are not late, they are delivered in the agreed time. When they are late, the assumption was that the late time follows an exponential distribution, determined by the parameters late average and maximum lateness. This can be better understood through the observation of the following picture.

The challenge here was to define the exponential part of the above distribution. It was defined separately, through the following methodology:

- The exponential distribution function is, in general terms, defined by $F(x) = 1 - e^{-x/\beta}$
- $F(\text{LateAv}) = 0.5 \Rightarrow \text{LateAv}/\beta = 0.69315 \Rightarrow \beta = \text{LateAv}/0.69315$, where LateAv is the average late time
- $F(x)$ can be defined now by $F(x) = 1 - e^{x(0.69315/\text{LateAv})}$
- Because the purpose is to obtain $x$, given a random number $F(x)$, this is defined as follows: $x = (-\text{LateAv} \times \ln(1-F(x)))/0.69315$

This is the formula used in the code to calculate the lateness of a given delivery, when it is not in-time.

![SUPPLIER DISTRIBUTION FUNCTION](image)

*Figure 34: Suppliers performance function*

**Labour Cells**

In this case, it has been supposed that the efficiency of these cells follows a normal distribution where the mean comes from the efficiency parameter, pb. Given that the efficiency cannot be higher than 100%, it has been decided that the gap between 100% and the mean corresponds to 3 times the standard deviation ($\sigma$). This leads to the achievement of $\sigma$. The assumption of $3 \cdot \sigma = 100-(100-pb)$ is possible because it includes 49.84% of the normal distribution observations out of 50%.

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In the code, a random number based in the Normal distribution (0,1) is generated, multiplied by the standard deviation and added with the efficiency mean. The result is, then, multiplied by the nominal capacity of the cell to obtain the real capacity for that time step. The only restriction are the limits of 0% and 100% for the efficiency value.

**Machine Dependent Cells**

To characterise the efficiency of these kind of cells, a simple trigger working/not working during a given time step was adopted. This means that when a random number generated by an Uniform distribution goes above the nominal efficiency, the cell will not work in that time step, i.e. its capacity will be null.

### 4.11.4.2 Blocks Description

Some of the main blocks constituting the model are presented here. First is one example of the suppliers description. After that, a production sequence of a component. Then comes the description of the code which is related with the assembly operation, followed by the explanation of the ‘final assembly site’ readiness and final assembly. To conclude, it is presented the way measures of performance are taken out from the system.

**Supplier**

```
"Node 7 - Supplier to Operation 4
dbox7=MAX(boxB7+(IF tb7>tsup7 THEN b_box7 ELSE 0)-n7*p5,0)
stn7=IF tb7<1 THEN 0 ELSE (IF (tb7>0 AND tb7<2) THEN RECT(t) ELSE st7)
pdf7= IF stn7>(1-pb7) AND pb7>0 THEN -1*(ln(1-(1-stn7)/(1-pb7)))/0.69315 ELSE 0
tsup7=tsup07+MIN(ROUND(pdv7)*ad7,tmax7)
tbn7=IF dbox7<c*L_box7+1 OR (tb7>0 AND tb7<tsup7+1) THEN tb7+1 ELSE 0
```

Each stock from a supplier is defined by the variable box, and in the next time step by dbox. This is useful to explain the first line of the code. The stock level will be, in the
next step, equal to the present stock level minus the amount used in the present time, plus a replenishment quantity if the supplier makes a delivery. The next three lines are used to define the time for delivery when an order is placed to the supplier, according to the distribution function explained in the previous section. Finally, the counter for the supplier delivery time is defined. When the floating reorder point is reached, the counter starts, meaning that an order was sent to the supplier. It will stop when the counter passes the delivery time fixed before.

![Figure 36 - Stock level variation and time for delivery (manipulated units)](image)

**Component sequence**

The explanation of the code used to describe the production flow is shown below.

![Figure 37 - Component manufacturing sequence](image)

*Node 4 - Operation 3*

send4=IF dauxb2<box2+1 THEN 1 ELSE 0
check4=IF (send4 AND tb4<1) AND tb2<1 AND bufB4<1 AND bufB3<1 THEN 1 ELSE 0
tbn4=IF (tb4>0 AND cumpB4<box2^2*n3*n4) OR check4>0 THEN tb4+1 ELSE 0
pm14=IF CLtb3>0 THEN MAX(INT(pm4-CLp3),0) ELSE pm4
pl4=(1-MAX(0,MIN(pb4*(1+100)));1)))^pm14
pl4=MIN(MIN(MIN(boxB5/n5,boxB6/n6),boxB9/n9),boxB10/n10,boxB11/n11)
p4=IF tbn4>0 THEN ROUND(MIN(MIN(p4,pl4),box2^2*n3*n4-cumpB4)) ELSE 0
dcump4=IF tbn4>0 THEN cumpB4+p4 ELSE 0
dbuf4=MAX(bufB4+(IF cumpB4<box2^2*n3*n4 AND tbn4>0 THEN p4 ELSE 0)-n4*p3,0)

If the re-order point of the stock, defined by inventory present in the end of the sequence is reached an order will be sent to the first operation of the sequence. Then, if there isn’t any batch being produced along the sequence, the production will start. There
is a counter that will run while the batch is not complete in this operation. The production is subject to some conditions:

- the cell is shared with the production of another component. In this case it has been considered that the capacity can be split and in each time step the two products are manufactured, though the capacity is reduced.
- A normal distribution defines the efficiency of the cell, given that it is mainly dependent of labour (according to the definition of the previous section)
- The production will be ruled by the availability of components that are below in the product tree. They can be either internal or external supplied.
- The maximum value for the production will be the necessary to obtain the batch size. It will not be possible to produce more than that.

The work in process after this operation is defined by the value present in the last step minus the production of the next operation plus the amount produced in this time step.

```
"Node 3 - Operation 2
p3=ROUND(MIN(IF (1-RECT(t))>pb3 THEN pm3 ELSE 0,bufB4/n4))
tbn3=IF cumpB3<b_box2*n3 THEN tb3+1 ELSE 0
dcump3=IF tbn3>3 THEN cumpB3+p3 ELSE 0
dbuf3=MAX(bufB3+(IF cumpB3<b_box2*n3 AND tbn3>0 THEN p3 ELSE 0)-n3*p2,0)
```

If WIP is queueing behind this operation, it will try to produce, according to the capacity limits and the efficiency of the cell. In this case it has mainly a machine dependent one, meaning that it has available the maximum capacity or none (according to the definition of previous section).

The WIP after this operation is obtained in a similar way as the one for the previous operation.

```
"Node 2 - Operation 1
p2=ROUND(MIN((1-MAX(0,MIN(pb2*(1+NORM(t)/3),1)))*pm2,bufB3/n3))
tbn2=IF (tb2>0 OR bufB3>0) AND cumpB2<b_box2-p2 THEN tb2+1 ELSE 0
dcump2=IF tbn2>3 THEN cumpB2+p2 ELSE 0
dbox2=MAX(boxB2+(IF cumpB2>b_box2-p2-1 THEN b_box2 ELSE 0)-n2*p1,0)
dauxb2=auxb2+(IF cumpB2>b_box2-p2-1 THEN b_box2 ELSE 0)-n2*fcast
```

Here again, if any WIP is located before this operation, it will try to produce under the capacity and efficiency restrictions.

While the batch production is not complete, the counter for this operation will be active. The physical stock is defined, for each time step, as the previous step value plus the production minus the parts needed for assembly.

The last line presents the stock controller. Because, at the factory the assembly starts about 4 weeks after the order is received, the production of components can be ruled by real demand for the next month. It is used a value denominated 'fcast' which means the value for the production in 4 weeks time. The value of the stock controller is defined by the previous value, plus the real production, minus the parts needed for the assembly taking place in about one month time.
Assembly operations

"Node 1 Assembly
need1=due-de1
need11=sale-dee11
ap1=MAX((p1+sc1*(sl1-buf1)+mc1*(need1-p1))*10,0)/10
p11=MIN(MIN(MIN(MIN(MIN(MIN(A2box,BRbox),CLbbox),EBbbox),E1bbox),E2bbox),H1bbox)
p1=MIN(MIN(MIN(MIN(MIN(MIN(H2bbox,H3bbox),Ibbox),LBbbox),LBbbox),OBbbox),OBEbbox),TBbbox)
aux1=MIN(MIN(aux1,pl1),pl1),2)
dp1=ROUND(aux1*(1-pb1*RECT(t))
buffer1=buf1+p1
dde1=MIN(buffer1-need1,0)
dde11=MIN(buffer1-need11,0)
dbuf1=MAX(buffer1-need11,0)

The final assembly is ruled by the input defined here by ‘sale’ which means the scheduled starting of production. Here the production is subject to the following restrictions:

- The production will only be possible if there is availability of the selected 2nd level components.
- The maximum capacity was considered as rigid and equal to two products per time step.
- The efficiency value for the assembly line will also rule the activities.
- It is defined a function that tries to adapt the capacity, according to delays, stocks and needs.

The delays are defined as the difference between the buffer and the need for products. The need at a given moment is defined as the previous one plus the cumulative delay.

"Final assembly"
dbox1=DELAY(IF p1>0 THEN box1+p1-p0 ELSE box1-p0,15)
dboxS=boxS+ready-p0
need0=findue-de0
buffer0=buf0+p0
dde0=MIN(buffer0-need0,0)
dbuf0=MAX(buffer0-need0,0)
p0=MAX(MIN(dboxS,dboxS),0)
dp0=ROUND(p0)

The final assembly is processed after storage and transportation of the product to the place where it will be executed. The number of products available is defined by the production at the factory, minus the final assembled ones. It was considered here a time delay of 15 days since the product is ready out from manufacturing at the plant, until it can be available for final assembly. However the final assembly depends also on the availability of the Site. The value for this stock is increased by the values originated through the process explained in section 4.11.3, and decreased by the number of final assemblies.

In a similar way to the assembly, the need is defined by the number of final products that should be ready plus the delayed ones. The delays are here defined as difference between the number of final assemblies and the needs.
Performance measures

"CALCULATE DELIVERY PERFORMANCE FROM FACTORY
early = -MIN(duel-buffer1-de11,0) "taken as negative value for plot!!
late = MIN(buffer1-duel,0)
time = IF duel>0 THEN MIN(duel,buffer1) ELSE 0

"CALCULATE FINAL DELIVERY PERFORMANCE
early = -MIN(findue-buffer0-de0,0) "taken as negative value for plot!!
late = MIN(buffer0-findue,0)
time = IF findue>0 THEN MIN(findue,buffer0) ELSE 0

The performance measures out from the factory and at the final delivery are defined in a similar way. The differences are between the values, not the kind of variables. This allows to explain only one of performances, in this case the one out from the factory:

When the number of products that should be delivered in a given time is less the number of products which were produced minus the delays (always a value ≤ 0), it means that early deliveries can take place. Although it is better than having late deliveries, in terms of customer service, it is not so good to have a high value for this measure, because it means unnecessary inventory.

The late deliveries are defined by the number of products that should be delivered minus the amount of products available.

If in a given time step, there is a certain number of products to be delivered, the in-time deliveries will be defined by the minimum between that value and the available products.

4.11.5 Output

The output created by the simulation model can assume two distinct forms. On one hand there is a tabular form, which includes, for each time step, all the values of the selected variables and parameters. On the other hand, there are the graphs which are used to have a clearer view of the system dynamics.

Some examples of graphs which can be obtained with this model are shown below, having the values been modified due to confidentiality reasons. Two groups are presented, regarding to different processes and analysis. The first one shows some characteristics regarding the Assembly and Final Assembly. The second one presents the variations in the stocks of some components needed for the Assembly operations.

Follows a detailed explanation for each graph from the first group:

1. Start Assembly / Due Date: This data is real and read by the model from the file containing the input data. In red it is shown the scheduled number of products to start the assembly in each time step. In blue, the number of products to be ready from factory, in each time step.
1. **Assembly**: this is simulated data for the assembly operations. For each time step, it is shown:
   - In blue, the number of products assembled.
   - In black, the number of products which are delayed according to the definition of section 4.11.4.2
   - In red, the number of products which are in stock

2. **Simulated Deliv. perf. from fact.**: The final objective of this work is to study the final delivery performance of the chain, however an intermediate phase was considered, the performance from the factory. In green, it is represented the number of products produced in time according to the due date mentioned before. In red, the number of products which are delivered from factory with delay.

3. **Real Deliv. perf. from Fact.**: In order to conclude about the veracity of the results, the obtained performance of the factory in real life is here presented, in a similar way as before.

4. **Final Assembly**: After the product is assembled, there is a fixed time lag of some time steps, until it is available for final assembly. This is due to storage and packaging activities, as well as transportation. Anyhow, the final assembly will only start when the site is ready. The availability of the Final Assembly site is represented in red and means the cumulated deliveries minus the ones which have already been assembled. In blue, it is shown the number of final products assembled.

5. **Total S.C. Deliv. Performance**: Although the real supply chain delivery performance is not available, the final goal of this study is to make the analysis of it. Here again, in green is shown the in-time deliveries and in red the late ones. This measure is done according to the final due date generated by the process described in section 4.11.3.
In the second group of graphs, each one respects to one component. This means that when explaining one of them, the others will be also understood. The only difference between them appears in the first graph, only to demonstrate some other features which can be performed besides the stock levels (in red). So, in the first graph, it is also presented the cumulative production of the batch in blue, and the stock controller for that component, as explained in section 4.11.3.

Besides these graphs, it could have been also shown the WIP's all over the factory and the production of all the cells considered in the model. This is important to identify, in an easy and fast way, the problems in the production of components.

Another possibility of the model is to show the stocks from external supplied parts, either for assembly or component manufacturing, and observe the times the suppliers spend with deliveries.

4.11.6 Experimentation and presentation of results

In order to be valid, the experimentation has to be repeated several times. The reason for this is that the model uses many random processes which can originate different reactions in different runs. From here, it comes that the goal is to obtain the average performance of the model. In the present case, the best phase to conclude about the validity of the model is when the product leaves the factory. This because, it is the only place where data on the real performance is available.

Five model runs were executed and the average in-time and late deliveries calculated. The results were as the following:
A Case Study on Supply Chain Dynamics

<table>
<thead>
<tr>
<th></th>
<th>1st Run</th>
<th>2nd Run</th>
<th>3rd Run</th>
<th>4th Run</th>
<th>5th Run</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>% In-time</td>
<td>33.68</td>
<td>29.82</td>
<td>27.72</td>
<td>31.23</td>
<td>33.68</td>
<td>31.23</td>
</tr>
<tr>
<td>% Late</td>
<td>66.32</td>
<td>70.18</td>
<td>72.28</td>
<td>68.77</td>
<td>66.32</td>
<td>68.77</td>
</tr>
</tbody>
</table>

A graphical analysis can already demonstrate that the model does not reflect the reality in terms of the factory performance:

![Simulated Delay perf from Fact](image1)

![Real Delay perf from Fact](image2)

*Figure 40 - Simulated vs Real factory performance (manipulated units)*

Recalling the values obtained for the real performance out from factory in chapter 4.10 and comparing them with the results obtained before, one can surely conclude that the model, is not yet valid:

<table>
<thead>
<tr>
<th></th>
<th>Average Run</th>
<th>Real life</th>
</tr>
</thead>
<tbody>
<tr>
<td>% In-time</td>
<td>31.23</td>
<td>62.00</td>
</tr>
<tr>
<td>% Late</td>
<td>68.77</td>
<td>38.00</td>
</tr>
</tbody>
</table>

### 4.11.7 Discussion about results

Time restrictions did not allow to go deeper in this study and investigate the reasons for the differences between the real performance and the simulated one. The opinions of the system's experts should be asked in order to validate the model. Making a relation with the flow diagram presented in chapter 3.4, the work stopped in the phase where one questions if the coded model reflects the real system. Here the answer was 'no' and this means that more collection of information on system operating procedures would have to be done.

The process to have the main focus in the next phase would be the component's manufacturing, in what respects to its inventory control. This because, the model only
allows one batch to run at a time and that can be one of the reasons for the discrepancies that were obtained by the model. Although, it already includes the floating reorder point explained before, maybe the order quantity is not always rigid, like it happens within the simulation, or many batches can be ordered at the same time.

Another important aspect that should be pointed for the generation of those results, is the capacity of the assembly lines. It was considered here that it could make 2 products per day. However, given that there are 3 different assembly lines, it should be studied whether that capacity is rigid, or the lines can be adapted so that to handle more of those products at a time.

There is the thought that these changes could have serious impact on the system validity. Only after proving if the model could demonstrate the reality in a reasonable way, changes on the chain structure and performances of the different actors could be executed to conclude about its impact in the overall responsiveness to customer.
5. CONCLUSIONS / RECOMMENDATIONS

The theme and the obtained results

Due to competitive pressures, companies are shifting from a structure with rigid and pre-planned activities to an approach, that enables them to react quickly and appropriately to changes. To meet this objective, companies must put their effort not only in improving their internal processes, but also the relationships among the different actors present in the supply chain.

When considering a supply chain, one has to be aware about the uncertainty present in that system, thus generating complex dynamics that should be understood to better make decisions.

This study is based on the work with a company, which manufactures an assembly-to-order product. It has been an attempt to go along that company’s supply chain and detect the main factors influencing its dynamics, more exactly its response, with the help of a simulation model.

The model includes the processes and relations between one sales office, one of the factories and most of the suppliers. In order to simplify the construction of the model, one of the most sold products selected as an example.

The output to take out from the simulation was selected to be the performance of the company concerning to in-time/late deliveries. However, due to time restrictions and problems with the software performance (the version available at the time) the work could not be completed. The results which were obtained could not be properly connected with the ones from the real system. While the performance out from the factory is about 60% in-time deliveries in real life, the simulated result was only 30%.

Proposals for further study

The next step to perform in this work should be, as mentioned in section 4.11.7, the study of some processes in a more detailed way, so that to obtain a model that could ‘imitate’ the real system in a better way. Inventory control in the component’s production and the capacity of the assembly line, were taken in mind as the major sources for the discrepancies shown by the model.

Another change, that could be made, is changing the time step. It was not clear if the time step of one day was the most appropriate to model some operations in the factory. Maybe reducing it to half a day could improve some actions taken within the simulation, like some capacity utilisation.

Finally, considering the early deliveries by suppliers could also improve the validity of the model. A simplification was made concerning to supplier performance: all the early deliveries would be considered as in time, but this under-evaluates the behaviour of the supplier.
Besides the study presented here, there were two aims in the development of this simulation work, that were not achieved due to time restrictions:

- First, to integrate into the model the manufacturing of all the different models of the product. For that, it has already been asked to the plant information about components sharing by different products and the operation times they need. All the other information regarding demand and order administration times were already available.
- Second, to include in the model one other plant. Principal information about the processes, times, product structure and demand was already made available but could not be studied because of work overload.

To conclude, it is stressed that this kind of work requires high comprehension on the whole system, something that is not an easy task. Someone, making a work about supply chains has to obtain the commitment of many people along the network, in order to understand it better, and discuss the problems within a wider view, the view of the entire chain.
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