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Final Thesis

Strategic Inventory Positioning: A modeling perspective from DDMRP to AHP.

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Un ringraziamento alle persone che mi sono state vicino durante questi anni di studio e senza i quali questo percorso non sarebbe stato lo stesso. Un ringraziamento speciale a mio papà Angelo e a mia mamma Lorena per essermi stati sempre vicini ed aver sempre creduto in me; alla mia fidanzata Chiara per tutto il supporto che mi ha dato in questi anni; ai miei amici di sempre Pierluigi, Giacomo e Alessandro che mi accompagnano sin dall'infanzia.

Summary

Introduction:

This Master's Degree Thesis subject is Strategic Inventory Positioning, modelling and methodologies for this problem will be explained, analyzed and compared.

In the first chapter the evolution from MRP to DDMRP will be explained and the reason that led to this change will be highlighted. Understanding the transition from MRP to DDMRP and its causes it is fundamental to understand the new supply chain's necessities. In the first chapter it is presented an historical perspective of the evolution from MRP to DDMRP and important notions like bi-modal inventory distribution, bullwhip effect, nervousness, sales order visibility, planning horizon and especially decoupling will be introduced, these will be fundamental for the understanding of this research and represent the basis on which the research on Strategic Inventory Positioning and DDMRP are founded upon. In the last part of the first chapter DDMRP methodology will be presented; the methodological basis of DDMRP will be explained and confront, especially MRP and Lean Production, and the five elements of DDMRP will be explained and analyzed.

In the second chapter two methodologies and two models for Strategic Inventory Positioning will be presented; all of the models and methodologies answers to the question: "Where to position inventory in order to maximize the efficiency of the supply chain?". The first of the methodologies proposed in this research is DDMRP: Strategic Inventory Positioning from Ptak and Smith (2016)[1], which is the first element of DDMRP methodology. DDMRP's Strategic Inventory Positioning will be explained both for the definition of the decoupling point both for the distribution network configurations; these two parts defines DDMRP's Strategic Inventory Positioning. The first, of the two, models that will be explained in this research is the WY model from Wybark and Yang (1996).[2] This model is at the basis of Strategic Inventory Positioning and it deals with this problem in a context in which four control systems, each of them has a different re-ordering policy, are considered. The third of the models and methodologies that will be here explained is SPI model from Skintzi, Ioannou., and Prastacos (2001) [3], a model which deals with the problem of Strategic Inventory Positioning in a single product supply chain. The peculiarity of this model lies in the fact that it includes variables not included in other models considered in the Strategic Inventory Positioning literature like uncertainty

[1] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[2] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
[3] Skintzi G., Ioannou G., Prastacos G., "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40,2001

or the value added at each node of the supply chain, this model includes also a simple algorithm for the determination of the supply chain's node in which to locate the inventory. The fourth of the models and methodologies here proposed is Analytic Hierarchy Process for Strategic Inventory Positioning and in particular its application for the warehouse location selection in a supply chain, this case was considered by Al Amin, Apurba, Sumit and Imran Shikdar (2019).[4] This application of Analytic Hierarchy Process (AHP) is fundamental for this research as it is an implementation of Multi-Criteria Decision Making Technique, which includes both quantitative and non-quantitative factors, to solve the problem of Strategic Inventory Positioning. The four models and methodologies explained in this research are characterized by a high degree of heterogeneity between each other and for this is reason in the second chapter a comparison between models and methodologies has been proposed; Strategic Inventory Positioning models and methodologies have been compared along five dimensions: the ability to cope with a Desired Service Level, the ability to deal with uncertainties on important variables, ease of application, the ability to represent reduced lead times and the efficacy of the proposed reordering policy.

In the third chapter, stress tests are performed on model SPI and methodology AHP for Strategic Inventory Positioning. The reason why stress tests are important for this research is that they make possible to highlight which are the variables that affect the most the model and the solution proposed. The variables of the SPI model which have been stressed are mean demand, standard deviation, desired service level and value added. In the Analytic Hierarchy Process for Strategic Inventory Positioning case study proposed by Al Amin, Apurba, Sumit and Imran Shikdar (2019)[5] five criteria for the selection of one from five warehouses were considered, therefore, in order to stress out the model and see the consistency of the results and the impact of a new criteria, a new criterion has been added.

The results of the stress test are then commented in order to understand which are variables, or the criteria, that affect the most the decisions regarding the optimal inventory location.

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[4] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

[5] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

1. From MRP to DDMRP: Historical perspective.

1.1: History of MRP.

It is relevant for the purpose of our research to have an overview of the history that led from MRP to DDMRP, the role of MRP in companies and we will introduce some concepts that are fundamental in order to understand the transitions from MRP to DDMRP; these concepts are: flow, nervousness, bullwhip effect, bi-modal inventory distribution and “New Normal”.

APICS, American Production and Inventory Control Society, which is one of the most important supply chain management association defines MRP as:

" A set of techniques that uses bill of material data, inventory and the master production schedule to calculate requirements for materials, it makes recommendations to release replenishment orders for material. Further, because it is time-phased, it makes recommendations to reschedule open orders when due dates and need dates are not in phase. Time-phased MRP begins with the items listed on the MPS, Master Production Schedule, and determines: the quantity of all components and material required to fabricate those items and the date that the components and materials are required. Time-phased MRP is accomplished by exploding the BoM, bill of materials, adjusting for inventory quantities on hand or on order, and offsetting the net requirements by the appropriate lead times”.[6]

MRP is the successor of methodologies like EOQ (Economic order quantity) and ROP systems (Re-order point systems), the latter was a positional methodology that used historical data to forecast future demand; ROP systems were for the most manual system that, with the improvements in information technologies, were replaced by MRP in the early 1960s.

MRP methodology was developed in 1964 by Joseph Orlicky, the American engineer developed the algorithm and the principles of MRP when he was working at IBM as an alternative way to TPS (Toyota Production System), this latter methodology is the basis of “lean manufacturing”.

In the 1960 one of the main drivers, and for some authors the most important, was cost of production and this because in those times production was based on high-volume standardized production and stable demand. In this context the rise of MRP was disruptive due to its characteristics; MRP, differently from ROP, offered a forward-looking, demand-based approach for inventories and manufacturing planning that fitted perfectly with that stable environment described previously and in addiction MRP was the first methodology to introduce computerized reporting tools to analyze forecasted versus viable productions.

[6] APICS., “APICS Dictionary”, 14th ed. Chicago: APICS, 2013

By the mid 1970s it was estimated that there were approximately 700 users computerized MRP systems.[7]

In the 1980s MRP incorporated CRP (capacity requirements planning) to create the so called “closed-loop system” and MRP became MRP II; this was a revolution because the incorporation of CRP in MRP allowed companies to have an overall perspective on materials and production capacity requirements while considering also the constraints in calculation of overall production capabilities.

Nowadays nearly 80 percent of manufacturing companies that buy an ERP system also buy and implement an MRP module associated with that system.[8]

Every decade from the 1960s to the 2000s had its driving forces and the evolution of manufacturing planning and control systems followed these. In the 1960s competition was on costs and the MRP fitted perfectly in that environment, in the 1980s these driving forces were quality and world class manufacturing, greater processes control and reduced overhead costs were the main driver to build a competitive advantage and MRP II was created as an answer to these requests; but it is in the 1990s that started to emerge one those driving forces that triggered the transition from MRP to DDMRP: increased demand for highly customized products and increased customers sensitivity to delivery time and product quality.

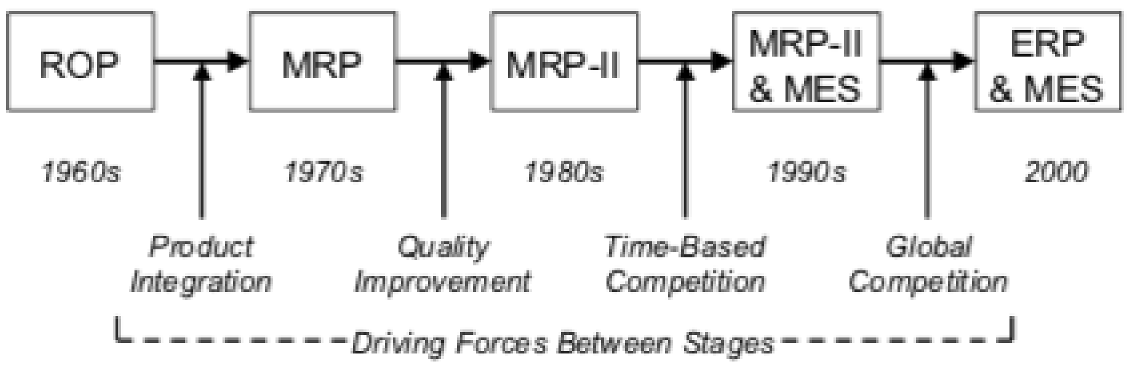


Figure 1 – Manufacturing planning and control stages.[9]

[7] Orlicky J., “Material Requirements Planning”, New York: Mc Graw-Hill, 1975

[8] Ptak C., Smith C., “DDMRP- Demand Driven Material Requirements Planning” – Industrial Press, 2016

[9] Rondeau P., Litteral L.A., "The evolution of manufacturing planning and control systems: From reorder point to enterprise resource planning.”, Scholarship and Professional Work - Business. 41, 2001

1.2: At the roots of Planning: Bi-Modal Distribution, Flow and Bullwhip Effect.

For the purpose of our research we will focus especially on the increased customers' sensitivity to delivery time but customization of products and its supply-chain implications will be also discussed further.

As we can understand, from a supply chain perspective, reducing lead time quickly became one of the important ways to gain a competitive advantage. In that dynamic environment, it became clear soon that MRP which was designed for stabile demand and mass production had some problems in this new scenario and it's because of the weaknesses in MRP design that was developed DDMRP methodology. In their book "Demand Driven Material Requirements Planning" the authors, Carol Ptak and Chad Smith, pointed out two assumptions about methodologies in general. The first assumptions is that a methodology is based on rules and this rules are based on assumption about the environment at the time they were made; we can clearly state that if the scenario between the 1960s and nowadays has changed so it should be also for some assumptions that are at the core of MRP. The second assumption made by the authors is that optimizing an inappropriate rule is counterproductive. The authors also made an important observation that companies and planning department are having a "work-around proliferation", which means basically to take corrective action, using most of the time spreadsheet, this is a very important observation because is at the basis of the concept of system "nervousness". We can define nervousness as: "The characteristic in an MRP system when minor changes in higher level records or the master production schedule cause significant timing or quantity changes in lower level schedules or orders". Methodologies like MRP were built to manage nervousness of the system and nervousness can be managed when demand was more constant, customers were more tolerant and the leading time were less important but in nowadays environment MRP can't deal with system nervousness as it should and this lead to serious consequences especially connected with the inventory management that can be resumed with one concept "inventory bi-modal distribution". Inventory bi-modal distribution and its effects can be explained using this scheme.

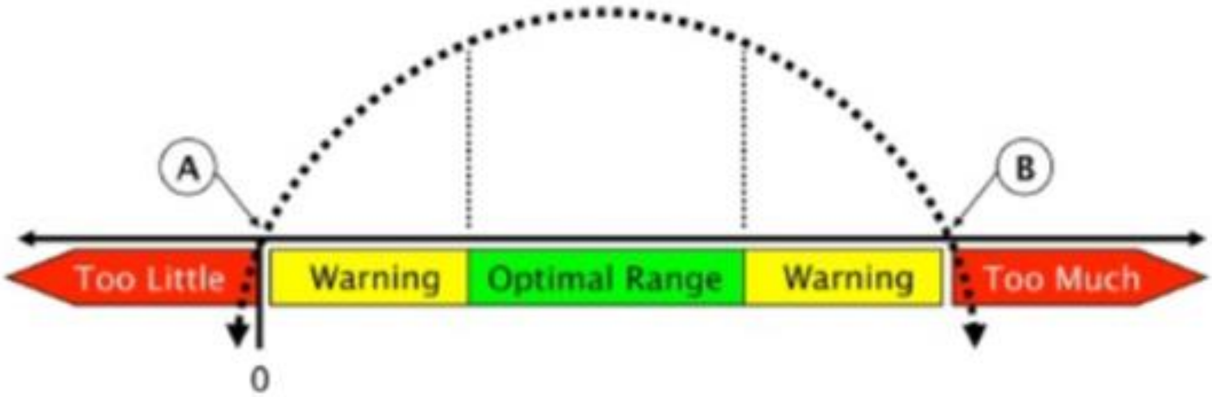


Figure 2: Bimodal Inventory Distribution[10]

Figure 2 shows the Bimodal Inventory Distribution, from the Figure we can see: Point A where company has zero inventories and it will like to experience shortages, this happens when supply chain is unable supply required inventory; Point B is the point where company has too much inventory, when a company has an excessive inventory is likely to experience waste both of goods and financial resources that are used when not necessary. The green zone is the level of inventory defined as "optimal zone" and the yellow zone are warning that inventory is increasing too much or decreasing excessively. Ptak and Smith (2016) made a survey about companies that uses MRP and the 88 percent of the companies interviewed reported that they showed a bi-modal inventory distribution pattern. We should now define which are the problem linked with having a bi-modal inventory distribution:

- High inventories costs: obsolete inventories and lowered profit margins as discounts are frequently used to clear out inventories.
- Frequent shortages: increasing in lead time and subsequent losses of customers and profits
- Bi-Modal distribution expenses: all the expenses that company faces to compensate the bimodal distribution (es: cross-shipment expenses or partial shipments).

To be able to understand concepts like Bi-Modal Distribution, Nervousness and "Bullwhip Effect" is therefore essential to introduce the notion of "flow". The concept of "flow" is rationalized by George Plossl, founding father of MRP, in the first law of manufacturing, which will be also a cornerstone for the development of Orlicky's Second edition Material Requirement Planning , states that "All benefits will be directly related to the speed of flow of information and materials".[11]

[10] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[11] Plossl G., Orlicky J., "Material Requirements Planning", 2nd edition, McGraw-Hill, New York, N.Y., p.4, 1994

At the core of the manufacturing processes there is the flow of material from suppliers, through plants and then through distribution channels and customers and all of these phases are intertwined with the flow of information.

"All benefits will be directly related to the speed of flow of information and materials"[12], the benefits to which Plossl is referring to are several:

- Service: having a good flow of material and information will ensure a good service for the customers, this benefit it is particularly important for our research because he's connected with in-time delivery which will on the main problems to focus on when dealing whit inventory positioning.
- Revenue: providing a good service, especially in the "New Normal" conditions, is a competitive advantage that preserve revenues from eroding.
- Quality: good flow of information and materials will avoid confusion and expediting.
- Inventories: the less the time that is used to transform raw material into product and delivering it to the customer the less the need to have a huge inventory investment. The material that enter in the system should be adequate to the material that exit to the system.
- Expenses: poor flow of information and material will lead to additional expenses; an example could be additional orders led by nervousness that will lead to additional inventory expenses.
- Cash: a good flow of materials and information will produce a quick conversion of product into cash and this will ensure a more predictable cash flow.

The fundamental implication of Plossl's first law of manufacturing is that rules and practices should be implement in order to protect and promote the flow of information.

Another observation that should be made about Plossl's first law is that the flow of information should be about relevant information; company nowadays have access to a huge amount of data and information but in order to avoid redundancy and "noise" because of these data they should be able to extract relevant and required information. Information are considered relevant when they are able to synchronize the assets of a business with the market's desires.

Nervousness and Bi-Modal Distributions are connected also with the so called "Bullwhip Effect" which is an extreme change in the supply position upstream in a supply chain generated by a small change in demand downstream in the supply chain.

[12] Plossl G., Orlicky J., "Material Requirements Planning", 2nd edition, McGraw-Hill, New York, N.Y., p.4, 1994

The distortions in flow of material and information created by the Bullwhip Effect have serious implications as they reduce the overall efficiency of the supply chain and more specifically, they have these consequences:

1. Inventory backlog: upstream suppliers often maintain more inventory levels than downstream suppliers in order to face the uncertainty caused by the lack of communication
2. Increased operating costs: companies will face increased operating costs due to volatility of clear information that creates problems in forecasting demand, and this will lead to excessive inventory, which means more holding costs, and cross-shipments costs between nodes to face uncertainty.
3. Reduced customer level: uncertainty cause by bullwhip effect will cause problems in supply chain's nodes to forecast demand and this will lead to delay in production, shipment and increasing in lead time.

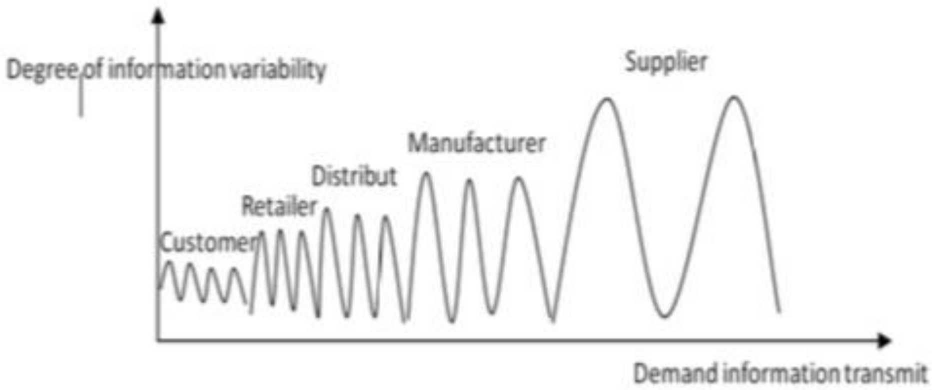


Figure 3: Bullwhip Effect[13]

Nervousness, bi-modal distribution inventory and bullwhip effect are undermining supply-chain performance, and this is mostly because the environment where MRP is used has changed while MRP did not. The new environment defined "New Normal"[14] by Ptak and Smith is characterized by more complex and various products, low customer tolerance times and reduced product life cycle; in this scenario we can states that supply chain management increases tremendously its importance and therefore that it seems clear that a transformation of MRP is necessary to adapt this methodology to the "New Normal" and that's what happened with DDMRP as we'll see in the next chapter.

[13] Jianhua D., Shibao L., Shengbo P., "Analysis on causes and countermeasures of bullwhip effect", MATEC web of conferences, 100, 2017
[14] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

1.3: Transition from MRP to DDMRP: technical perspective

After having defined the "New Normal" and highlighted which are the context in which companies need to operate nowadays we need to understand which are the major reason that led from the transition to MRP to DDRMP. One of the reasons is inherent in the MRP's nature, MRP basically it is a calculator and it needs input to determine what it is necessary to order and when. Demand is the most important input used by the MRP; APICS defines demand as: "A need for a particular product or component. The demand could come from any number of sources (e.g., a customer order or forecast, an interplant requirement, a branch warehouse request for a service part or the manufacturing of another product)".[15]

We can consider demand as being composed by two elements: forecasted demand and actual demand.

Forecasted demand is constructed using future demand; it can be constructed using both qualitative and quantitative methods.

Actual demand instead is composed by customer orders.

The ability of MRP is to order exactly what is needed given correct demand signal, if this is exact MRP is designed to net perfectly to zero, with no excess which is reflected by inventory costs.

In this assumption behind MRP lies the problem; it is not possible to forecast exactly future demand because every forecast bring with itself a certain margin of error and also it is very difficult to forecast precisely for long-time horizons, the more farther the forecast goes the less accurate it will be.

Previously we said that demand is composed by forecasted demand and actual demand, a fundamental question is: why also forecasted demand should be included when calculating demand? Forecasted demand is not as "relevant" are sales order which are certain purchases by the customers, so why it should be included? The answers is that due to the New Normal conditions like reduction of customer tolerance that has induced company to reduce their cumulative lead time the only way to respect those restricted time-frame is to be able to forecast demand more precisely than before, there is a dissonance between sales visibility horizon and planning horizon that force companies to forecast demand but MRP is constructed to work properly in a more stable environment where most of demand it's composed by sales order, as before the New Normal, and not by forecasted demand; this conditions increase system "nervousness" as expressed before.

[15] APICS., "APICS Dictionary", 14th ed. Chicago: APICS, 2013

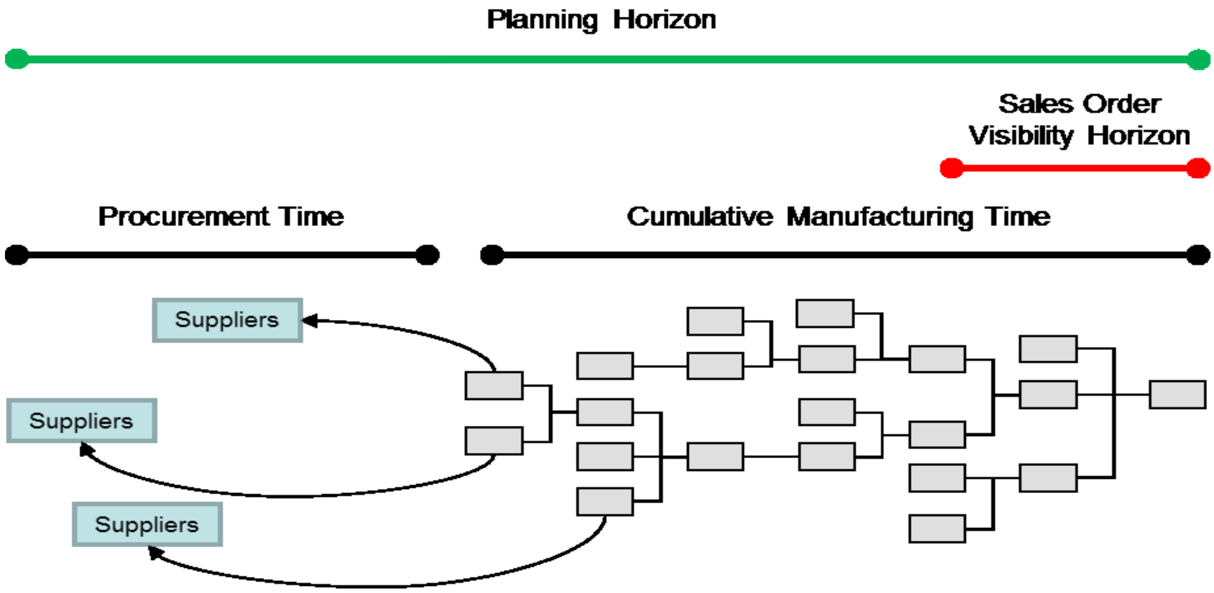


Figure 4: Planning Horizon and Sales Order Visibility Horizon[16]

Companies in order to overcome inherent limitation in MRP's ability to manage nervousness tried to use different techniques that worsened the situation: weekly bucket and flattening the bill of material. Companies typically plan in weekly buckets to correct system nervousness and they plan weekly in order to cope with daily requirements but this practice has two downsides: it shift the planning horizon further than on daily basis making even more difficult to forecast demand and also it creates a latency between weeks and so the level of change between MRP runs will be higher. Weekly bucket produces one big change once a week instead of a small change every day but the result is the same: increasing nervousness and distortion of orders. Flattening the bill of material is the practice of eliminate intermediate positions from the MRP, this is made in order avoid redundant "signal" from MRP and produce more relevant information; it does not work as eliminate interdependencies in the MRP won't produce more relevant information and it could lead also to oversimplification.

Weekly bucket and the flattening of the bill of material were practice put in act from companies to deal with nervousness, but we've seen that MRP's low flexibility and inadequacy to forecast demand produce also "bullwhip effect". This latter has a serious impact on planning: distortion to relevant. Bullwhip effect generates distortion to relevant materials on companies that use MRP because as said before MRP order the exact quantity based on the input and assumptions that it has but being this assumption and input, as demand, most of the time not perfect this will lead to delay accumulation; the second reason why it will be impossible for MRP to work perfectly is because of "common cause variation", because of intrinsic variability in every environment and process there

[16] 16 Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

will be ever variability in process which can be calculated and reduced but it is not possible to eliminate.

Batching policies, when in use, create relevant distortions in material and information and amplify the bullwhip effect. Batching policies are used to reduce order cost or due to process limitations. When in use they have a distortion on MRP in two sides: they create a demand signal distortion and they have an impact also on the supply side because it influences the processes and the flow of material in the entire supply chain.

It is therefore clear that implementing batching policies is from one side useful in order to obtain better unit cost performance but on the other side has tremendous effect on planning and in the use of MRP as it leads to distortion and delay the entire supply chain.

1.4: Decoupling:

MRP makes everything dependent, each part is dependent from the other, and as we have seen before this characteristic of MRP has some serious implications that can be resumed in two effects: nervousness and bullwhip effect, another observation that should be made is that these collateral effects are caused by the inherent inability of MRP to quickly respond to actual demand because of too long manufacturing and procurement cycles and inexactly forecasting of demand. The concept of decoupling moves from one question: “what if we remove dependency?”

If we remove dependency, in theory we should be able to ensure the perfect flow of relevant material and information because it is the dependency between parts of the supply chain that create and amplify distortion to system flow. Our aim to correct MRP should be to eliminate accumulation and impact of supply chain and demand variability to stop bullwhip effect and nervousness; this can be done using decoupling.

APICS provides us a definition of decoupling:

“Decoupling is creating independence between supply and the use of material. It refers to inventory that often is collected between operations so that fluctuations in the production rate of the supplying operations do not limit the output of the next operation.”[17]

Decoupling avoid that delay in one part of supply chain have effect in other parts and are spread along the whole chain. We can obtain decoupling through “decoupling point” they are those places where inventory is placed in order to achieve independence between entities or processes. Where to have a decoupling point is a strategic decision that will have a deep impact on the supply chain on one hand because it will require an investment in inventory but on the other hand the creation of decoupling point can avoid accumulated signal distortion and protect flow. Where to place inventory is the main question of this thesis and different approach will be deeply analyzed further and taking into account also strategic inventory positioning in DDMRP. Decoupling point are also referred with the term “buffers” and are those point where quantities of inventory are kept to decouple demand from supply.

[17] APICS., “APICS Dictionary”, 14th ed. Chicago: APICS, 2013

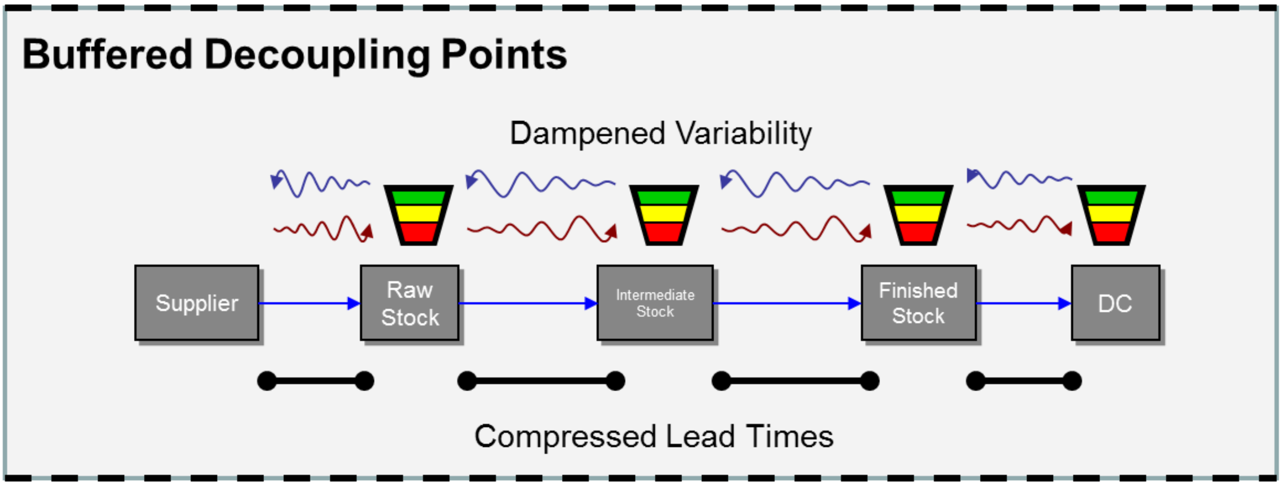


Figure 5: Buffered Decoupling Points: Impact on signal distortion and Compressed Lead Times[18]

Decoupling points have positive impact on lead time, which we'll see in next chapters, it is a fundamental metric for strategic inventory positioning and reducing lead time has impact also on quality of service and inventory implications. The use of decoupling point has impact not only on flow of relevant material but also on flow of relevant information as if the decoupling point are placed into the sales order visibility horizon it will allow the system to use only sales order and will avoid the use of inaccurate forecasts, which we have seen are one the reasons why MRP is affected by nervousness and bullwhip effect.

In the New Normal environment the use of decoupling point, or buffers, should be encouraged due to the increasing of complexity of supply chain which is reflected in increasing of variability in supply chain and difficulty to plan; being able to effectively manage supply chain flow of relevant material and information in this fast-changing and unstable environment it has become a source of competitive advantage and should be carefully considered when designing supply chain.

[18] Smith C., Smith D., "Demand Driven Performances: Using Smart Metrics", McGraw-Hill,2013

1.5: DDMRP: a brief introduction.

It has become clear that due to inability of MRP to cope with the New Normal more volatile and complex environment it was requested that a new method should have been found and a new technology should have been developed in order to ensure a good management of both inventory and production.

Before we had an overview of how DDMRP was born and the historical context in which it was developed, now we will focus on the more technical aspects of DDMRP.

What "Demand Driven" stands for? Carol Ptak in 2002 provide a definition of it: "Sense changing customer demand and adapt planning and production while pulling from suppliers all in real time"[19].

Demand Driven is a total new approach that shifts from cost-based operational methods and place its emphasis on actual demand and flow. It is not a new way of forecasting as we've pointed out that the focus is on actual demand and the ability to use actual demand derives from the management of buffers or, more technically, decoupling point.

Ptak and Smith (2016) provide a definition of DDMRP:

"Demand Driven Operating Model, a supply order generational, an operational scheduling, and execution model using actual demand in a combination with strategic decoupling and control points and stocks, time, and capacity buffers in order to create a predictable and agile system that promotes and protects the flow of relevant materials and information within the tactical relevant operational range. A demand driven operating model's key parameters are set through the Demand Driven Sales and Operations Planning process to meet the stated business and market objectives while minimizing working capital and expedite-related expenses". [20]

DDMRP is a method that has its roots in different methods and theory like MRP, Lean production and Theory of Constraints; DDMRP gathers elements from these different theories and melt it in a unique way with its own unique element.

[19] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[20] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

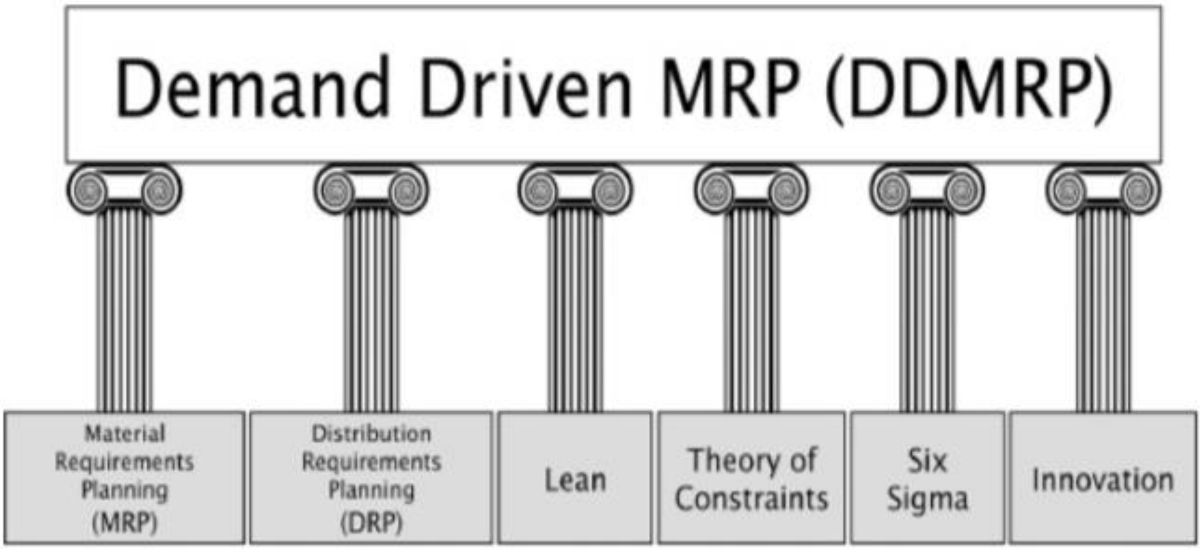


Figure 6: Six pillars of DDMRP[21]

It is therefore necessary to understand the two methodologies that are at the roots of DDMRP: MRP and Lean Production.

One thing should be made clear: these two methodologies share the same goal of protect and promote flow; they differ in the way they try to achieve it.

MRP and Lean represent the contrast that exists between "Push" and "Pull" approach.

MRP is based on "Push", production is therefore forecasted, and the flow of part and materials is "pushed" to the next stage of production, the pushing of these must follow the schedule, which is called Master Production Schedule (MPS). It is a system that relies heavily on the accuracy of schedules and forecasting, which are in turn dependent on the ability to forecast customers' demand and lead times. MRP is able to depict the complexity of production and the interrelatedness of its processes but in the "New Normal" it is increasingly difficult to forecast demand, and this undermine MRP's reliability and often generates confusion for planners.

Lean methodology is based on "Pull", raw material and parts are "pulled" to the next stage of the production; it works on the contrary of the "Push" approach. Pull adapt to real customers' demand while controlling the work in process. This philosophy is at the basis of Just-in-time (JIT) production and found its most famous and first application in Toyota Production System[22]. Lean is based on "Kanban positions" and "Supermarkets", they are independent inventory placed at each resource position; Kanban position are concerned with resource level while "Supermarkets" are placed at part

[21] Ptak C., Smith C., *DDMRP- Demand Driven Material Requirements Planning* – Industrial Press, 2016

[22] Miclo R., Lauras M., Fontanili F., Lamothe J., Melnyk S., "Demand Driven MRP: assessment of a new approach to materials management". International Journal of Production Research, Taylor & Francis, 57 (1), pp.166-181, 2019.

level. They are both sized according the consumption of the resource (Kanban) or the part (Supermarket). The role of Kanban and Supermarket is to make everything independent.

It becomes clear even from a brief description of Lean and MRP methodology that even if they share the same goal of protecting and promoting flow they have almost irreconcilable positions. In order to understand how can DDMRP be the synthesis of these two methodologies it is requested to highlights the main differences between the two methodologies.

The first difference is that MRP makes everything dependent while Lean makes everything independent.

MRP makes everything dependent because of its need to "synchronize complex and dynamic environments"[23] in order to protect and promote flow and this is achieved by defining the dependencies between the parts of the production. Lean supporters see dependency in MRP as an overcomplexity of the methodology that creates nervousness in the system and threaten the flow.

Lean instead makes everything independent, using Kanban positions, the system provides clear signals for every resource if it has to be produced or not just by looking at Kanban's signal. MRP supporters dispute this approach because in their opinion it is clearly oversimplifying the complexity and the interrelatedness between the different parts of the production.

The second difference lies in the fact that they have different "timing"

MRP schedules orders in advance for consumption, this methodology tries to forecast and anticipate demand to synchronize it with the complex manufacturing process. Lean production instead generates orders as a response to consumption, the production processes must keep the pace of actual demand; there is no forecasting in Lean production.

[23] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

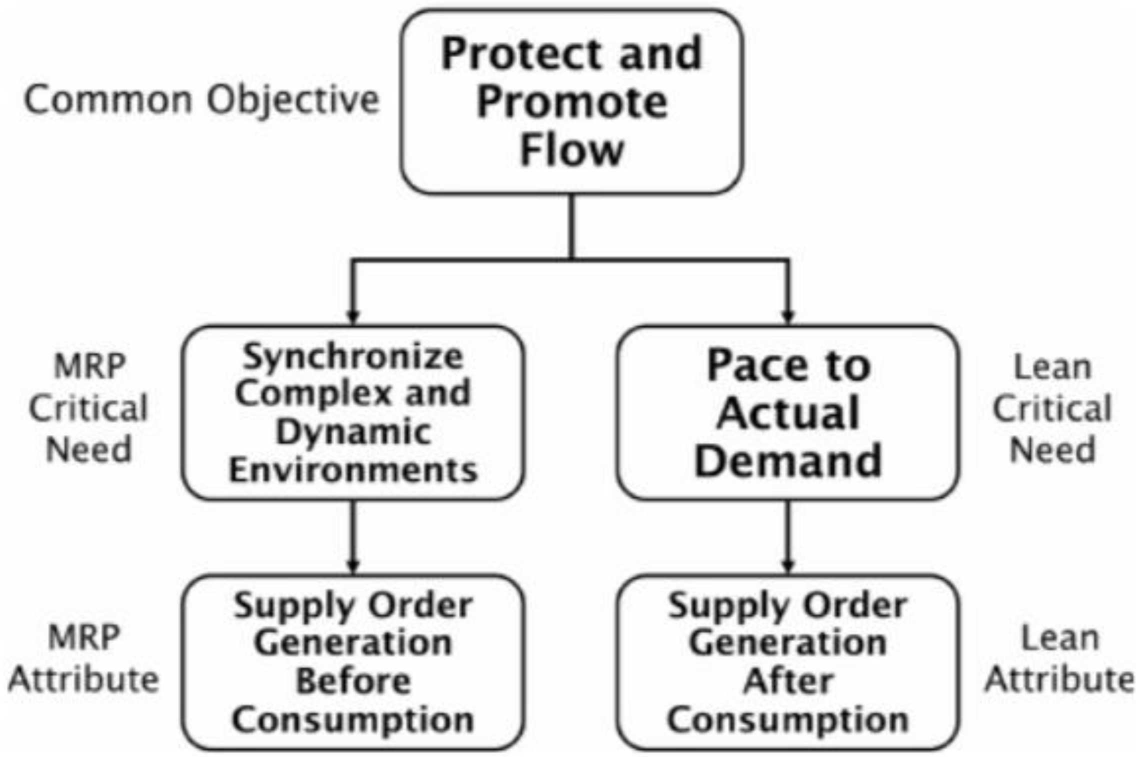


Figure 7: Methodological differences between MRP and Lean[24]

It almost seems impossible from a methodological point of view to have both the advantages of the methodologies at the same time: MRP's synchronization and Lean's clear signals.

The two methodologies also have weaknesses, we have broadly discussed the problem that affect MRP in the "New Normal" but also Lean have problems in today environment due to its inability to seize the relationships between independent kanbans and the production system as a whole.

Demand Driven Material Requirement Planning was developed as synthesis between these two antithetical methodologies.

[24] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

1.6: DDMRP's five components

DDMRP is composed by five sequential components:

- Strategic inventory positioning
- Buffer profiles and levels
- Dynamic buffer adjustment
- Demand Driven Planning
- Visible and collaborative execution

It should be noted that the notion of components of DDMRP it is different from the methodological foundation which is represented in Figure 6.

Strategic inventory positioning:

As stated, we have said that DDRMPR is composed by five sequential elements, they are said to be sequential because they follow the planning of the whole supply chain designing and operative execution.

Strategic inventory positioning or Strategic Decoupling is the first component of DDMRP, in this methodology we use this term to define the operation of positioning of the decoupling points, or buffers. Strategic inventory is both a technical operation and a strategic operation as it has an enormous impact on the service provided to the customers and to the expenses born by the company as it affects inventory holding costs. Strategic Decoupling it is not only a strategic operation but has also technical implications because it allows to stop the variability both from manufacturing and customers' side by allowing the company to shorten planning horizon getting it closer to sales order visibility this will be fundamental in reducing variability as company will use actual demand instead of forecasted demand for its planning activities. Strategic inventory positioning is allowed by decoupling and its effectiveness it's enhanced by decoupling which for its own nature won't be possible in MRP, that makes everything dependent.

Buffer Profiles and Levels

The second component of DDMRP consists in the operation of the creation of buffers point and the definition of levels of activity in these points that are sufficient to absorb distortion in demand e decrease variability. With the term "buffer" in this context we are referring to the level of that is sized and maintained, to determine the service level we have different methods that include the use of historical data, forecasts and data extracted using DDMRP. Every buffer is composed by three zone:

green zone, yellow zone and red zone; every zone is calculated in different way as they are different also their purposes.

Dynamic Buffer Adjustment

This DDMRP's component allows the planner to protect the buffers' activity level by adapting them both for internal and external deviation. Buffers are adjusted according the ADU (Average Daily Usage), it is a fundamental component because it prevents buffer from stock out and allows different adjustments for different buffers. Dynamic Buffer Adjustment is automatic but in uncertainty scenarios (promotion for stock clearance or seasonality), is suggested to adjust manually buffers' activity level.

Demand Driven Planning

Demand Driven Planning is the fourth component of DDMRP methodology; this component is the process to which by which supply orders, which include manufacturing orders, purchase orders and stock transfer orders, are generated. It is a process, an algorithm, that with the other components of DDMRP allows the planner to make orders using almost only actual sales orders within a short-time horizon.

Visible and Collaborative Execution

It is the fifth, and last, component of DDMRP. In order to properly define the last component, we should make clear the distinction between Planning, fourth component, and Execution. We are referring to "planning" when we are generating supply orders using the elements of the fourth component and the process of planning ends once the recommendation has been approved and becomes a sales order. "Execution" is the management of supply orders against relevant criteria which are two: buffer status and synchronization; the first deals with the projection and current status of decoupling point position while the latter deals with problem regarding the dependencies of the Demand Driven Operating Model. In "Execution" therefore using these "signals" we are able to identify priorities where it is necessary to pay attention or take actions. Priorities are defined by the buffer's level, the lower the level the higher the priority. These "prioritization" it is something that is present in original MRP but in that case prioritization is based on due date while in DDMRP is based on buffer's level. It should be highlighted the importance of the transition from a due date prioritization to the DDMRP's one. Prioritization using due date is used in MRP because fundamentally MRP is a planning system but not an execution system; lacking the execution everything is managed by due dates and everything should work according to due dates, without delays for example, because this is the assumption that is made when planning using MRP or the MRP won't work properly. MRP's inability to manage execution processes is reflected by its fragility when manufacturer it is not able to meet customer's due date and in order to avoid negative business implication (lost opportunities or increasing expedite-related expenses) and manufacturing company starts to manage everything by due date, the closer the due date the more important it is. It is a very fragile way to conduct a business which is reflected by poor flow protection and that lead to bullwhip effect and systemic nervousness. Using buffer's level prioritization instead of prioritizing by due dates has several advantages but the most important is the ability to synchronize the production and its requirement, such as maintaining buffer's level activity with the due dates priorities. Using buffers' level prioritization means not using the net flow Equation, which is used for supply order generation, but using on hand values only offering a completely perspective from the MRP's one and making the planner able to ensure the integrity of decoupling point. This type of prioritization allows a better flow protection, less nervousness and less bullwhip effect.

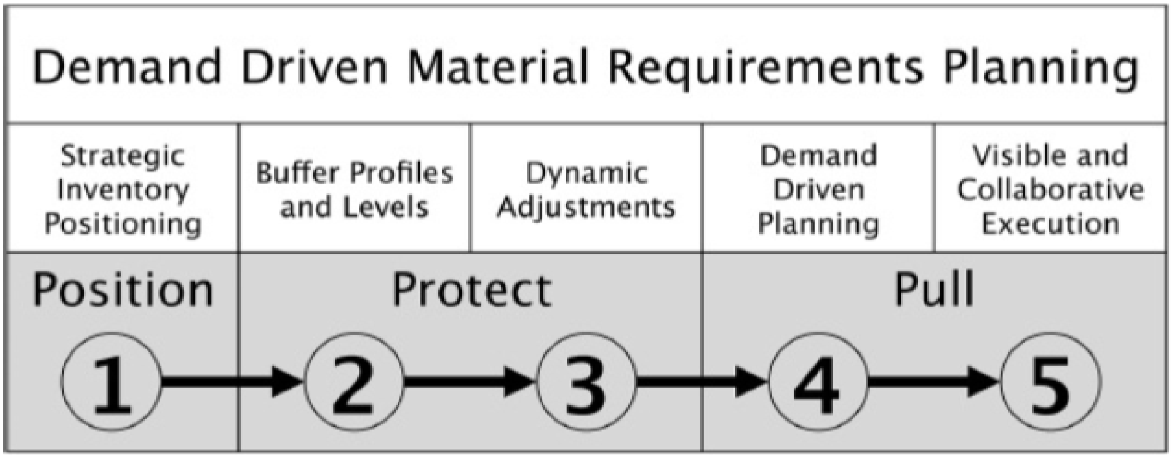


Figure 8: Five components of DDRMP[25]

In this chapter a brief historical perspective of the evolution from MRP to DDMRP has been proposed.

Fundamental concepts, for the purpose of our research, have been defined like flow, nervousness, bi-modal inventory distribution and bullwhip effect.

It has been defined the environment in which companies are operating today, the "New Normal" and why it has been the real engine for the development of new operational methodologies like DDMRP.

[25] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

Lastly, DDMRP methodology has been introduced. The methodology behind the development of DDMRP have been explained, like MRP and Lean, with their strengths and weaknesses. Thereafter the five components of DDMRP have been briefly explained: Strategic Inventory Positioning, Buffer Profiles and Level, Dynamic Adjustments, Demand Driven Planning and Visible and Collaborative Execution.

This first chapter is a basic premise to introduce the first methodology of our research which is also the first component of DDMRP: Strategic Inventory Positioning, that will be extensively explained in the next chapter.

2: Strategic Inventory Positioning

In this chapter the main theme of our research, Strategic Inventory Positioning, will be deeply analyzed and we will examinate different models and authors that have tackled the problem of Strategic Inventory Positioning (SIP).

The models we are going to talk about present similarities, they are based on some shared criteria, and many differences between them because of the multidisciplinary nature of the Strategic Inventory Positioning different researchers from different disciplines (management, statistics and engineering) have addressed the problem. They do certainly answer to the same questions but from different perspectives: "Where to position inventory in order to maximize the efficiency of the supply chain?".

The first of the Strategic Inventory Positioning model here proposed is the DDMRP's one.

Strategic Inventory Positioning is the first component of DDMRP.

2.1: DDMRP: Strategic Inventory Positioning (SIP)

Strategic Inventory Positioning is the first component of DDMRP.

Traditional planning questions are: "How much do we want to produce?" and "When we want to produce in order to satisfy demand?"; DDMRP Strategic Inventory Positioning instead is the answer to the question: "Where we should decouple in our supply chain in order to maximize our efficiency?"

Decoupling is what characterizes DDMRP and what makes DDMRP Strategic Inventory positioning so interesting for the purpose of our research and differentiate it from other models.

Deciding where to place decoupling points and their respective buffers it is a choice that has a deep impact on the efficiency of the organization's supply-chain which in turn reflects the quality and quantity of the service provided, cash flow and ROI.

2.1.1: Six Key Factors

Every model has some assumptions, Ptak and Smith (2016) defines they are assumptions "Key Factors".

The six Key Factors must be applied systematically across the entire production system in order to determine where to decouple, they are the guideline of DDMRP Strategic Inventory Positioning.

There are six "Key Factors":

- Customer Tolerance Time
- Market Potential Lead Time
- Sales Order Visibility Horizon

- External Variability
- Inventory Leverage and Flexibility
- Critical Operation Protection

Customer Tolerance Time

It indicates the time that customers wait for the delivery of a product or a service until they start looking for an alternative; it can be referred to also as Demand Lead Time.

Market Potential Lead Time

It indicates the lead times that will allow me to increase the prices or the number of sales.

Determining the Market Potential Lead Time involves Sales and Customer Service. Reduction in market potential lead time may have different impacts going from increase in price or increase in the number of sales. Reducing the Market Potential Lead Time of a quarter may bring new customers but reducing for the half the Market Potential Lead Time may bring only an increase in new customers but also in the prices of services/products delivered.

Sales Order Visibility Horizon

It indicates the time frame in which the organization becomes aware of sales orders.

For example: in retail Sales Order Visibility Horizon will be approximate to zero instead when dealing with orders that are made and not expected to be receipt at the same time it will be longer than zero.

Sales Order Visibility Horizon is intertwined with Customer Tolerance Time, the longer the first the better will be in order to not exceed Customer Tolerance Time.

The longer the Sales Order Visibility Horizon will be the greater will be the ability to prevent spikes in demand and to get the right signals for production.

External Variability

- <u>Demand Variability</u>: It defines the variability in demand and the probability of spikes in it that can exceed actual resources. It can be calculated through standard deviation or mean absolute deviation or heuristically by experienced planners. It can be divided in three types of demand variability: high, medium and low. The frequency of spikes is the determinant of one type of variability or another.

- Supply Variability: it can be calculated as variance of promises date against variance of actual date. It defines the variability in supply that may cause the interruption of the flow of resources needed for the production. As demand variability also supply variability can be divided in three types of supply variability: high, medium and low. The frequency of supply disruption is the determinant of one type of variability or another.

Inventory Leverage and Flexibility

It refers to the key points of the Bill of Material or the distribution network that can contribute the most in reducing the lead time. These key points are intermediate components, subassemblies and purchased materials.

Critical Operation Protection

This Key Factors refers to the necessity to protect key areas or operations from shortages or spikes in demand because they have a deep impact on the flow of the organization. Critical Operation can be area with limited capacity or operations the rely on suppliers which can be disrupted or area where variability is amplified.

A**pplying Key Factors: an illustration**

In order to provide a detailed explanation of the six Key Factors of DDMRP Strategic Inventory Positioning we will apply them to a simple example.

The Figure shows the BoM for two products: FPE and FPF.

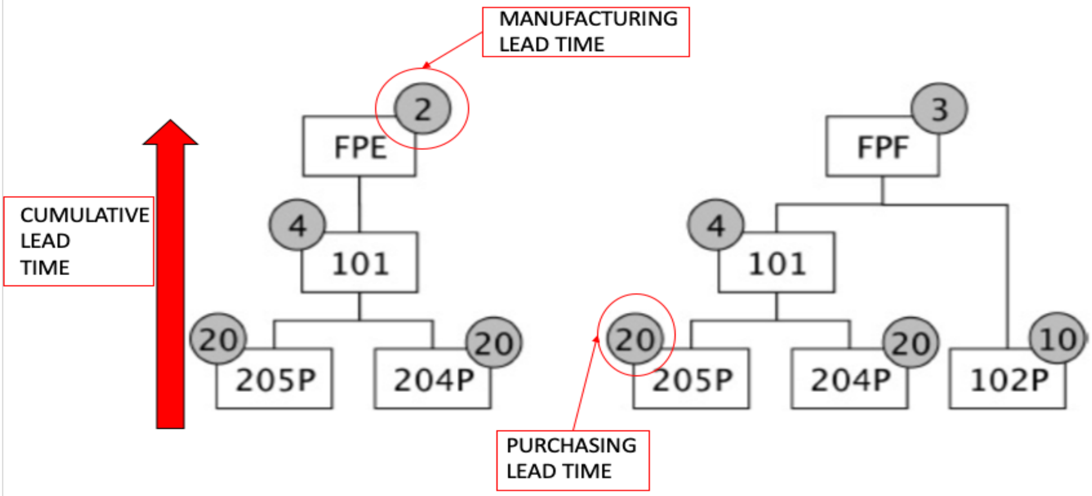


Figure 9: Cumulative Lead Time, Manufacturing Lead Time and Purchasing Lead Time for product FPE and FPF[26]

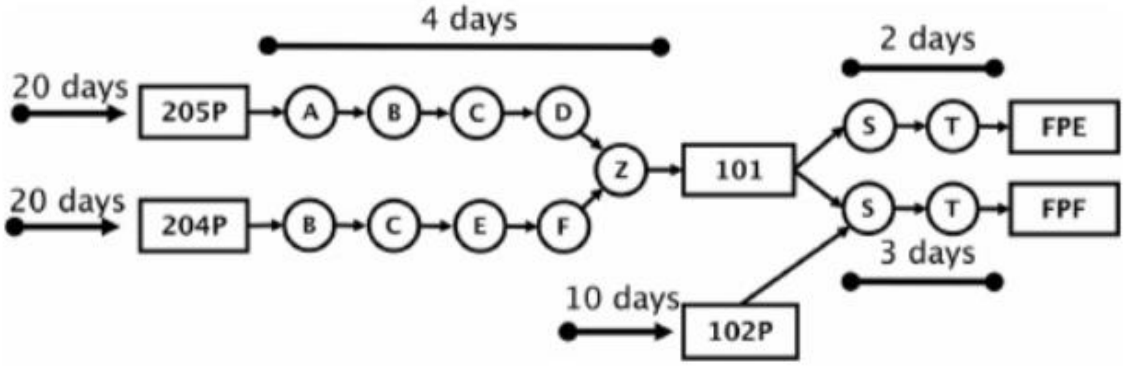
In order to understand Figure 9, we have to introduce three concepts: Cumulative Lead Time, Purchasing Lead Time and Manufacturing Lead Time.

Purchasing Lead Time (PLT): it is the total lead time necessary to acquire an item. It includes order preparation, transportation, receiving the order, inspecting it and putting it away. In our example 205P takes 20 days to become available, so 20 is its Purchasing Lead Time of 205P.

Manufacturing Lead Time (MLT): it is the total time required to manufacture an item. It includes order preparation, set-up time, run time, move time, inspection and putting it away. In our example the Manufacturing Lead Time of FPE is 2, it takes 2 days to produce FPE when parts and materials are available.

Cumulative Lead Time (CLT): it refers to the longest planned path to produce the item.
For example: to produce FPE the Cumulative Lead Time is 26 which is given by 20 Purchasing Lead Time of 205P, 4 Manufacturing Lead Time for 101 and 2 Manufacturing Lead Time for FPE.
Important: Cumulative Lead Time assumes no decoupling; it is simply the longest product structure to produce the item.

[26] Image modified by: Ptak C., Smith C., “DDMRP- Demand Driven Material Requirements Planning ” – Industrial Press, 2016



[27]

Figure 10: Product Structure and routing for products FPE and FPF

Figure 10 illustrates Product Structure and "routing" for products FPE and FPF. "Routing" can be defined as the sequence of operation to be performed to manufacture a particular item.

From the Figure we can notice that product FPE and FPF have a "convergent point", that is a point where the routing of different products merges together. It is particularly important to notice that this kind of point in the product structure may be potential bottleneck and source of delays, something that we must consider in our decision for the strategic placement of decoupling points.

It should also be noticed that "101" is the opposite of "Z", the first is a "divergent point", which is a point that defines when different products follow different paths and it is also the point where costs of production cannot be anymore reversed. As for convergent points also divergent points should be subjected to an analysis for Strategic Inventory Positioning.

In order to understand how to place strategically decoupling point applying the six Key Features we should make some realistic hypothesis about are products and they production processes.

In order to produce FPE and FPF we must purchase three components from the suppliers: 204P, 205P e 102P. It is normal to suppose that some of suppliers may not be reliable, we may suppose for example that the supplier of 102P is notorious for its delays and bad quality and this affect the Purchasing Lead Time of 102P.

An interesting insight is offered by the difference in Manufacturing Lead Time between FPF and FPE, let's suppose that the first is a higher-valued product (price higher, sales lower) while the latter is a product with lower value-added but higher sales.

[27] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

The second hypothesis about the model is the possibility to increase the sales if product FPF is delivered in the same timeframe of FPE, if this is achieved, sales for product FPF are expected to grow.
The last hypothesis is that customer tolerance time is three days.

To determine where to locate the decoupling points, we have to rely on the Six Key Features of DDMRP:

- **Customer Tolerance Time:** if the customer tolerance time is three days, we should consider the option to place the decoupling points at the final products, the divergent point 101 and the purchased resource 102P, which also has problem with supplier's reliability.
- **Market Potential Lead Time:** one of the hypothesis that we have mentioned before was that if FPE would be able to delivered at the same time of product FPF there would be a market increase for the first and this can lead us to place a decoupling point at FPE for this reason.
- **Sales Order Visibility Horizon:** the decoupling at point 101 and 102P will make the orders visible in time in order to keep the pace the with sales order, there will not be distorted signals for the planners.
- **External Variability:** as we said before it is composed by demand variability (spikes) and supply variability; in this case it could represent a problem if decoupling is not made at point 102P, due to the lack of reliability of the supplier.
- **Inventory Leverage and Flexibility:** the divergent point 101, for its contribution to the production, in this case is the one where we should decouple in order to protect the flow toward the end item.
- **Critical Operation Protection:** as we said in the definition of this Key Features, we should protect those operations that are fundamental in our production and have limited capacity or rely on suppliers. 205P and 204P are provided by suppliers and therefore should be protected by a decoupling point as we already told about 102P, but for different reasons.

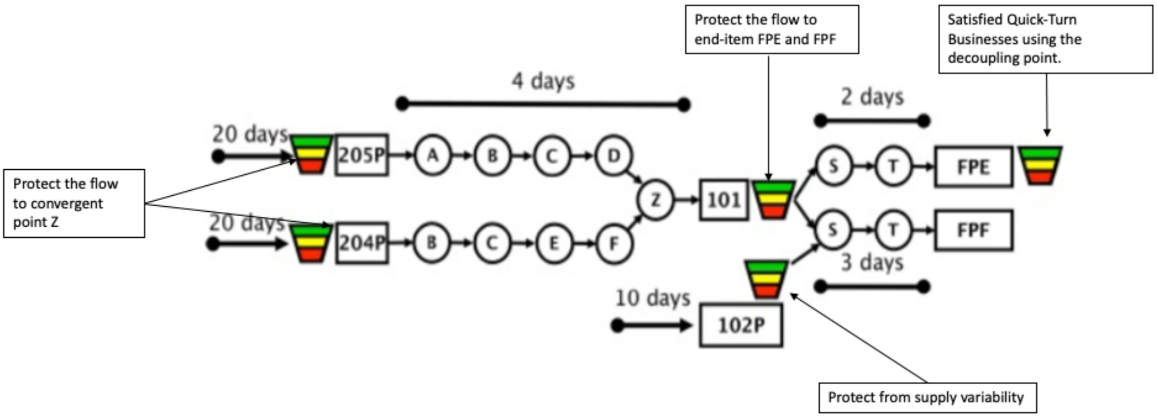


Figure 11: Decoupling made according to six Key Features[28]

Figure 11 shows how will be the products structure after having decoupled according to six Key Features and the reason why this decoupling point have been placed.

Two important considerations should be made: one regarding the flattening of the bill of Material and one concerning the impact of using different decoupling point at the same time.

We can define the "flattening of the bill of Material"[29] as the process to which intermediate levels are removed from the bill of material, typically this is done in order to decrease costs (no more intermediate processes means no "controlling" cost for example) and to reduce lead time; particularly this last "advantage" could be instead a disadvantage.

Let's imagine removing divergent point "101" from our product structure.

There will be an immediate changing which is that the lead time of the finished product will become 6 days for FPE and 7 days for FPF which both exceed the customer tolerance time, which we have assumed to be 3 days, and this will lead to the first consequence which is the necessity to keep high inventory stock of the finished product; the second consequence is that also the variability will be increasing, given that the lead time now is six days and there are no decoupling point to absorb variability. This example leads us to a consideration: that the simultaneous use of decoupling points in key processes/area, determined by following the six Key Features, can be beneficial as they "essentially protect each other"[30].

[28] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[29] https://www.businessprocessglossary.com/11231/flat-bill-of-material
[30] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

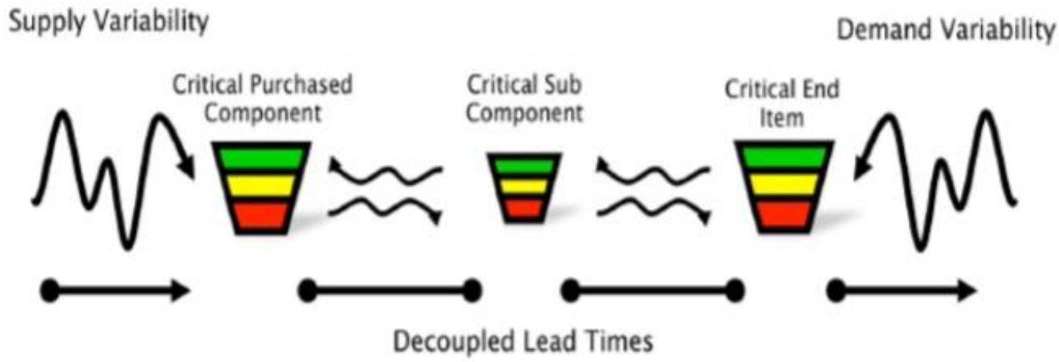


Figure 12: Decoupling beneficial effect on purchased component, subcomponent and end item

2.2.2: Decoupled Lead Time

Before, when explaining the difference between Purchasing Lead Time (PLT), Manufacturing Lead Time (MLT) and Cumulative Lead Time (CLT), was mentioned the fact that Cumulative Lead Time assumes there is no decoupling and also conventional MRP uses only CLT and MLT.
Two considerations should be made:
"Manufacturing Lead Time is the time it takes to manufacture the part exclusive of lower-level lead times"[31], this assumes that all parts will be ready when requested and by doing so it does not takes into account the variability that is accumulated in the routing of the product and underestimate the time required for the production.
Cumulative Lead Time, assuming no decoupling, by the contrary makes an overestimation of the time required for the production because thanks to decoupling they may be available before than forecasted. It becomes clear that if DDMRP expect the presence of decoupling points a proper measure of lead time should be introduced.
Decoupled Lead Time (DLT) is defined as: "The longest cumulative lead time chain in a manufactured item's product structure. It is a form of cumulative lead time but is limited and defined by the placement of decoupling points within a product structure".
Decoupled Lead Time is the synthesis that allows the planner to avoid Cumulative Lead Time overestimation of lead time and Manufacturing Lead Time underestimation of lead time.
Decoupled Lead teams is calculated by "summing all the manufacturing lead times and purchasing times and in that chain".[32]

[31] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[32] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

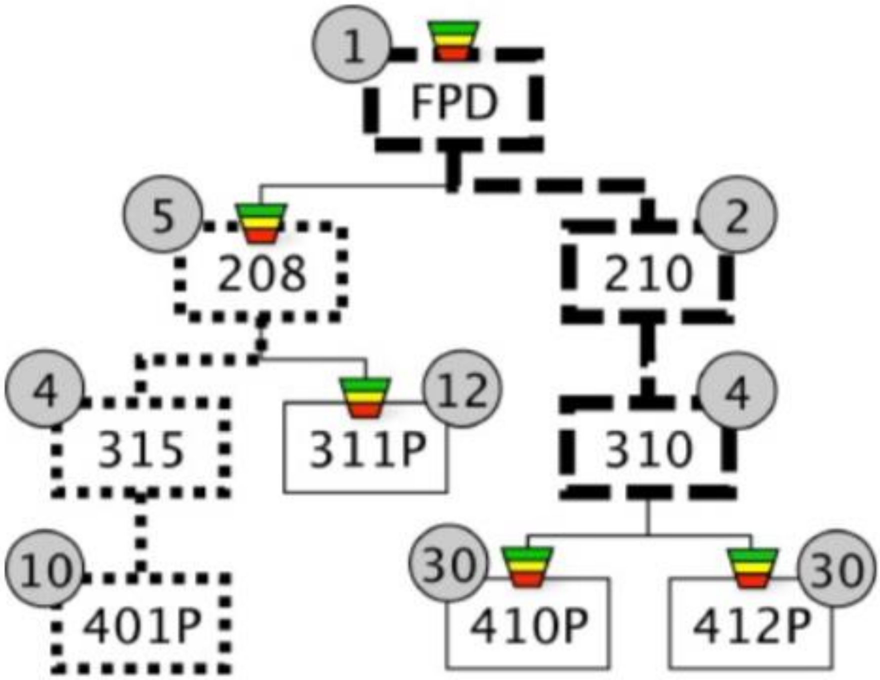


Figure 13: FPD Decoupled Lead Time.[33]

Here if we considered the Cumulative Lead Time to have the finished product FPD available we have to considered it available in 37 days, which is an overestimation that do not consider the presence of decoupling points; the decoupled lead time for FPD in reality is only 7 days.

Some considerations are required to understand the role of Decoupled Lead Time in DDMRP's Strategic Inventory Positioning. Decoupled Lead Time it it's an appropriate measure when dealing with multiple products that belong to the same groups and typically have common parts and are represented in a BoM Matrix.

[33] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

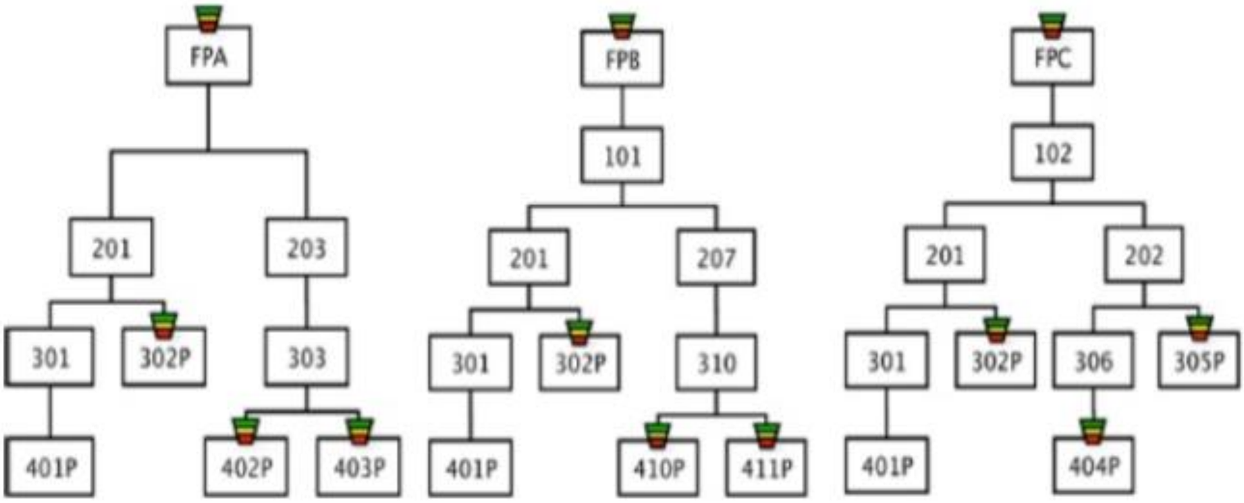


Figure 14: Product structure of FPA, FPB and FPC[34]

Here are represented the product structure of products FPA, FPB and FPC and we can clearly see that are some shared components and some relationships that appear in every product structure like the connection between 201 and 301 which is present for three times; typically this connection is represented using the BoM Matrix which allows the planners to know how many times this products are linked in the same way. The lack of the Matrix BoM is in the representation of what are the connections that matter the most, the only thing that represent the Matrix BoM is how many times a relationship occur; it is in this context that the use of the Decoupled Lead Time assumes a more relevant role given the reason that it is able to represent the real lead time of a certain component therefore it should be used as a complement to the matrix BoM. Decoupled Lead Time is able to give dynamism to the Matrix BoM by highlighting what are the relationships that matters the most, how the lead time will be affected if some changes occur and where it is important to decouple in a context with multiple product structures. Typically decoupling should be used in position that are shared between various products (for example position 201), this will allow to reduce the overall decoupling lead time of the product involved and it should be avoided for the components or parts that belongs to only product (for example part 207) or does not have an impact on the decoupled lead time that justify the costs to decouple. Before, we said that the Decoupled Lead Time add dynamism to the Strategic Inventory Positioning, and this is particularly true if we consider the perspective of the Customer Tolerance Time. Decoupled Lead Time gives a real signal of the real availability of a product to a certain date which is fundamental if the organization wants to stay within the timeframe of the Customer Tolerance Time.

[34] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

	Parent items												
Component items	FPA	FPB	FPC	101	102	201	203	207	202	301	303	310	306
101		1											
102			1										
201	1			1	1								
203	1												
207				1									
202					1								
301						3							
302P						3							
303							1						
310								1					
306									1				
305P									1				
401P										3			
402P											1		
403P											1		
410P												1	
411P												1	
404P													1

Figure 15: Matrix BoM of products FPA, FPB and FPC. Shaded numbers are decoupled/stocked positions, the numbers represent the number of relationships between the same components in the three products[35]

[35] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

2.2.3: DDMRP'S Distribution Positioning

We have discussed about the decoupling points and what they are but for the purpose of our research the fundamental question was where they should be located. Decoupling, which is an aspect distinctive of DDMRP, is only a part of Strategic Inventory Positioning; this indeed takes also into account the problem of Distribution Positioning. Later in this chapter we will see how Strategic Inventory Positioning and in particular Distribution Positioning has been studied by different authors with different methodologies.

"Distribution is aligning finished product to best meet consumption"[36], this sentence defines the tension that emerges in distribution system between the need to satisfy consumers within the customers' tolerance time and the need to keep inventories low in order to avoid costs and convert stocks into profits. The principles that define the six Key Features are applied also in distribution, in which the decoupling takes a fundamental role. There are some concepts that are necessarily clear when dealing with Distribution Positioning: demand variability, standard deviation and coefficient of deviation. Demand variability represent the biggest issues for the distribution. It is a common practice, in order to reduce uncertainty, the forward location of inventory. In the typical distribution network in Figure 16 we can see that in the "region" variability is higher than at the source, this happens because of "smoothing effect"[37] that is caused by the fact that the high variance present in the region is smoothed when aggregated and perceived by the sourcing unit. This process can be mathematically calculated by using the coefficient of variation which is "a statistical measure of the dispersion of data points around the mean"[38], coefficient of variation = $\frac{\sigma}{\mu} * 100\%$ and it is useful when comparing data from different series as in the regions' case.

[36] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[37] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[38] https://corporatefinanceinstitute.com/resources/knowledge/other/coefficient-of-variation/

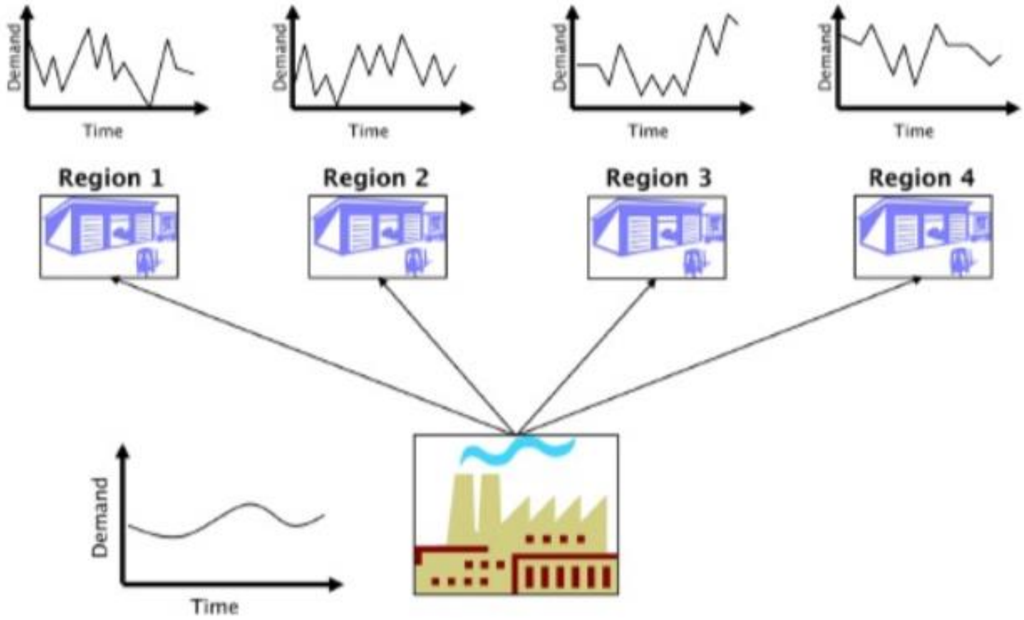


Figure 16: Typical distribution network. Demand variability and "smoothing effect" are represented[39]

Figure 16 depict the typical distribution network, it is consistent with a particular dynamic that has characterized the distribution network: the inventory pushed next to the consumer; it is something that has been studied in the literature and suggested also by other authors such as Whybark and Yang(1996)[40] as we will see later. The inventory closer to the point of consumption is justified by some purposes:

It is presumed that the shipment of goods will be optimized and the inventory closer to the consumers will reduce the transportation costs per unit also by using large shipment quantities and the use of large batches instead of small batches it is presumed to have a positive impact also on the sourcing unit as it free more space in the latter, it is particularly important if the sourcing unit has no storing capacity. Generally, there is the presumption that the closer the inventory to the consumption point the greater will be the ability to meet the demand, this will be challenged especially by Skintzi, Ioannou and Prastacos (2001)[41]. as we will see later.

Truthfully, this positioning of the inventory, as depicted in Figure 16, produces longer lead times because there is no hub between the sourcing unit and the point of consumptions therefore this will lead to two serious intertwined consequences: high demand variability and difficulty to stay within the customer tolerance time. What happens is that the consumption points, region 1 to 4 in our

[39] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[40] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
[41] Skintzi G., Ioannou G., Prastacos G., "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40. (2001).

example, are the place that are affected by the highest level of variability and to face this variability, which may causes shortages, they make orders to the sourcing unit which receive a distorted demand's signal; this situation creates difficulties for the planners of the sourcing unit to forecast demand and the latter will rely on the distorted, by high variability demand, signals of the regions. This situation creates problem of transportations because cross-shipment between regions increase costs (particularly cost of transportation per unit as trucks may not be full loaded) and the difficulty to respect the planned production but what it is worst is that this situation may be self-reinforcing because when regions perceive the possibility of shortage they will order more products and this will lead to an increasing of the bullwhip effect just described.

The introduction of a decoupling hub seems to be the solution to prevent the described above situation. It is particularly interesting the research of Ghaffari-Nasab, Ghanzafari and Teimoury (2015)[42], who propose two types of Hub and Spoke solutions, in that case designed for third party logistics service providers.

Hub and Spoke distribution networks are based on the use of "Hubs" in which the flow of goods from several sources is consolidated, allowing economies of scale, and redirected to the consumption points, or in some cases, other hubs.

The major concern in the Hub and Spoke distribution network is the "Hub Location Problem" which is "the design of such networks in which the location of the hubs as well as the path for transferring the flows have to be determined".

The first solution (a) is locating the inventories as closer as possible to the consumption unit who replenish the inventories according to a planned inventory policy, this is the model proposed also by Ptak and Smith. The second solution (b) to solve the Hub Location Problem (HPL), is to establish several hubs near the suppliers (the sourcing unit) in order to serve the manufacturers (the consumption units) from these hubs.

[42] Ghaffarinasab N., Ghazanfari M., Teimoury E., "Hub and Spoke logistics network design for third party logistics service providers", International Journal of Management of Management Science and Engineering , 2015

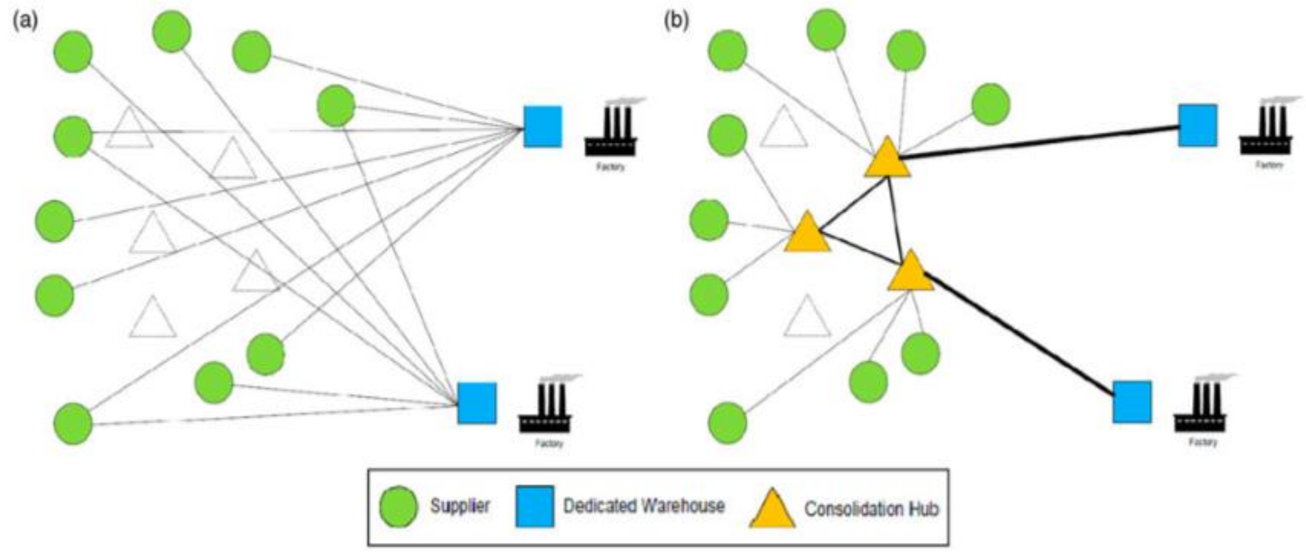


Figure 17: Distribution networks: (a) distribution network with direct shipping, (b) distribution network with consolidation hubs[43]

The thickness of the line in distribution configuration (b) represents the correspondent level of consolidation along the links. The links less consolidated are between the supplier and the consolidation hubs but the first still have the advantage to have the latter located nearer than the dedicated warehouse of distribution network (a), the most consolidated links are between the consolidation hubs and the consumption point this means that the closer is the consolidation hub to the point of consumption the greater will be the possibility to achieve economies of scale (minimizing the transport cost per unit for example using full trucks) and consequently costs savings; the cost saving effect is achieved mathematically by using a discount factor α that makes less costly a hub-point of consumption connection less costly than a spoke-point of consumption connection. With this model also the consumption point, the factory in the example, has also a benefit because it has reduced lead time from the consolidation hub and decreased planning horizon "this will allow them to manage uncertainty in their assembly plant more effectively"[44].

Using decoupling HUB has several advantages:

- Elimination of costly cross-shipments between regions
- Decreased planning horizon which in turn means clearer demand signals and decrement of bullwhip effect

[43] Ghaffarinasab N., Ghazanfari M., Teimoury E., "Hub and Spoke logistics network design for third party logistics service providers", International Journal of Management of Management Science and Engineering , 2015

[44] Cheong, M. L. F., Bhatnagar, R., & Graves, S. C., "Logistics network design with supplier consolidation hubs and multiple shipment options. Journal of Industrial and Management Optimization", 3, 51–69, 2007

- Hub allows increased flexibility of the manufacturer given that the planning horizon is decreased the planning can adjust in time to the buffer requirement.
- The spokes (regions in our example) have reduced lead time, if compared to typical distribution network, because the lead time is defined by the transportation time only and not by transportation time + plant lead time.

Ghaffari-Nasab, Ghanzafari and Teimoury (2015) research shows that "Numerical results reveal substantial cost savings as a consequence of using a hub-and-spoke network configuration compared to a direct shipment strategy" [45](as in Figure 16).

The Hub-and-Spoke network distribution configuration unfortunately may not be feasible for different reasons: a wholesale distributor may face problems with his suppliers and also problem of storage, due to space restrictions, may exist at the sourcing units and this will prevent the adoption of a model with a Hub.

Fortunately, the Hub-and-Spoke distribution configuration is flexible and can be adapted to different circumstances.

In the case of the wholesale distributor, who receive the shipments from different sourcing units, in the typical wholesale distribution network every regions' warehouse receive separate shipments directly from the suppliers. The typical wholes distribution network lead to longer lead times as the distributor's facilities may be distant from each other and there may be problem with freight optimization because of the common practice of the supplier of the minimum order requirement and in particular this last may cause shortages in some consumption points while in other lead to excessive inventory, the only method for the consumption point to face this issue is the costly practice of cross-shipping.

[45] Ghaffarinasab N., Ghazanfari M., Teimoury E., "Hub and Spoke logistics network design for third party logistics service providers", International Journal of Management of Management Science and Engineering ,2015

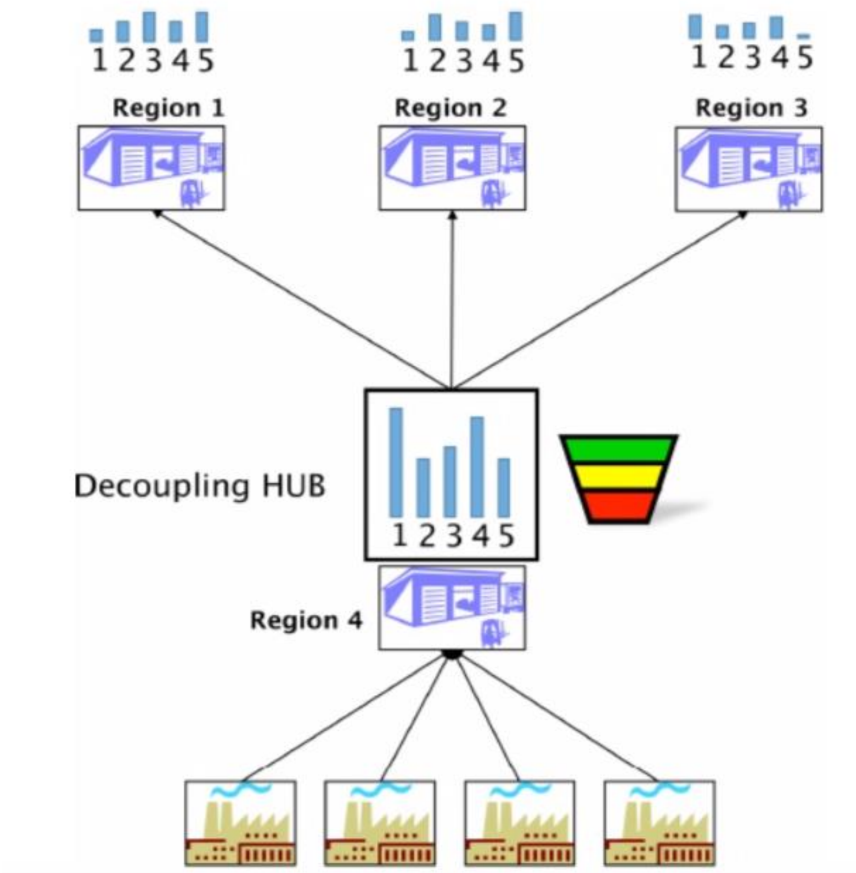


Figure 18: Wholesale Distribution Network with region 4 converted as a decoupling HUB

This solution is feasible for every distribution network that has one or more distribution point. Converting a distribution point into a decoupling hub has several advantages: shortening of the lead time will occur as the lead time will be only based on transportation time, the negative of the minimum order quantity is mitigated, demand variability is better absorbed the hub than from the regions which we have seen are characterized by spikes and this will also avoid costly cross-shipping and lastly the large shipments from the suppliers to the hub allow to minimize the freight costs.

The "multi-hub configuration" is the last of the configurations of distribution network considered by Ptak and Smith (2016), it is based on a different example with the purpose to take into account bigger network: there are 4 regional warehouses and each of them has supplier that are closer than the other regional warehouses; 12 suppliers are present and each of them supply every regional warehouse. The peculiarity of the multi-hub configuration is that every hub is at the same time both hub and spoke, they will be hub because they serve as a decoupling point for their regional suppliers but at the same time they are spokes for the products received by the suppliers of other regions.

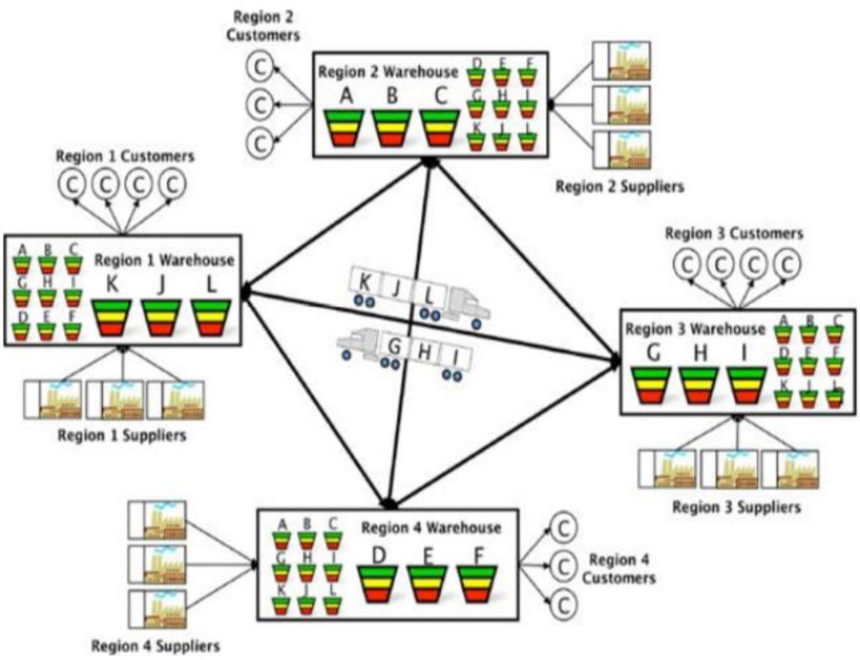


Figure 19: Multi-hub distribution network configuration[46]

The peculiarity of this network configuration is that brings the advantages of the hub configuration and add the transportation benefits. The advantages of the hub configuration are given by the fact that each region warehouse is hub for the region's products (es: Region 1 will be hub for product K,J and L) but at the same time it will be spoke for the products received by other regions' suppliers (from A to F if we consider Region 1). The transportation advantages given by this configuration lies in the fact that the freight costs can be optimized since "the transportation lanes between each warehouse are now bidirectional"[47].

Ptak and Smith (2016) theorized also the "hybrid model" which is characterized by its ability to manage the flow of slow-moving items. Planners are worried by slow-moving items because of their particular minimum order requirement that may cause excessive stocks if compared with their rate of usage. The hybrid model uses a decoupling point at the sourcing unit for the slow-moving item while using the typical distribution network for other network; the advantage of using the hybrid model is that by using a hub for slow-moving items, which are determined by using a flow index, the region that have the need for slow-moving items received reliable and with reduced lead time supplies and at the same time there is no need to store the slow-moving items at the regional level which increase costs and can create demand distorted signals due to policy of minimum order

[46] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016
[47] Ptak C., Smith C., "DDMRP- Demand Driven Material Requirements Planning" – Industrial Press, 2016

requirement moreover the decoupling of slow moving items allows a better planning for the fast-moving items which continues to be based on the typical distribution network seen in Figure 16.

2.3: Whybark and Yang Inventory Positioning (WY Model)

It is particularly interesting for the purpose of our study the research of Whybark and Yang (1996)[48] about Inventory Positioning. It sparked our interest because it is at the root of the modern methodologies for Strategic Inventory Positioning. Inventory Positioning for the Whybark and Yang (1996) means to define the place where to position inventory in a distribution network and in this methodology two positions are considered: next to the customers or at a warehouse closer to the facility which is the answer to question "where to position inventory to get the best service level, given a set of transportation, and inventory control system resources"[49]. The fill rate is the measure for the service level, and it is calculated as the percentage of the demand that can be filled from inventory. There is very little agreements between managers and planners on where to keep inventory, for some of them the inventory should be as close as possible to the customers in order to respond fast to the demand, for others some inventory should be kept at the warehouse and sent to the retail stores later; this methodology provides an answer for these opposite thoughts. There was in fact also a huge debate and contrasting ideas also between researchers, for example Jackson (1998) [50] , Jonsenn and Silver (1987)[51] argued that the were positive implications at having inventories at central warehouse while Badinelli and Schwarz (1988)[52] concluded that only a minimum portion of the inventory should be kept at the warehouse. These divergencies between researchers may be explained by the fact that in their simulations they have used different control inventory systems, and they have not taken into account the impact that different shipment's frequencies may have on inventory positioning and have used different models of demand.

In the Whybark and Yang model all of these different control systems were introduced and controlled in order to give a consistent answer on where to position inventory.
Hereinafter to indicate the Whybark and Yang's model we will use the acronym WY model.

48 Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
49 Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
50 Jackson P.L., "Stock allocation in a two-echelon distribution system or 'what to do until your ship comes in'". Mgmt. Sci., 34,1998
51 Jonssen, H. and Silver E.A. "Stock allocation among a central warehouse and identical regional warehouse in a particular push inventory control system", Int. J. Prod. Res., 25:,pp.191-205,1987
52 Badinelli, R.D. and Schwarz L.B., "Backorder optimization in a one-warehouse N-identical retailer distribu- tion system". Naval Res. Logist. 35, 1988

2.3.1: Model description

This model simulates an environment with eight retail stores, in a market where product availability is fundamental, and a warehouse which is supplied by a supplier with unlimited capacity. The only movement of goods allowed are between the suppliers and the warehouse and between the latter and the retailers, these last cannot make shipments between each other's (no cross-shipments allowed). The lead time from the warehouse and the retailers is fixed at 1 and also between the warehouse and the supplier. The eight customer stores have the same demand attributes, when the demand cannot be satisfied there is a backorder, and the demand will be satisfied by the next shipment received. To create a realistic demand model data from the pharmaceutical industry were used, these defined a demand characterized by small mean and the succession of periods with high demand and periods with no demand and a coefficient of variation around one.
"Management discretion in this system involved the choice of inventory control system, the frequency of shipments to the warehouse and to the retailers, the amount of inventory to have on hand overall, and, of course, where to position the inventory"[53].

Factors

The simulation has five key factors:

- Inventory positioning between the warehouse and the retailers' stores
- Four control systems, each of these has different information requirement and decision rules
- Fill rate of average level of inventories
- Degree of uncertainty of demand
- Shipping frequency.

The inventory positioning is defined as the ratio of the "average inventory at the retail stores to the average distribution system inventory"[54] ; where a ratio of 1 means that all inventory is kept at the warehouse vice versa a ratio of 0 means that all inventory is kept closer to the retail stores. The four inventory control systems will be explained below.

[53] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
[54] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

Inventory Control Systems

In this model four inventory control systems are simulated. What these lasts have in common is the re-ordering rule. The replenishment rule (or "decision rule") is (R, s ,S) which means that the stocks of inventory are reviewed every "R" periods and if the inventory is less than or equal to "s" an order is made to bring the inventory to the acceptable stock level "S"; conversely if inventory is greater than "s" no orders are placed until the next period. In order to conduct the experiment on the Inventory Positioning the value "R" is fixed while "s" and "S" were variables.
What distinguishes the four inventory control systems is the type of information, which is used to implement the decision rule, inventory status may be known by global information (that flow within the whole system) or local information.

<u>Control System 1:</u>
In Control System 1 the facilities of the distribution systems are managed independently, in this configuration the information is local.
The inventory status is defined as: available inventory + inventory on order at the facility.
The decision rule is R=1 in the warehouse and in all the retail stores.
All the retail stores are filled until there is inventory available, if not "the inventory is distributed to the retail stores by minimizing the maximum unfilled retail order"[55] .
Because of the fact that the information is "local" and the only signal available for warehouse are orders, the retailers that don't have placed any order are not considered.
The information in this control system is local which means that if a retail store has unfilled orders these are not backorder at the warehouse and also that the retail store will not know the quantity of the next shipment until it is received.

<u>Control System 2:</u>
Control System 2 utilizes global information.
The inventory status is defined as: available inventory + in-transit inventory for the warehouse and the retail stores.
We define "in transit" inventory those shipments that have left the warehouse but have not received yet the retail stores.
The decision rule is R=1 for the replenishment of retail stores and the warehouse.

[55] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

Due to the global character of information of this control system all the stores are considered even those that does not have placed any order, differently from Control System 1.

Control System 3

Control System 3 uses global projected information, which are the opposite of global actual information of Control System 2.

"Every period (i.e., R = 1) each retail store projects their inventory balance for several periods into the future, using distribution requirements planning (DRP) logic every period"[56], this is made in order to avoid that prevented projected inventory balance goes below "s"; if a retail store has a projected inventory below level "s" an order is made to increase it to the acceptable stock level "S". Difference between Control System 3 and Control System 2 is in the fact that the first used projected orders to make the plan for the shipments while the latter instead use the actual order that are made by the retail stores in real time.

Control System 4

Control System 4 use global actual information and use the same method of Control System 2 to calculate inventory status which is defined as: available inventory + in transit inventory for the warehouse and retail stores.

Replenishment in Control System 4 is based on 6 period. The decision rule is the same of other Control Systems (R, s, S) but in this case R=6.

The peculiarity of this Control System is that "In this system, retail replenishment is taken care of by the warehouse and no orders are calculated by the retail stores"[57]. A percentage of the replenishment stock received by the warehouse is sent to the retail stores, while the residual part is kept at the warehouse to be distributed later.

To avoid stockout the probability that a stockout occurs is calculated for each retail store and is used to determine how much replenishment stock to send it.

[56] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

[57] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

2.3.2: Results and remarks

The results of the simulations conducted by Whybark and Yang (1996) showed that there is a clear correlation between high levels of fill rate and high levels of positioning ratio, which means that there should be a preference for keeping inventories closer to the retailers' stores. If we look at Figure 20, we can see that the Control Systems that have performed better are Control System 3,2 and 4 which uses global information instead of local information as Control System 1. What all the control systems have in common is that the positioning ratio the achieve the better fill rate is high for of all them, this means that the positioning of the inventory affects the performance more than the control system used; it is a non-trivial observation as it highlights the importance of our research.

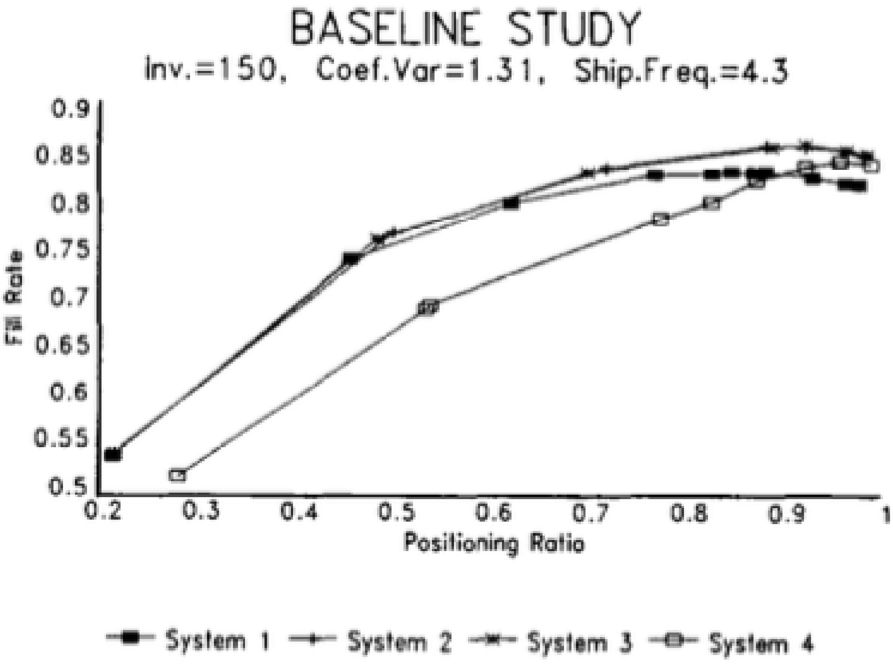


Figure 20: Baseline Study[58]

A positive relation between the average system inventory level and fill rate was found, the latter increases while the first does.

[58] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

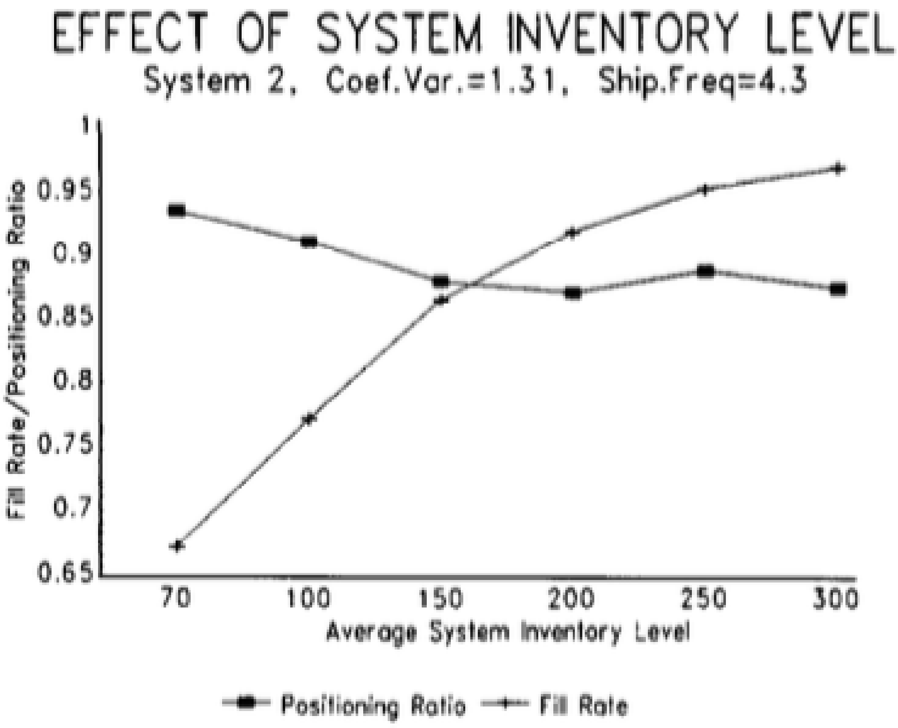


Figure 21: Relationship between Average System Inventory Level and Fill rate[59]

Figure 22 shows that there is a positive relationship between the increasing of shipment frequency and fill rate which means that if the average number of periods between shipments is reduced, we will achieve a better fill ratio. It may seem a trivial relationship, but the WY model is the first to introduce the shipment frequency as a factor.

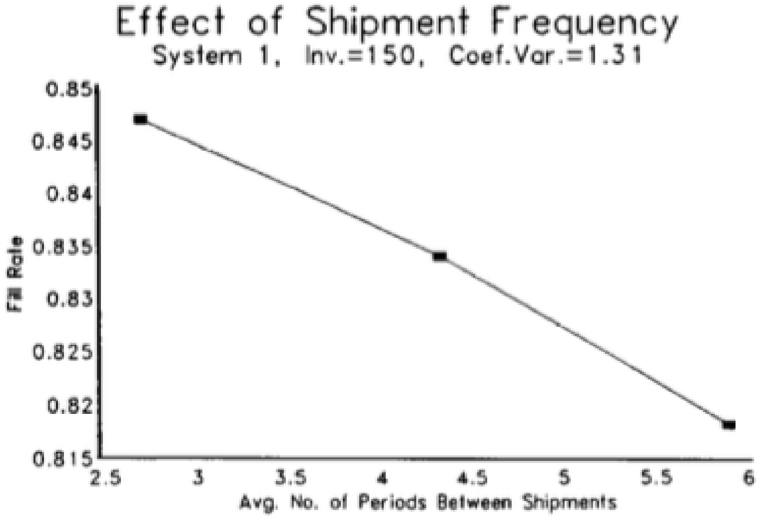


Figure 22: Fill rate vs. Average Number of Periods between Shipments[60]

[59] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996
[60] Whybark D.C., Yang S. "Positioning Inventory in Distribution Systems", Int. J. Production Economics 45, pp. 271-278, 1996

In conclusion we can say that the findings of Whybark and Yang (1996) are extremely important as their research has highlighted the necessity, in order to achieve a better fill rate, to position the inventory closer to the customer; it is a finding that is in contrast with the beliefs of many managers and researchers that thinks that keeping inventory, or part of it, near the warehouse provide them flexibility. The most relevant finding of this research is that the correct positioning of inventory has more impact on the fill rate than the choice of the inventory control system.

It was important to explain the WY model, for the purpose of our research, because it is the only Strategic Inventory Positioning model that has introduced different inventory control systems in the simulation. The introduction of the four inventory control systems in the experiment it is extremely important as it allows to understand how deeply the inventory positioning affect the performance, in this case measured by the fill rate.

2.4: Strategic Inventory Positioning in a Single Product Supply Chain (SPI Model)

The third methodology that will be exposed has been theorized by Skintzi, Prastacos and Ioannou (2001).[61] in “Inventory Positioning in a Single-Product Supply Chain”.

The credits for its theorization are on Skintzi, Prastacos P. and Ioannou (2001), for this reason we will refer to this model as “SPI Model”.

The work of these authors was inspired by a literature research on the changing of the environment in which supply chains need to operate which has become increasingly fast and competitive for several reasons: shorter products life cycle, increasingly request for customized goods and growing variability of demand. In this framework Supply-Chain Management has become increasingly important as it is “viewed as a fundamental strategic concept and an opportunity to gain competitive advantage”[62]. The rising importance of supply chain management leads to the need of a re-definition of the supply chain design; one of the reasons for the re-designing of the supply-chain is postponement. “Postponement is the operating concept that aims at delaying activities until actual customer orders have been received and is used by companies to achieve customization costs hitherto associated with customization costs, such as set-up costs and the costs of storing finished goods” [63]. Three types of postponement exist: time postponement, which is the delaying of activities until orders are received, place postponement, which is the delaying of the movement of goods downstream until orders are not received, and form postponement, which is the delaying of those processes that determine form and function of a product until orders are not received. Postponement manufacturing can bring several advantages especially regarding reduced inventory holding costs.

In particular our research will be focused on place postponement. Billington and Lee[64] , in a research on Hewlett-Packard company, found that keeping inventories of semi-finished goods in a central warehouse reduce the inventory holding and investment costs. In this framework Skintzi, Ioannou and Prastacos (2001) elaborated their model, and for a holistic appreciation of it, has been necessary an introduction of the context in which it has been developed and for which purposes.

[61] Skintzi G., Ioannou G., Prastacos G., "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40,2001

[62] Skintzi G., Ioannou G., Prastacos G., "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40,2001

[63] Van Hoek R.I., “Logistics and virtual integration: postponement outsourcing and the flow of informations”, International journal of Physical Distribution & Logistic Management, vol. 28, n°7, 1998

[64] Billington C., Lee H., “Materials Management in decentralized supply chains” , Operation Research, 41.5, pp. 835-847, 1993.

SPI model addresses the problem of Strategic Inventory Positioning with the same question of WY's model, which is "Where it the supply chain node where inventory should be kept in order to minimize holding costs while guaranteeing an appropriate fill rate?".

The premises of the work however are different. WY's model has been developed in order to provide a consistent answer to the different way of thinking among the researches using different control systems, while this model has been developed in order to provide a concrete and simple methodology for supply chain design.

2.4.1: Assumptions of the model.

The problem is based on a single-product supply chain with multiple nodes and unidirectional fixed transportation path.

In every supply chain node, a different process takes place; a process refers to "all types of value adding activities that are related to the manufacture or distribution of a product"[65]. Examples of processes are assembly operations, quality control and distribution operations.

At the end of the supply chain there is a "Point of Sales" (POS), they are the terminating nodes of supply chain and the places where demand enter in the system.

The supply chain which we are referring to is a single-item supply chain, every node performs its processes and add value until the product reach the point of sale. The time that take each node to perform its activities it is given.

It takes also time to bring raw materials, semi-finished goods and components from one node to another, the amount of time that it takes is related to the modes of transportation and type of products (in fact we have seen in DDMRP's hybrid distribution network configuration the problems connected with slow-moving items). The time of transportations are approximated because the model implies a certain degree of uncertainty.

In our model the inventory is stored in one and only one node of the supply chain.

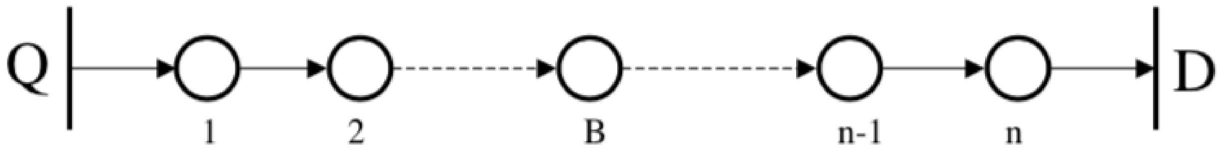


Figure 23: Single-product supply chain. "B" is the "buffer node" which is the point in which inventory is held.[66]

As we can see from Figure 23, in the single product supply chain we have the point "*B*". The point *B* is the "Buffer Node" which is the point that "decouples upstream and downstream processing"[67]. "*Q*" indicates the quantity of product that enters in the system. "*D*" indicates the demand that needs to be satisfied; is assumed that demand is normally distributed[68].

[65] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.
[66] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.
[67] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.
[68] Normal distribution may have negative values but this scenario it is not considered in this model, therefore the model use values of mean demand such that the probability of having a negative demand is irrelevant.

The objective of the model is twofold: on hand is aimed to minimize holding costs, on the other hand the goal is to achieve high order fill rate. This objective is dependent from the time that it took to the products to reach the point of sales (POS) from the selected inventory location.
In Figure 23 "*n*" indicates the node of the supply chain while "*n-1*" indicates the number or routes connecting the nodes.

2.4.2: Model Description

As seen in Figure 23, we use "*n*" to indicate the nodes of the supply chain and to identify a specific nodes we use "*i*" and "*j*", which values ranges from 1 to *n*, and the pair *ij* refers to routes.
Quantity "*Q*" is a variable of our problem, it indicates the quantity that enters in the system from nodes *i=1*, the quantity will exit from the system at period *n=1*.
"Demand "*D"* which is modelled by a continuous nonnegative random variable, with mean μ and standard deviation σ. "[69]
Every node has three parameters:

1. C_i , which is the Inventory Value Added that represent the increasing of the product's value consequent of the value-adding activities that are performed in each node.
2. Q_i, is the quantity stored at each node. One of the assumptions of the model is that the quantity that enters in the system is stored only in the buffer node which means that it will be zero in every node different from the buffer.
3. φ_i, which represent the extra quantity, expressed as a percentage that can be delivered to the buffer because of the proximity of the buffer to the Point of Sales (POS).

$$C_h = \sum_{i=1}^{B} C_i \tag{1}$$

Equation 1, in which *"h*" represents the holding costs, means that the "inventory value added" C_i is equal to the inventory holding cost per unit C_h at the buffer node "*B*".

$$q_i = \begin{cases} Q, if \text{ “}I\text{” is the buffer building node} \\ 0, if \text{ “}I\text{” } is\ not\ the\ buffer\ building\ node \end{cases} \tag{2}$$

Equation 2 means that it is necessary to satisfy the assumption of the model that the inventory is stocked only in one node of the supply chain, which is the buffer building node.

[69] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.

$$Q = \sum_{i=1}^{n} q_i$$

(3)

Equation 3 indicates that the quantity stocked at each buffer is equal to the quantity produced.

$$\sum_{i=1}^{j} \varphi i = \frac{\sum_{i=i}^{j} pt_i + \sum_{i=1}^{j-1} tt_{i,i+1}}{\sum_{i=1}^{n} pt_i + \sum_{i=1}^{n-1} tt_{i,i+1}} \; x \sum_{i=1}^{j} \alpha_i$$

(4)

Equation 4 indicates the probability that the product will reach the customer if the buffer node is at j=B. "pt_i" indicates the processing time at node I, "$tt_{i,i+1}$" defines the time transportation time from node i to node i+1, α_i is the uncertainty factor and it refers to anything unexpected during the transportation of the production and that can delay the delivery of it, of course α_i change if mode of transportation or distance between the buffer node and point of sales does.

Quantity "*q*" is the portion of starting quantity "*Q*" that enters in the system because part of it can be lost during the processing or transportation passing between node, so "q" may be slightly less than "*Q*"; quantity "*q*" is calculated using Equation 5.

$$q = \sum_{j=1}^{n} (\sum_{i=1}^{j} \varphi_i) q_j$$

(5)

The model does not explicitly define time, but this can be derived by "q" and "φ_i".

The last element of this model is the "desired service level β", which is the portion of the demand that the management desires to be covered by the stock and probably will be able to meet, β takes values [0,1].

If we compare SPI model with WY, we can clearly see that what was called "fill rate" by the latter is the same as the desired service level β.

2.4.3: Solution Algorithm

Inventory positioning's algorithm is composed by 4 steps:

1) Define the holding costs as function of q_i
2) Development of the expected shortages per period expression as function of *D* and and *Q*.
3) Determine the value of *Q* and the holding cost if buffer is placed at node *i*=1. Repeat the calculations for the case that the buffer located at nodes *i*=2 to *i*=*n*.[70]
4) Define the optimal quantity to be produced, which will correspond to the lowest holding costs.

The first step of the solution algorithm is the development of inventory holding cost function.

$$C(Q) \ = \ (\sum_{i=1}^{B} C_i) * Q \ = \ (\sum_{i=1}^{B} C_i) * Q_b \ = \ \sum_{j=1}^{n}(\sum_{i=1}^{j} C_i) * q_j$$

(6)

In the Equation 6 we can see the "Inventory holding cost function". The elements that composes Equation 6 are the cost per unit of inventory "C_q" multiplied by the quantity stored in that specific node "q_j". It is important to remember that Equation 2 implies that the product can be stored only in a node, which is the buffer building node. "For the buffer building node j=B, the inventory holding cost will be the holding cost per unit times the quantity stored at the buffer q_b which is equal with the quantity that entered the system Q"[71].

The second step of the solution is to calculate the expected number of stock-outs.

A stock-out happen when Q < D, which means that the system is not able to cover the demand because buffer is too far from the point of sales. It should be remembered that one of the assumptions of the model is that demand is normally distributed.

$$E(\max(D-Q,0)) = \int_{Q}^{\infty} (x - (\sum_{j=1}^{n}(\sum_{i=1}^{j} \varphi_i) q_j) f(x) dx$$

(7)

[70] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.

[71] G. Skintzi, G. Ioannou, G. Prastacos. . "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40, 2001.

Equation 7 is the expected number of shortages.
We have used Equation 5 in order to explicit part of Equation 7.
If φ_i is equal to 1 then the quantity produced "Q" is equal to the quantity stored "q".

$$(1-\ \beta)=\frac{Expected\ number\ of\ shortages\ per\ period}{Expect\ demand\ per\ period}=\frac{S(q)}{\mu}$$

(8)

$$(1-\beta)=\frac{S(q)}{\mu}$$

(9)

Equation 8 the part of demand that is not met in time. The expect number of shortages per period is indicated with S(q); μ defines the expected demand per period.
"To determine $S(q)$, since D is normally distributed, we can use the normal loss function, $NL(z)$. Specifically, the expected number of shortages that will occur during one period is $\sigma NL(z)$"[72]
If we have in stock a quantity that is equal to the average demand and z standard deviation (($\mu+z\sigma$) then the expected number of shortages per period should be $\sigma NL(z)$, where NL(z) indicates the normal loss function.
Two observations should be made:

1. If we increase the quantity to be delivered, we should expect less shortages.
2. If we locate the buffer node B near the point the of sales the expected number of shortages per period decreases because the probability of deliver the product on time $\sum_{i=1}^{j}\varphi_i$ is increasing the quantity q that is delivered increases leading to a decline in the expected number of shortages per period.

"Since $S(q)=\sigma NL(z)$, $NL(z)$ can be directly calculated, and then z can be found from appropriate tables" [73] we can calculate the quantity $q=\mu+z\sigma$ that it is truly delivered to the point of sales. Once we have calculated the quantity "q" we can define the quantity that the reach buffer node B in the different position of the supply chain and subsequently the holding costs for each of them. We should remember that the goal of our objectives is, at the same time, to minimize the holding costs and maximizing the fill rate; if our only purpose was the costs minimization, we should simply select the first node as buffer building node; conversely if our only goal was to increase as much as possible the desired service level β it would have been sufficient to select the last node as buffer building node.

[72] Winston W.L., "Operations Research: Applications and Algorithms", 3rd edition, Duxbury Press, 1997
[73] Winston W.L., "Operations Research: Applications and Algorithms", 3rd edition, Duxbury Press, 1997

The algorithm for Strategic Inventory Positioning in Single Product Supply Chain is based on 5 steps:

1. Calculate the expected number of shortages per period S(q).
2. Obtain *"z"* and NL(z)
3. Calculate the quantity necessary to satisfy the indicated fill rate.
4. Calculate the inventory level and the holding costs if the buffer node is placed at i = 6.
5. Repeat step 4 for other nodes.

2.4.4: Remarks

In conclusion, this model provides a simple and effective methodology to determine where to position the inventory in a supply chain. A numerical example below will provide a concrete application of the model to a fictional but realistic case, in which the node of the supply-chain where to keep the stocks will be identified, under the restraints of the desired service level, in order to minimize the holding costs.

This methodology is therefore really different from the methodologies presented previously.

Especially, for the purpose of our research, it should be particularly useful to compare this model with WY model.

SPI model differently from the previous doesn't use different control systems and in this model is not included a re-order policy at all; in the model are defined the quantity "Q" that enter is the system and the quantity "q" that reach the customers but re-ordering policy or control system are not considered.

The second difference lies in the fact that WY model utilizes as key factor the "shipping frequency" while this it is not considered in SPI model.

The third difference is at the fact that SPI model includes factor α which is the factor related to the uncertainties of the delivery, this is not included in WY model where the only uncertainty is relative to the demand but delays or problems with deliveries are not considered.

Both the model shares the "constraint" of the fill rate that needs to be achieved.

The fundamental difference between the models is that they both tackles the inventory positioning problem but from different perspective. WY model is an experiment, based on simulations, with the purpose to discover where, using four different control systems for simulations, the inventory should be placed ; SPI model instead wants to provide a simple algorithm for the determination of the node where to position the inventory in a supply-chain.

SPI methodology has been further expanded in the work "Inventory Positioning in Multiple Products Supply Chain"[74], where the SPI model 's algorithm is integrated with new steps in order to obtain the node where to keep inventories also in a multiple products supply chain.

[74] Ioannou G., Prastacos G., Skintzi G., "Inventory Positioning in Multiple-Product Supply Chain", Annals of Operations Research 126, 195-213, 2014

2.5: AHP: Strategic Inventory Positioning

2.5.1 Introduction:

The fourth methodology that will be presented is Analytic Hierarchy Process for Strategic Inventory Positioning. In Appendix A the methodological basis of Analytic Hierarchy Process are explained in detail.

Our research on AHP for Strategic Inventory Position is based on the scientific article "Warehouse Selection Problem Solution by Using Proper MCDM Process"[75] from Al Amin, Apurba, Sumit and Imran Shikdar (2019) In which the problem of Strategic Inventory Positioning is tackled by using the multi-criteria decision-making methodology AHP.

The research of Al Amin, Apurba, Sumit and Imran Shikdar (2019) it is particularly interesting not only for the application of Analytic Hierarchy Process methodology for Inventory Positioning but also because the research explains the reasons why this specific multi-criterion decision-making methodology has been chosen instead of other including Fuzzy AHP, SMART (simple multi attribute rating technique), Grey Theory and ELECTRE; the topic of our research is not to define which from these methodology is the best suited for this kind of problem so it will be explained only why the authors have decided to choose Analytic Hierarchy Process instead of other techniques but not the reason that makes these lasts techniques not sufficiently able to deal with the problem.

Why Analytic Hierarchy Process?

In the article "Warehouse Selection Problem Solution by Using Proper MCDM Process" by Al Amin, Apurba, Sumit and Imran Shikdar (2019).[76] it is considered a problem regarding the strategic inventory positioning of a company in the garment industry for the stocking of finished good.

Five warehouse locations are considered in the problem.

The first part of the problem is to identify which is the multi-criteria decision-making technique that allows the decision maker to take an optimal solution.

The authors have chosen to use Analytic Hierarchy Process as their preferred methodology to deal with this problem.

Analytic Hierarchy Process have been chosen for different reasons:

- Problem is based on very limited alternatives and criteria and it is a problem relative to a location selection

[75] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019
[76] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

- In this problem criteria have a binary nature. It means that a criteria or alternative is better or worse than another without uncertainties, this is the reason why other methodologies such as Fuzzy Analytic Hierarchy Process cannot be applied to this problem because for its own nature it deals with uncertain judgements and evaluations and this is not the case.
- The data provided may be inconsistent. Analytic Hierarchy Process is a methodology that does not require consistency but allows a certain degree of inconsistency, which can be measured by consistency test to validate or not the evaluations.
- The solution must be an optimal one, a solution that "it must be such that it optimizes all the resources to the fullest extent", so it fits with AHP's requirements and eliminates Grey Theory which does not find an optimal solution.[77]

These are the reasons behind the choice of Analytic Hierarchy Process for the Strategic Inventory Positioning problem.

[77] Sifeng L., Yingjie J.F., Yang Y., "A brief introduction to grey systems theory", Grey Systems: Theory and Application, Vol. 2 Iss 2 pp. 89 – 104, 2012

2.5.2 Problem Description:

The Strategic Inventory Position problem here presented is based on company which operates in the garment industry and has to select the optimal location for its warehouse.

Five warehouse locations for the stocking of finished goods are considered in the problem, these will be indicated as warehouse 1,2,3,4 and 5.

To implement Analytic Hierarchy Process, it is required to construct a hierarchy composed by goal, objectives, sub-objectives and alternatives.

In this case the alternatives are the 5 warehouse locations.

The criteria, that defines objectives and sub-objectives, in this case were selected according industry's experts which provided their opinion.

The five criteria selected are:

1. Unit cost: "It is basically the amount of money spent on a single unit kept in the warehouse. It can be determined by dividing the cost by the number of materials that can be kept in the warehouse." [78] Unit cost is selected as criterion instead of total cost because the latter may not be representative of the real cost borne by the company because it can be lower due to less item stocked than other warehouses.
2. Movement flexibility: it represents how easily objects can be inside and outside the warehouse. It has been determined, using a scale from 1 to 4 where 1 means bad and 4 means very good, with experts' opinion.
3. Layout: it is "how much the layout of the buildings affects the warehouse" [79]. It has been determined in the same manner of movement flexibility.
4. Distance from the main factory: it is particularly important as an increasing in distance from the main factory leads to an increasing in transportation costs.
5. Stock holding capacity: it one of the most important criteria. The greater the stock holding capacity of a warehouse will be and the greater it will be its appeal.

[78] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

[79] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

2.5.3: Applying AHP

The AHP methodology is fully explained in Appendix A therefore our focus for this part of our research will be on highlighting the formulas used and the adaptation of the AHP methodology for the problem of Strategic Inventory Positioning; for what it concerns the technical application of AHP methodology, the reader is suggested to read the Appendix A.

After having defined and analyzed the criteria that compose our problem it is time, following the Analytic Hierarchy Process algorithm, to construct the pairwise comparison matrices.

In Figure 24 we can see the values, that reflects the judgments of the decision maker, that can attribute to the values of the pairwise comparison matrices. For example: the decision maker may judge that stock holding capacity is absolutely important if compared to layout and this will be expressed by number 7, conversely the importance of layout compared to stock holding capacity will be $\frac{1}{7}$.

A peculiarity of this application of Analytic Hierarchy Process to the Strategic Inventory Positioning regarding the criteria should be highlighted. Amin et al. decided to divide the criteria in two groups: value-adding criteria and value-declining criteria. "If the abundance of a certain is positive for the warehouse it is thought of as value adding criteria while if increased value of a certain criteria is unwanted then that particular criteria is thought of as value declining criteria"[80].

For example: stock holding capacity is considered to be a value adding criteria as the abundancy of capacity is a positive element conversely the unit cost is considered to a value declining criterion as the increasing of cost is considered a negative element.

The problem of Strategic Inventory Positioning is solved by following the 4 steps of its algorithm:

1. Construction of Structural Hierarchy.
2. Construction of Pairwise Comparison Matrices.
3. Weight Determination through normalization procedure.
4. Synthesis of weight and consistency test.

[80] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

2.5.4: Remarks

Analytic Hierarchy Process is a multi-criteria decision-making methodology that can be used in multiple situation and Strategic Inventory Positioning is one of them.

It has been particularly important for the purpose of this research to highlight which are the adaptation of the traditional AHP that have been implemented for Strategic Inventory Positioning such as the distinction between value adding criteria and value declining criteria.

The selection of the five criteria, agreed with industry's experts, it is especially important as it give insights for application of this model in other contexts.

2.6: Methodologies Comparison

In this second chapter four methodologies have been explained:

- DDMRP's Strategic Inventory Positioning
- Whybark and Yang's (WY Model) Strategic Inventory Positioning.
- Strategic Inventory Positioning in a single product supply chain (SPI Model)
- Analytic Hierarchy Process for Strategic Inventory Positioning

After having outlined these four methodologies what has emerged is the profound heterogeneity of the approaches that have tried to deal with the Strategic Inventory Positioning problem.
What it is missing in the literature of Strategic Inventory Positioning is a classification for the different methodologies that address the problem.
We have decided to compare the four methodologies along five dimensions in order to compare the different approaches to Strategic Inventory Positioning.
The five dimensions are:

1. The ability to cope with a Desired Service Level
2. The ability to deal with uncertainties on important variables
3. Ease of application
4. The ability to represent reduced lead times
5. The efficacy of the proposed reordering policy

To understand why these were the five dimensions selected a brief explanation of each dimensions is required.

Desired service level: it is related to the fact that the model, or methodology, includes the goal or the restraint of a certain desired service level to achieve or that the demand has to be satisfied in a certain time frame. For example, in SPI model it is represented, as we have seen before, by the variable β; in DDMRP's Strategic Inventory Positioning it is represented by the customer tolerance time which indicates the timeframe in which the demand has to be satisfied.

Uncertainty: it is related to the fact that model, or methodology, includes uncertainty or not. It includes every type of uncertainty from demand to delay in deliveries. For example, in SPI model uncertainty is represented by the variable α.

Ease of application: it is related to the fact that a model may be easy, or not, to apply to the real world's needs of supply chains. For example, mathematical models like SPI or WY will be more difficult to apply to real world's exigencies than AHP. It is important to highlight that the ease of application of a model does not means that a model is superior to another, but it means only that we have some model that are more versatile than other.

Reduced lead time: this dimension defines if the model has, or not, the purpose to reduce the overall lead time. For example, AHP's Strategic Inventory Positioning does not include improvement to reduce lead time while conversely DDMRP's Strategic Inventory Positioning does.

Reordering policy: it is related to the fact that a model includes, or not, reordering policies in the Strategic Inventory Positioning's problem. For example, WY model includes reordering policy conversely from AHP's Strategic Inventory Positioning.

Methodology Comparison	Desired Service Level	Uncertainty	Ease of Application	Reduced Lead Time	Reordering Policy
WY Model	In WY Model the desired service level is expressed with the fill rate of average level of inventories	In WY model uncertainty is included and it is expressed as the degree of uncertainty of demand	The WY model due to its assumptions it is difficult to apply in a real environment but the different use of four control systems made it appealing the use of one them in a environment similar to the one of simulations	The goal of the WY is to achieve a better fill rate by selecting an optimal location of the inventory but not to reduce the lead time, therefore lead time reduction it is not included in this model	Wy Model includes different types of reordering policy, defined by control systems. Re-ordering Policy and frequency of shippings are taken into account by WY model
AHP's Strategic Inventory Positioning	In AHP' Strategic Inventory Positioning no measure for desired service level is taken into account	In AHP's Strategic Inventory Positioning no measures for uncertainties are provided by the methodology	AHP' Strategic Inventory Positioning is a very versatile and easy to implement methodology. In this case the ease of application is higher.	AHP does not have the goal to reduce lead time neither lead time measures are included in the model	AHP's methodology does not include any kind of reordering policy
SPI Model	In SPI model the desired service level is expressed as a percentace using the variable β	In SPI model uncertainty is considered and expressed using the variable α which represents anything unexpected that can happen during processing and transportation time	SPI Model is a simple and easily implentable methodology but some of its assumptions may limit its application.	SPI model does not have the goal to reduce lead time neither lead measures are included in the model	The SPI model does not have different reording policy. The only indication to order is the quantity "Q" that enters in the system but there are no indications of the reordering policy that it is implemented.
DDMRP's Strategic Inventory Positioning	In DDMPR's Strategic Inventory Positioning it is present the measure of customer tolerance time, which is the time tolerated by the customer before seeking an alternative.	Decoupling reduces uncertainty but it would be incorrect to states that uncertainty, or variables that represent it, are included in the model	DDMRP's requires huge investements but its application to real company's needs is total. DDMRP's Strategic Inventory ease of application is superior to other models.	DDMPR's Strategic Inventory Positioning has in lead time reduction its main goal. In this methodologies are present different measures of lead time, the most important of them is decoupled lead time	DDMRP includes reordering policies in its methodology but they are not taken into account in DDMRP's Strategic Inventory Positioning, which is the first component of DDMRP but not the only one

Figure 24: Comparison between models and methodologies for Strategic Inventory Positioning[81]

[81] Personal elaboration.

Figure 24 shows a comparison between the five dimensions and the four methodologies.

- Desired service level: it is the first dimension that is compared between different models. In WY model the desired service level is expressed with the fill rate of average level of inventories; in AHP's Strategic Inventory Positioning no measures for desired service level neither the goal to achieve a certain desired service level is taken into account as the five criteria of AHP considered does not include it, in SPI model desired service level, represented by variable β , is considered and achieve a certain fill rate while simultaneously minimizing total holding cost is the goal of the model; in DDMRP's Strategic Inventory Positioning it is not used a measure similar to the desired service level, which is based on the fill rate, but the customer satisfaction it is represented by the customer tolerance time which is the time tolerated by the customer before seeking an alternative.
- Uncertainty: If we compare the dimension uncertainty through the various models we can see that it is included in WY model but in this case uncertainty is referred to the uncertainty of demand which is different from the uncertainty considered by the SPI model, express by variable α, which instead refers to anything unexpected that can happen during processing or transportation. In AHP SIP uncertainty it is not considered, in DDMRP' Strategic Inventory Positioning uncertainty is considered but indirectly it means that is not clearly defined but there are techniques, like decoupling, which are aimed to reduce uncertainty.
- Ease of application: it is the third dimension, WY model is difficult to apply to real supply chain needs because of its assumption behind the model (for example cross-shipping, which is a common practice, it is not allowed) but the fact that it considers four control systems suggest an application whether the environment is similar to that one described in simulations, it is important to highlight the fact that the WY model's purpose was to define where to locate the inventory (upstream or downstream) but not to provide a methodology. AHP's Strategic Inventory Positioning is easy to apply to real supply chain's needs, AHP methodology is really versatile and easy to implement. SPI model it is a simple methodology to determine in which nodes of the supply chain locate the inventories but its assumptions (for example the fact that is based on a single product supply chain) may limit its application. DDMRP requires huge investments but its application to real supply chain's needs is very high, superior of any other model/methodology here considered.
- Reduced lead time: it is the fourth dimension, for what it concerns WY model the goal of is to achieve a better fill rate by selecting an optimal location of the inventory but not reduce lead time therefore lead time reduction it is not included in this model; AHP methodology and SPI model don't have the goal to reduce lead time; DDMRP's Strategic Inventory Positioning

has in lead time reduction one of its main goals and this is reflected by the fact that different measured of lead time are presents in this methodology and the most important of them, for what it concerns lead time reduction, is decoupled lead time.

- Reordering policy: it is the fifth dimension of Figure 25, AHP Strategic Inventory Positioning does not include any kind of reordering policy in the methodology; SPI model does not have different ordering policies, the only indication about ordering policies in this model is the quantity "*Q*" that enters in the system but there is no indication regarding how the quantity is defined and when the order is made; DDMRP includes in its methodology reordering policies but these are defined in other components of DDMRP not in Strategic Inventory Positioning; WY model considers four different control system and every of these has a different re-ordering policy, in this model is considered not only the re-ordering policy but also the frequency of shipping.

The comparison of these models and methodologies has highlighted the heterogeneity of the approaches to the complex problem of Strategic Inventory Positioning; the weaknesses and the strong points of every model have been highlighted and discussed. Every of these models/methodologies has its own ability to represent, and solve, the problem in a unique way, the discriminant of whether to apply a model or another is the context/environment in which a decision should be taken.

3: MODEL STRESS TESTING: SPI MODEL AND AHP

In this chapter stress tests on SPI model and AHP' Strategic Inventory Positioning will be performed in order to have a deeper understanding on which are the factors that affect the most the decisions on Strategic Inventory Positioning.

3.1: SPI MODEL STRESS TESTING

A concrete example of how SPI model works is provided. The example is based on the supply chain of Figure 25.

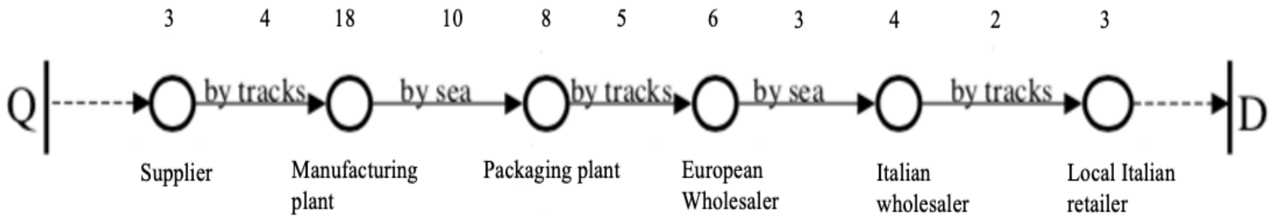


Figure 25: Single-product supply chain[82]

Figure 25 shows the single-product supply chain of our example. It is the supply chain of a smartphone components located in China. The raw materials are sent by tracks to the manufacturing plant in which they are processed, after the transformation processes they are sent to the packaging plant and after that they are transferred by tracks to a European wholesaler who re-packages the products and then sends them by sea to an Italian wholesaler who sold and deliver the products by tracks to local Italian retailers. In Figure 26 are indicated the processing time and transportation time for every phase of the supply chain.

In Figure 26 are presented the problem value parameters.

Pt_i , is the processing time of node "i".

$Tt_{i,i+1}$, is the transportation time from node "i" to node "i+1".

C_i, is the value added at every process in the nodes.

[82] Personal elaboration.

$\sum_{i=1}^{B} C_i$, is the sum of the value added during the processes in the nodes.

$\sum_{i=1}^{B} \alpha_i$, is the sum of factor α_i which refers to the uncertainties that may happens during the delivery of the product and may cause losses of product or delays.

φ_i , is the extra quantity, expressed as a percentage, that can be delivered to the buffer due to the closeness of the buffer to the point of sales (POS).

$\sum_{i=1}^{B} \varphi_i$, is the sum of φ_i.

Node	Pt_i	$Tt_{i,i+1}$	C_i	$\sum_{i=1}^{B} C_i$	$\sum_{i=1}^{B} \alpha_i$	φ_i	$\sum_{i=1}^{B} \varphi_i$
1	3	4	10	10	0,00	0,00	0,00
2	18	10	120	130	0,90	0,25	0,25
3	8	5	60	190	0,95	0,13	0,38
4	6	3	50	240	0,97	0,37	0,75
5	4	2	40	280	0,98	0,16	0,91
6	3	0	20	300	1,00	0,09	1
Total	42	24					
Total time		66					

Figure 26: Problem value parameters[83]

We have assumed to have a:

- Mean demand of 1000 units.
- Standard deviation of 90 units.
- Desired service level of 97%.

Five steps are needed to determine the optimal inventory position.

Step 1: Calculate the expected number of shortages per period S(q).

[83] Personal elaboration.

The formula to calculate the expected number of shortages per period is S(q) = (1-β)μ. In our case S(q) = (1-0,97) *1000 = 30.

Step 2: Obtain z and NL(z)

After we have calculated S(q) we have to calculate the Normal Loss Function NL(z), to calculate it is necessary to obtain from the table[84] the value of z. S(q) = $\sigma NL(z)$, thus 30 = 90 NL(z). NL is 0,333 and from the tables we can obtain z = 0,14.

Step 3: Calculate the quantity necessary to satisfy the indicated fill rate.

In our example we have decided to indicate 97% of the fill rate, which means that we want our model to provide an optimal inventory location in which the system is able to provide to the 97% of request at least.

The formula to calculate it is q=z*σ + μ.

We obtain q = 0,14 * 90 + 1000 = 1012,6.

Step 4: Calculate the inventory level and the holding costs if the buffer node is placed at i = 6.

Firstly, we have to calculate the inventory level for node I = 6, we can do it by using the following formula: $q = \sum_{i=1}^{n}(\sum_{i=1}^{j}\varphi_i)q_j = (\sum_{i=1}^{6}\varphi_6)q_6$ and in the calculation is: 1012,6 * 1 = 1012.

Secondly, we have to calculate the holding costs, these are calculated by using the following formula:

$holding\ costs\ node\ 6\colon q_i \sum_{i=1}^{B} C_i = q_6 \sum_{i=1}^{6} C_i$.

If we perform the calculation the result is: 1012,6 * 300 = 303780.

Step 5: Repeat step 4 for other nodes.

In order to define which is the node that achieved the desired fill rate and minimizes the holding costs we have to calculate these for every node of the supply chain.

[84] https://www.ime.unicamp.br/~moretti/ms715/1S_2012/Z-Chart%20&%20Loss%20Function%20v05.pdf

In Figure 27 we can see the results of the calculation.

Node	Inventory level qi	Total holding cost
1		
2	4079,20	530296
3	2683,68	509900
4	1359,73	326336
5	1120,66	313785
6	1019,80	305940

Figure 27: Inventory level and holding costs for every node at 97% fill rate.[85]

The results of the calculation clearly indicate that node in which the inventory should be positioned is buffer 6.

To validate the robustness of our results tests with other desired service level, respectively 98% and 99% fill rate, have been performed as can be seen in Figure 28 and 29.

[85] Personal elaboration.

Node	Inventory level qi	Total holding cost
1		
2	4151,20	539656
3	2731,05	518900
4	1383,73	332096
5	1140,44	319323
6	1037,80	311340

Figure 28: Inventory level and Holding Costs for every node at 98% fill rate[86].

Node	Inventory level qi	Total holding cost
1		
2	4302,40	559312
3	2830,53	537800
4	1434,13	344192
5	1181,98	330954
6	1075,60	322680

Figure 29: Inventory level and Holding Costs for every node at 99% fill rate[87].

We can see, from Figure 29 and 30, that the optimal position for the inventory is still the node 6, this means that the result is robust.

[86] Personal Elaboration
[87] Personal Elaboration

In these first tests the variable that has changed is the desired service level, expressed by the fill rate, and if from one hand it has been demonstrated the robustness of the model from the other hand we have seen that the impact of a variation in desired service level β on the decision it is minimal. In the next test the variable that will be stressed is the *mean demand.*

The problem's values parameters are those of Figure 27.

Node	Inventory level qi	Total holding cost
1		
2	2050,40	266552
3	1348,95	256300
4	683,47	164032
5	563,30	157723
6	512,60	153780

Figure 30: Inventory Level and Total Holding Costs with Mean Demand= 500[88]

In Figure 30 we have considered the scenario where the mean demand is halved, therefore the mean demand is 500 units; the node where it is optimal to locate the buffer remains the node 6.

[88] Personal elaboration

Node	Inventory level qi	Total holding cost
1		
2	8050,40	1046552
3	5296,32	1006300
4	2683,47	644032
5	2211,65	619262
6	2012,60	603780

Figure 31: Inventory Level and Total Holding Costs with Mean Demand = 2000[89]

In figure 31 the scenario where the Mean Demand μ is doubled from 1000 units to 2000 units. Even in this case the optimal buffer location is still at node 6.

After having seen the results of these scenarios we can conclude that the Mean Demand has, obviously, an impact on the total holding costs but it does not influence the buffer building point considering that the optimal node location is at node 6 with 500,1000 and 2000 units of mean demand.

The second variable that will be considered is the standard deviation. In the first simulation we have assumed to have a standard deviation of 90 units. It is interesting for the purpose of our research to discover what happens to the buffer building node if we change the standard deviation.

For these simulations we have assumed to have a Mean Demand μ of 1000 units.

We have simulated the scenarios where the standard deviation is 200 units and 50 units for three levels of Desired Service Level β respectively 97%,98% and 99%.

In figure 32 and 33 we can see the inventory level and total holding costs respectively with 200 and 50 units of standard deviation given the desired service level β of 97%.

The optimal inventory location is still a node 6, simulation with desired service level of 98% and 99% have been performed and the results indicate that the optimal buffer building node is at node 6 even in those scenarios.

[89] Personal elaboration

Simulations made clear that, in this model, the standard deviation has no impact on the choice where to locate the inventory. However, it should be noted the effect of an increasing, or decreasing, of the standard deviation on the total holding cost; we can see, if we compare Figure 27,32 and 33 that when the standard deviation increase then also the total holding cost increase and vice versa when it decrease the total holding costs act accordingly.

Node	Inventory level qi	Total holding cost
1		
2	4528,00	588640
3	2978,95	566000
4	1509,33	362240
5	1243,96	348308
6	1132,00	339600

Figure 32: Inventory Level and Total Holding Costs with σ = 200 and $\beta = 0{,}97$

Node	Inventory level qi	Total holding cost
1		
2	4044,00	525720
3	2660,53	505500
4	1348,00	323520
5	1110,99	311077
6	1011,00	303300

Figure 33: Inventory Level and Total Holding Costs with $\sigma = 50$ and $\beta = 0{,}97$

Like the Mean Demand μ, the Standard Deviation σ affects, in this model, only the total holding cost but does not influence the decision regarding the optimal buffer building point.

The third variable that has been analyzed is C_i, which "represents the increase in the value of the product after it has completed the process at node *i*"[90].
In order to understand how this variable affected the decision about the optimal inventory location multiple simulations have been performed by changing the C_i of the nodes to assess how this variable contributes to the optimal inventory location; the total value added $\sum_{i=1}^{B} C_i$ had not been changed but what had been changed is the value added of the single nodes.

Node	Inventory level qi	Total holding cost
1		
2	4050,40	121512
3	2664,74	239826
4	1350,13	189019
5	1112,75	200295
6	1012,60	303780

Figure 34: Inventory Level and Total Holding Cost if C_2 =20 and C_6=120.

Following the problem value parameters of Figure 26 the value of C_2 = 20 and C_6 = 120 have been changed. The changes in the value added had impact on the optimal inventory position as it shifted from node 6, as can be seen in Figure 27, to node 2. The total holding costs of Figure 34 if compared with that of Figure 27 are lower, this can suggest that an upstream location of the inventory may have a cost-saving effect.
Other simulations have made changing, sequentially, the value of C_3, C_4 and C_5 with C_6. The results showed that in these 3 scenarios the optimal inventory location is node 5 as we can see Figure 35.

[90] Skintzi G., Ioannou G., Prastacos G., "Inventory Positioning in Single Product Supply Chains", Les Cahies du Management Technologique, 11 (2), 33-40. (2001).

Node	Inventory level qi	Total holding cost
1		
2	4050,40	526552
3	2664,74	399711
4	1350,13	270027
5	1112,75	267059
6	1012,60	303780

Figure 35: Inventory Level and Total Holding Cost if $C_3 = 20$ and $C_6 = 60$.

Node	Inventory level qi	Total holding cost
1		
2	4050,40	526552
3	2664,74	506300
4	1350,13	283528
5	1112,75	278187
6	1012,60	303780

Figure 36: Inventory Level and Total Holding Cost if $C_4 = 20$ and $C_6 = 50$.

Node	Inventory level qi	Total holding cost
1		
2	4050,40	526552
3	2664,74	506300
4	1350,13	324032
5	1112,75	289314
6	1012,60	303780

Figure 37: Inventory Level and Total Holding Costs if $C_5 = 20$ and $C_6 = 40$.

These simulations showed that the variable C_i, which represent the value added in every node, is determinant for the optimal inventory location.

Two remarks about the variable C_i and the role it plays in determining the optimal inventory location should be made, one about the total holding cost and one about the node.

If we consider Figure 27,34, 35, 36 and 37 we can see that, given $\mu = 1000, \beta = 97\%$ and $\sigma = 90$, the total holding cost are increasingly growing as the inventory is placed downstream.

The second remark is that, if the optimal inventory location is influenced by the value adding activities performed in each node , supply chain should be designed considering that the position of value adding activities influence the strategic inventory positioning as from our simulations we can see that nodes with lowest C_i are probably the preferred optimal inventory location as we can see from Figure 27, 34, and 36 the inventory should be placed in the node with the lowest value adding activities.

Stress testing the model have made clear that, when designing supply chain, according to this model also the value added C_i of each node should be considered for the optimal inventory location and moreover that should be considered the impact of standard deviation σ, mean demand μ and value added C_i on the total holding costs.

3.2: Analytic Hierarchy Process for Strategic Inventory Positioning

In this part an example of how Analytic Hierarchy Process is applied for the selection of an optimal warehouse location is provided.

The application of AHP methodology for SIP is based on Al Amin, Apurba, Sumit and Imran Shikdar (2019) "Warehouse Selection Problem solution by using proper MCDM process.[91]

In our example a new element has been introduced to the original case, a sixth criterion.

The problem is based on a supply chain in the garment industry in which the optimal location for inventory has to be selected for the stocking of finished goods.

In the problem are considered five alternatives warehouses.

As described above, the five alternatives are weighted against five criteria, which were selected by experts of the industry, and these were:

1. Unit Cost
2. Stock Holding Capacity
3. Movement Flexibility
4. Layout
5. Distance from the main factory

"Market" has been introduced in our example as sixth criterion. The reason why it has been considered necessary to introduce "Market" is that from our research on Strategic Inventory Positioning emerged the necessity to being able to satisfy a certain desired level and that a common trait of Strategic Inventory Positioning research is that the position of the inventory is in a constant tension between having it located upstream (near the factory) or downstream (near the point of sales); this tension was not represented in the five criteria considered by Al Amin, Apurba, Sumit and Imran Shikdar M (2019) and for this reason emerged the necessity to introduce the sixth criterion "Market".

By "Market" we define the proximity of the warehouse to the market and the scope for future expansion for the market.

The first step, to evaluate which alternative is the optimal one, is to compare and weight the criteria in order to assess which are the most relevant; this is done by using a pairwise comparison matrix as we can see in Figure 38.

[91] Al Amin M., Apurba D., Sumit R., Imran Shikdar M., "Warehouse Selection Problem Solution by Using Proper MCDM Process". International Journal of Science and Qualitative Analysis. Vol. 5, No. 2, pp. 43-51, 2019

Criteria Comparison	Unit Price	Stock Holding Capacity	Average distance to factory	Flexibility	Layout	Market
Unit Price	1,00	1,20	1,00	3,00	2,00	1,50
Stock Holding Capacity	0,83	1,00	1,00	2,50	1,67	1,50
Average Distance to Factory	0,83	1,00	1,00	2,50	1,67	1,00
Flexibility	0,33	0,50	0,40	1,00	0,67	1,00
Layout	0,50	0,60	0,60	1,50	1,00	0,50
Market	0,67	0,67	1,00	1,00	2,00	1,00

Figure 38: Criteria pairwise comparison matrix.[92]

In order to obtain the weight of each criteria we calculate the geometric means of each row, then we sum the geometric mean of each row in order to obtain the sum of the geometric means; the number obtained allows us to normalize the geometric means by diving the each criterion's geometric means for the sum obtained before and this calculation will give us the normalized weight of each criterion.

Criteria	Geometric Means	Weight
Unit Price	1,486747759	0,235027327
Stock Holding Capacity	1,31658771	0,20812817
Average Distance to Factory	1,230555635	0,19452809
Flexibility	0,595163447	0,094084335
Layout	0,716235146	0,113223531
Market	0,980560918	0,155008548
Sum	6,325850615	1

Figure 39: Weighting and normalizing Criteria.[93]

After having obtained the normalized weights, it is necessary to assess the consistency of the Pairwise Comparison Matrix and the relative weights. In order to assess the consistency, we have to calculate λ which is necessary to calculate the Consistency Index.

In figure 40 we can see the lambda estimates, they are obtained by multiplying the matrix with the column of the weights and then the result of each row is divided by the weight of each alternatives. After having performed this mathematical operation we obtain the lambda estimates as we can see from Figure 40.

[92] Personal Elaboration
[93] Personal Elaboration

Criteria	Lambda Estimates	
Unit Price	1,421	6,044
Stock Holding Capacity	1,255	6,030
Average Distance to Factory	1,177	6,053
Flexibility	0,585	6,216
Layout	0,691	6,103
Market	0,966	6,229

Figure 40: Lambda Estimates.[94]

Once obtained the lambda estimates we have to calculate the mean of them which will return us the value of lambda λ which will be used to calculate the Consistency Index.

The Consistency Index CI is defined as: $\frac{\lambda - n}{n-1}$.[95]

After having calculated the Consistency Index we have to calculate the Consistency Ratio in order to define if our judgements are acceptable or not.

The random consistency index for 6 criteria is 1,24.

The formula for the Consistency Ratio is: $\frac{CI}{CI_{max}}\ \% \leq 10\%$

Therefore, to calculate the Consistency Ratio: $\frac{0{,}02245}{1{,}24}$ % = 1,81% which is acceptable and proves that our judgements are consistent.

Lambda	Consistency Index	Maximum Inconsistency	Consistency Ratio
6,11225	0,02245	1,24	1,81%

Figure 41: Lambda, Consistency Index, Maximum Inconsistency for 6 criteria and Consistency Ratio.[96]

The same mathematical procedures are needed to be followed for each criterion in order to define the ranking of each alternative for every criterion and to assess that the evaluations, and the pairwise comparison matrix, are consistent the consistency ratio needs to be calculated for every of these.

In Figure 42 we can find the pairwise comparison matrix regarding the first criterion: unit cost.

94 Personal elaboration
95 For more details about Consistency Index and AHP methodology see Appendix A.
96 Personal elaboration

In Figure 43 the alternatives are weighted and normalized on the basis of unit cost; what has emerged after the calculation is that the alternative preferred on the basis of unit cost is Warehouse 1.

On the basis of Unit Cost	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	1,17	1,27	1,27	1,07
Warehouse 2	0,85	1,00	1,08	1,08	0,91
Warehouse 3	0,79	0,93	1,00	1,00	0,84
Warehouse 4	0,79	0,93	1,00	1,00	0,84
Warehouse 5	0,94	1,10	1,19	1,19	1,00
Sum	4,37	5,13	5,53	5,53	4,66

Figure 42: Pairwise comparison matrix on the basis of Unit Cost[97]

Alternatives	Geometric Means	Weight
Warehouse 1	1,1496	0,2289
Warehouse 2	0,9798	0,1951
Warehouse 3	0,9076	0,1807
Warehouse 4	0,9076	0,1807
Warehouse 5	1,0778	0,2146
Sum	5,0224	1,0000

Figure 43: Alternatives weighted and normalized on the basis of unit cost.[98]

The second criterion is the stock holding capacity, in figure 44 and figure 45 we can see that, accordingly to the alternatives considered, Warehouse 3 is the preferred alternative on the basis of the stock holding capacity.

[97] Personal Elaboration
[98] Personal Elaboration

On the basis of Stock Holding Capacity	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	0,89	1,33	1,33	1,17
Warehouse 2	1,12	1,00	0,95	1,50	1,32
Warehouse 3	1,19	1,06	1,00	1,58	1,40
Warehouse 4	0,75	0,67	0,63	1,00	0,88
Warehouse 5	0,85	0,76	0,72	1,13	1,00
Sum	4,91	4,37	4,63	6,55	5,77

Figure 44: Pairwise comparison matrix on the basis of Stock Holding Capacity.[99]

Alternatives	Geometric Means	Weight
Warehouse 1	1,1311	0,2187
Warehouse 2	1,1617	0,2246
Warehouse 3	1,2263	0,2371
Warehouse 4	0,7745	0,1498
Warehouse 5	0,8777	0,1697
Sum	5,1713	1,0000

Figure 45: Alternatives weighted and normalized on the basis of Stock Holding Capacity.[100]

The third criterion considered is the Average Distance to the factory, in figure 46 and 47 we can respectively see the pairwise comparison matrix on the basis of stock holding capacity and the alternative weighted and normalized.

In this case the preferred alternative is warehouse 1.

On the basis of Average Distance to Factory	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	1,19	1,10	2,38	2,14
Warehouse 2	0,84	1,00	0,92	2,00	1,80
Warehouse 3	0,91	1,09	1,00	2,17	1,96
Warehouse 4	0,42	0,50	0,46	1,00	0,90
Warehouse 5	0,47	0,56	0,51	1,11	1,00
Sum	3,64	4,33	3,99	8,67	7,80

Figure 46: Pairwise comparison matrix on the basis of Average Distance to the factory.[101]

[99] Personal Elaboration
[100] Personal Elaboration
[101] Personal Elaboration

Alternatives	Geometric Means	Weight
Warehouse 1	1,4608	0,2747
Warehouse 2	1,2271	0,2308
Warehouse 3	1,3338	0,2509
Warehouse 4	0,6135	0,1154
Warehouse 5	0,6817	0,1282
Sum	5,3169	1,0000

Figure 47: Alternatives weighted and normalized on the basis of Average Distance to the Factory.[102]

The fourth criterion is flexibility. In Figure 48 the pairwise comparison matrix on the basis of flexibility can be observed while in Figure 49 we can see that the warehouse that the highest score on flexibility are warehouse 1 and warehouse 4.

On the basis of Flexibility	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	2,00	2,00	1,00	2,00
Warehouse 2	0,50	1,00	1,00	0,50	1,00
Warehouse 3	0,50	1,00	1,00	0,50	1,00
Warehouse 4	1,00	2,00	2,00	1,00	2,00
Warehouse 5	0,50	1,00	1,00	0,50	1,00
Sum	3,50	7,00	7,00	3,50	7,00

Figure 48: Pairwise comparison matrix on the basis of Flexibility.[103]

Alternatives	Geometric Means	Weight
Warehouse 1	1,5157	0,2857
Warehouse 2	0,7579	0,1429
Warehouse 3	0,7579	0,1429
Warehouse 4	1,5157	0,2857
Warehouse 5	0,7579	0,1429
Sum	5,3050	1,0000

Figure 49: Alternatives weighted and normalized on the basis of Flexibility.[104]

The fifth criterion we have considered in our analysis is the layout of the warehouse. Figure 50 shows the comparison matrix on the basis of layout, while Figure 51 illustrates the alternatives

[102] Personal Elaboration
[103] Personal elaboration
[104] Personal elaboration

weighted and normalized. The warehouse that have the highest weight with respect to flexibility are Warehouse 1 and Warehouse 4.

On the basis of layout	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	3,00	3,00	1,00	1,50
Warehouse 2	0,33	1,00	1,00	0,33	0,50
Warehouse 3	0,33	1,00	1,00	0,33	0,50
Warehouse 4	1,00	3,00	3,00	1,00	1,50
Warehouse 5	0,67	2,00	2,00	0,67	1,00
Sum	3,33	10,00	10,00	3,33	5,00

Figure 50: Pairwise comparison matrix on the basis of Layout[105]

Alternatives	Geometric Means	Weight
Warehouse 1	1,6829	0,3000
Warehouse 2	0,5610	0,1000
Warehouse 3	0,5610	0,1000
Warehouse 4	1,6829	0,3000
Warehouse 5	1,1220	0,2000
Sum	5,6098	1,0000

Figure 51: Alternatives weighted and normalized on the basis of Flexibility.[106]

The sixth, and last, criterion is market. In Figure 52 we can see the pairwise comparison matrix of the alternatives on the basis of Market and in Figure 53 the alternative weighted and normalized on the basis of the Market criterion. The alternatives that has the highest weight in Market criterion is Warehouse 2.

On the basis of Market	Warehouse 1	Warehouse 2	Warehouse 3	Warehouse 4	Warehouse 5
Warehouse 1	1,00	2,00	1,50	0,50	1,00
Warehouse 2	0,50	1,00	1,50	2,00	2,00
Warehouse 3	0,67	0,67	1,00	1,00	2,00
Warehouse 4	2,00	0,50	1,00	1,00	1,50
Warehouse 5	1,00	0,50	0,50	0,67	1,00
Sum	5,17	4,67	5,50	5,17	7,50

Figure 52: Pairwise comparison matrix on the basis of Market.[107]

[105] Personal elaboration
[106] Personal Elaboration
[107] Personal Elaboration

Alternatives	Geometric Means	Weight
Warehouse 1	1,0845	0,2131
Warehouse 2	1,2457	0,2447
Warehouse 3	0,9767	0,1919
Warehouse 4	1,0845	0,2131
Warehouse 5	0,6988	0,1373
Sum	5,0902	1,0000

Figure 53: Alternatives weighted and normalized on the basis of flexibility.[108]

After having calculated the weight of each alternative for each criterion, consistency tests have been made in order to assess the consistency of the matrix for each pairwise comparison matrix and the test confirmed the consistency of all the pairwise comparison matrices.

Results	Unit Cost	Stock Holding Capacity	Average Distance to Factory	Flexibility	Layout	Market
Weights	0,2350	0,2081	0,1945	0,0941	0,1132	0,1550
Warehouse 1	0,2289	0,2187	0,2747	0,2857	0,3000	0,2131
Warehouse 2	0,1951	0,2246	0,2308	0,1429	0,1000	0,2447
Warehouse 3	0,1807	0,2371	0,2509	0,1429	0,1000	0,1919
Warehouse 4	0,1807	0,1498	0,1154	0,2857	0,3000	0,2131
Warehouse 5	0,2146	0,1697	0,1282	0,1429	0,2000	0,1373
Sum	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000

Figure 54: Alternatives weighted.[109]

In figure 54 we can see the evaluation of every warehouse according to each criterion. To obtain the priority vector, which will define the best alternative, we have to multiply each warehouse's weight row for its related weighted criterion.

Figure 55 shows the priority vector and the best alternative which is Warehouse 1.

Priority Vector	Scores
Warehouse 1	0,2466
Warehouse 2	0,2002
Warehouse 3	0,1951
Warehouse 4	0,1900
Warehouse 5	0,1681
Sum	1

Figure 55: Priority Vector[110]

[108] Personal Elaboration
[109] Personal Elaboration
[110] Personal Elaboration

Figure 54 shows the weight of each criterion and the evaluation of every warehouse according to it. We can see from the table that we have one cost criterion, which is Unit Cost, and five criteria related to benefit which are Stock Holding Capacity, Average Distance to Factory, Flexibility, Layout and Market; this situation fit perfectly with SMART methodology.

"Simple Multi Attribute Rating (SMART) is a comprehensive model of decision-makers to account for things that are qualitative and quantitative"[111], we can use it to validate the decision made with AHP and checking if the two methodologies provide the same alternative as the chosen one.

SMART it is particular suited for this kind of problem as it is a techniques that is able to deal with both quantitative factors (like unit cost) and non-quantitative factors (like layout, flexibility or market) and especially for the fact that this methodology allows to balance the trade-off between costs and benefits. In order to achieve an evaluation of the best alternative using SMART, the cost criterion and the benefits criteria have been separated, using the value of Figure 54, which means that Costs (defined by first criterion Unit Cost and indicated with *w*) are 0,2350 and the Benefits (the other five criteria) are defined by 1-*w*, therefore Benefits = 1-0,2350 = 0,765; then the Benefits values have been normalized as we can see in Figure 56.

Benefits SMART	0,2081	0,1945	0,0941	0,1132	0,1550
Normalized Weight Values	0,272072686	0,254294168	0,122990452	0,148009903	0,202632791

Figure 56: Benefits Values and Normalized Benefits Values.[112]

After having obtained the normalized weight values, the values of the alternatives (from Figure 54) are multiplied for their relative weight, the values obtained after the weighting are shown in Figure 55.

Weights	Stock Holding Capacity	Average Distance to Factory	Flexibility	Layout	Market
Weights values	0,272072686	0,254294168	0,122990452	0,148009903	0,202632791
Warehouse 1	0,05951005	0,06986509	0,035140129	0,044402967	0,04317093
Warehouse 2	0,061120227	0,058688162	0,017570065	0,014800986	0,049590376
Warehouse 3	0,064515826	0,063791481	0,017570065	0,014800986	0,038881467
Warehouse 4	0,040746837	0,029344081	0,035140129	0,044402985	0,04317093
Warehouse 5	0,046179747	0,032605355	0,017570065	0,029601978	0,027819089

Figure 55: Alternatives weighted and weights values.[113]

[111] Risawandi R., Rahim R., "Study of the Simple Multi Attribute Rating Technique for Decision Support", IJSRT, volume 2, issue 6, 2016.
[112] Personal Elaboration
[113] Personal Elaboration

	Costs	Benefits
Weights	0,235027327	0,764972673
Warehouse 1	0,053797759	0,252089166
Warehouse 2	0,045850354	0,201769815
Warehouse 3	0,042471909	0,199559824
Warehouse 4	0,042471909	0,192804962
Warehouse 5	0,050435396	0,153776233

Figure 56: Weighted Costs and Benefits for each warehouse.[114]

Figure 56 shows the weighted costs and benefits for each of the alternatives.

To obtain the final ranking of the alternative, Costs and Benefits have to be multiplied by their corresponding weights.

Alternatives	RANKING
Warehouse 1	0,205485267
Warehouse 2	0,165124481
Warehouse 3	0,162639872
Warehouse 4	0,157472586
Warehouse 5	0,129488312

Figure 57: Alternatives Ranked according to SMART methodology.[115]

From Figure 57 we can see that even using SMART methodology, instead of AHP, the preferred alternative for the decision maker that has the highest final scoring is Warehouse 1.

Figure 58 shows the alternatives and the efficient frontier, the only alternative that belongs to the efficient frontier is Warehouse 1; in order to belong to the efficient frontier an alternative at least a value of *w* that makes that alternative the preferred one must exist.

[114] Personal Elaboration
[115] Personal Elaboration

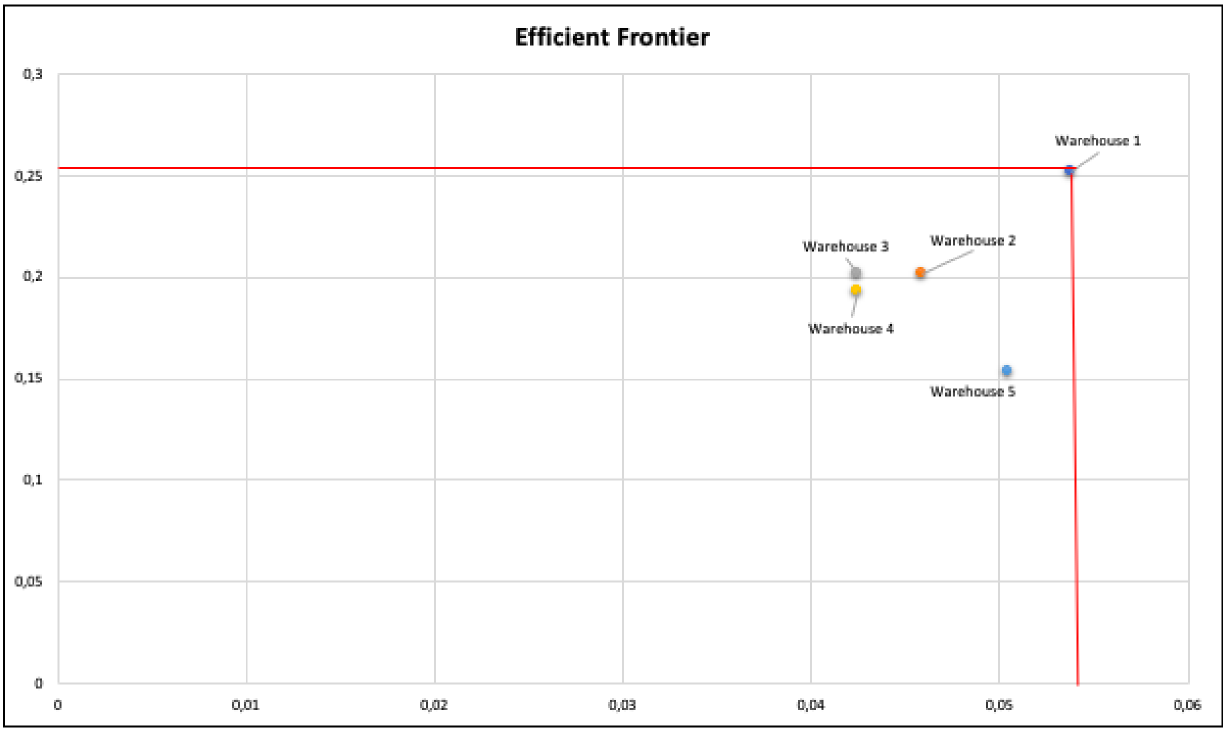


Figure 58: Efficient Frontier [116]

In conclusion, AHP has proved to be reliable and very versatile for Strategic Inventory Positioning thanks to his ability to deal with both quantitative and non-quantitative factors and weighting them with respect to the decision maker's preferences.

AHP has proved to be versatile, for the purpose our research the "Market" criterion has been added to the other five and other criteria can be easily implemented if the decision maker consider it required; this characteristic is one of the most important of AHP which makes it a methodology adaptable to different kind of problems and environments.

Versatility is not the only strong point of AHP methodology for Strategic Inventor Positioning as it has proved also to be reliable, in fact we have verified the results of AHP by using the SMART methodology for the same problem and the results were consistent and the methodology itself, through the consistency ratio, proves to be reliable.

[116] Personal Elaboration

Conclusion

The objective of this research was to define what Strategic Inventory Positioning is, why it is a subject of crucial importance for the supply chain management and which are the models and methodologies that can be helpful for the managers and the planners in the New Normal.
For the purpose of our research was necessary to define why these methodologies and models are necessary for planners and managers and, for this reason, in the first chapter the New Normal environment has been described in order to provide a context to the reader.
Giving a context to this research has been necessary as it was required to understand the transition from MRP to DDMRP. Demand Driven Requirement Material Planning is composed by five elements and the first element of those is Strategic Inventory Positioning.
This research has highlighted the heterogenous nature of the different models and methods here presented showing that a clear and unique approach to the problem of Strategic Inventory Positioning has not yet been found but also that many experts of different disciplines understood the importance of this problem.
DDMRP's Strategic Inventory Positioning has been the cornerstone of this research and the first methodology here explained, it has been fundamental to explain DDMRP before other methodologies because it introduced concepts like Decoupling, Decoupled Lead Time and Desired Service Level which are at the basis of almost methodologies and models of Strategic Inventory Positioning.
In this research two methodologies, DDMRP and AHP, and two models, SPI and WY, have been explained from theoretical perspective and concrete example of application of SPI model and AHP methodology for Strategic Inventory Positioning have been provided.
The four models and methodologies have been compared and what emerged from this comparison is that anyone of them is capable of taking into account all the dimensions on which the comparisons were based. From this research emerged that DDMRP's Strategic Inventory Positioning.
The research highlighted the fact that the SPI model and the WY model are the most theoretical and difficult to apply in a real context, because of their assumptions, but they are the only models that take into account re-ordering policies or issues concerning uncertainty which are not considered in the more "practical" DDMRP and AHP. Conversely, DDMRP's Strategic Inventory Positioning and AHP for SIP have been proved to be easily adaptable to real supply chain's needs and especially the first is the most reliable methodology; AHP is not only reliable but also very versatile thanks to his ability to deal with both quantitative and non-quantitative factors. Every of this models and methodologies has been proven has its strengths and weaknesses and it will be the context in which they are applied to determine which of them is the most suitable. More researches are needed in order

to create a model, or a methodology, that can satisfy all the comparison dimensions; a model that can deal with uncertainty, reordering policies, able to satisfy the required desired service level and easy to apply to supply chain's concrete needs, like reducing leading time, need to be developed in order to provide planners and a managers an effective tool for Strategic Inventory Positioning.

In conclusion, this research has highlighted that a unique approach to Strategic Inventory Positioning has not been found yet, but the most relevant methodologies and models have been explained, compared and their strengths and weaknesses have been deeply discussed with the purpose of providing a framework for the researchers who have interest in Strategic Inventory Positioning.

Strategic Inventory Positioning is a subject that needs to be investigated further, this Master's Degree Thesis has shown the importance of this topic in the New Normal and its importance for supply chain management, it is in the opinion of the author that in the next years the research on this subject will be intense and will involve researchers from different disciplines which will have the goal to find new methodologies and models that will overcome the weaknesses and limitations of the actual ones.

Appendix A: AHP methodology

AHP characteristics:

Analytic Hierarchy Process is a methodology for decision making developed in the 1970's by American professor Thomas L. Saaty at Wharton School of Business.
"Analytic Hierarchy Process allows decision makers to model a complex problem in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives, and alternatives." [117]
AHP is a multi-criteria decision-making methodology which means that it allows the decision-maker to consider both quantitative and non-quantitative factors in his decision.
AHP is a hierarchical methodology meaning that every problem is hierarchized as it follows:

- Goal: it is the overall objective of our decision
- Objectives: the objectives that we want to achieve with our decision, they are defined by criteria.
- Sub-objectives: they are the objectives that we want to achieve in every objective, they are defined by sub-criteria
- Alternatives: they are the elements that we will compare with respect to their ability to achieve sub-objectives, objectives and goal.

[117] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.

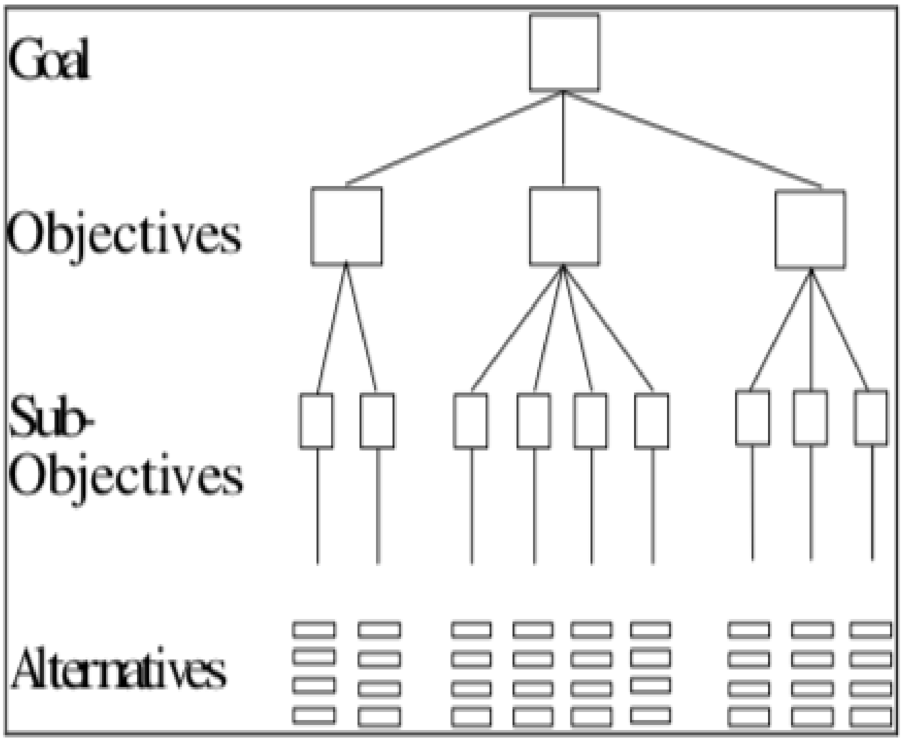


Figure 59: Hierarchic structure of AHP's decision[118]

Being hierarchical means that the elaboration of the decision will start from the goal, descending to the objectives and from these to the sub-objectives and lastly to the alternatives.

The elements of the hierarchy are clustered by homogeneity.

"The elements in each level are may be regarded as constraints, refinements or decompositions of the elements above"[119].

The hierarchy represented should be complex enough to represent adequately the problem but remain light enough to be sensitive to changes.

AHP is a multi-criteria decision-making methodology which means that it allows the decision-maker to consider both quantitative and non-quantitative factors in his decision.

Quantitative and non-quantitative factors were defined by Saati (1987) in his article[120] as physical and psychological events; the firsts are those tangible, know and objectively measurable while the latter are intangible, based on beliefs and measurable only subjectively.

The peculiarity of Analytic Hierarchy Process is that the weight of the criteria included in the decision are derived by the decision maker and not assigned arbitrarily.

[118] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.

[119] Saaty R.W., "The Analytical Hierarchy Process, what is it and how it is used", Math Modelling, vol 9, 1987.

[120] Saaty R.W., "The Analytical Hierarchy Process, what is it and how it is used", Math Modelling, vol 9, 1987.

Analytic Hierarchy Process is a "compensatory decision methodology"[121], it means that the alternatives are evaluated in every of the criteria considered and good attributes in some of these may compensate bad attributes in other criteria.
At the basis of AHP there is an assumption about human decision making; humans are better at giving relative judgements than absolute ones. It means that humans are more capable to establish if A is better than B or C instead of deciding if A is the better of all the alternatives and how much is better.
The Analytic Hierarchy Process uses pairwise relative comparisons for the reason above, humans are more able to recognize which alternative is better if looking at comparison of two alternatives.
Pairwise relative comparisons are based on judgements. Judgements on non-objective factors may be not consistent but it does not represent a problem as Analytic Hierarchy Process does not demand perfect consistency.
There are different causes of inconsistency:

- Clerical error: an example of this is entering the wrong number in comparison matrix.
- Lack of information: if the decision maker has insufficient information his judgment will probably be inconsistent because he will not be able to judge properly the criteria/alternatives considered.
- Inherent inconsistency of real world: inconsistency is present in real world. For example, in sports league often a team may lose and win against the same team, this represent inconsistency from the perspective that we are considering.
- Inadequate model structure: "cause of inconsistency is inadequate model structure. Ideally, one would structure a complex decision in a hierarchical fashion such that factors at any level are comparable, within an order of magnitude or so, of other factors at that level. Practical considerations might preclude such a structuring and it is still possible to get meaningful results"[122].

The fact that AHP does not require perfect consistency does not means that judgements will be inconsistent because, as we will see below, a measure to determine how judgements are consistent is present, the consistency ratio.
A consistency ration considered acceptable is below 10%.

[121] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.
[122] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.

Axioms and principles of AHP

Analytic Hierarchy Process has its roots on three principles which in turn are based on three axioms.

The three axioms are:

- Reciprocity: it requires that if a comparison is made between A and B and A is ten time bigger than B it is required that B is 1/10 time smaller than A.
- Homogeneity: "When constructing a hierarchy of objectives, one should attempt to arrange elements in a cluster so that they do not differ by more than an order of magnitude"[123]
- Hierarchy: judgements or statement of elements are not dependent by lower level elements.

Three principles of AHP are:

- Comparative judgement: it is at the basis of the pairwise relative comparison which are used to construct judgments and priorities of the elements into a cluster.
- Decomposition principle: is at the basis of the division into goal, objectives, sub-objectives and alternatives. It allows to structure the problem in clusters, sub-clusters and so on.
- Hierarchic composition: is applied to multiply the local priorities of elements in a cluster by the 'global' priority of the parent element, producing global priorities throughout the hierarchy and then adding the global priorities for the lowest level elements (the alternatives) [124]

The pairwise comparison matrix, in figure 59 is the cornerstone of AHP methodology.

The matrix is composed by pair of element *i,j* which are compared with each other with respect to the principles and axioms stated before. The comparison between element *i,j* is based on the level above of the hierarchy.

The element "*i*" is on the left side while the element *"j"* is on the top.

It is easy to understand that the pairwise comparison matrix answers to a simple question: "how much does *i* possesses a certain quality if compared with *j*?".

In figure 60 we can see that the majority, or not, of an element and its magnitude to another element is expressed by a number.

[123] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.

[124] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001

Numerical Value	Verbal Scale	Explanation
1.0	Equal importance of both elements	Two elements contribute equally
3.0	Moderate importance of one element over another	Experience and judgment favor one element over another
5.0	Strong importance of one element over another	An element is strongly favored
7.0	Very strong importance of one element over another	An element is very strongly dominant
9.0	Extreme importance of one element over another	An element is favored by at least an order of magnitude
2.0, 4.0, 6.0, 8.0	Intermediate values	Used to compromise between two judgments

Figure 60: Pairwise Comparison Scale[125]

The relationship between the element of the matrix is reciprocal along the diagonal of the matrix; it is particularly useful when we have to complete the matrix. A matrix is said to be consistent if $a_{ij}a_{jk} = a_{ik}$, $\forall i$, j, k.

What it is necessary to determine is the consistency of the matrix. In order to test the consistency, we have to consider the leading eigenvalue of the matrix.

If the matrix is perfectly consistent there will be a scoring vector, named “*w*”, such that $Aw = nw$, with *w* positive, $\sum_{i=1}^{n} w_i = 1$.

If the matrix is not perfectly consistent, there exists a vector *w* such that $Aw = \lambda w$, with *w* positive, $\sum_{i=1}^{n} w_i = 1$ and $\lambda_{max} > n$.

The closer λ_{max} is to *n* the more consistent will be the judgement, the farther λ is to *n* the more inconsistent it will be.

The difference $\lambda_{max} - n$, which is can be used as a measure for inconsistency, is used to form the consistency index.

The consistency index is: CI = $\frac{\lambda_{max}-n}{n-1}$.

[125] Forman E., Selly M. A., “Decisions by objectives. How to convince people that you are right” World Scientific, 2001.

According to the consistency index if CI_{max} = 0, there is perfect consistency; if CI_{max} is = 1 the judgements were made totally randomly.

$$\begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & \dots & w_{1/}w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \dots & w_3/w_n \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \dots & w_n/w_n \end{bmatrix} * \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ \dots \\ \dots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ nw_3 \\ \dots \\ \dots \\ \dots \\ nw_n \end{bmatrix}$$

$$\underline{A} \quad * \quad \underline{w} = n\,\underline{w}$$

Figure 61: Pairwise Matrix[126], scoring vector and eigenvector.

If there is no perfect consistency, it is possible to identify for each n a threshold of maximum inconsistency, as we can see from figure 62. For example, if our matrix size is 3 our CI_{max} will bel 0,58.

Matrix size	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Figure 62: Random Consistency Index[127]

[126] Forman E., Selly M. A., "Decisions by objectives. How to convince people that you are right" World Scientific, 2001.
[127] Saaty, T. L. "The analytic hierarchy process." McGraw-Hill, 1980.

The consistency ratio is defined “as the ratio of the consistency index for a particular set of judgments, to the average consistency index for random comparisons for a matrix of the same size.” Therefore, it is: $Consistency\ ratio$: $\frac{CI}{CI_{max}} \leq 10\%$.

AHP Methodology Step-by-Step.

After having defined the theory behind AHP methodology, now it will be shown how to implement this multi-criterion decision-making methodology.
The AHP is based on an algorithm composed by 4 steps that will be explained:

5. Construction of Structural Hierarchy.
6. Construction of Pairwise Comparison Matrices.
7. Weight Determination through normalization procedure.
8. Synthesis of weight and consistency test.

“Construction of Structural Hierarchy”.[128]

The first step of the AHP methodology is to decompose the problem; it will be decomposed, in descendant order, into goal, objectives, sub-objectives and alternatives.

“Construction of Pairwise Comparison Matrices”.[129]

After having defined the hierarchy of the problem, it is required by AHP to establish the priorities for every criteria and alternatives. The construction of Pairwise comparison Matrices will allow the decision maker to establish priorities within the alternatives and the criteria of the same level.
If we consider the pairwise comparison matrix, we can see that “A” represent the alternatives/criteria while the couples of values $a_{11} - a_{1n}$ represents the pairwise comparisons.
The preferences are assumed to be reciprocal.
The degree of importance of an element compared to another is defined by numbers from 1 to 9.

“Weight determination through Normalization procedure”.[130]

Weight determination and normalization can be done following two sequential steps:

- Computing geometric means along the columns
- Normalizing the geometric means by dividing them for the value of the sum of the geometric means. This will provide a relative ranking of the alternatives.

[128] Hannis Ansah R., Sorooshian S., Bin Mustafa S., “Analytic Hierarchy Process Decision Making Algorithm, Global Journal of Pure and Applied Mathematics. Number 4 , pp. 2403-2410, 2015.
[129] Hannis Ansah R., Sorooshian S., Bin Mustafa S., “Analytic Hierarchy Process Decision Making Algorithm, Global Journal of Pure and Applied Mathematics. Number 4 , pp. 2403-2410, 2015
[130] Hannis Ansah R., Sorooshian S., Bin Mustafa S., “Analytic Hierarchy Process Decision Making Algorithm, Global Journal of Pure and Applied Mathematics. Number 4 , pp. 2403-2410, 2015

$$Aw = \begin{bmatrix} \frac{a_{11}}{\sum a_{i1}} & \frac{a_{12}}{\sum a_{i2}} & \cdots & \frac{a_{1n}}{\sum a_{in}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{a_{n1}}{\sum a_{i1}} & \frac{a_{n2}}{\sum a_{i2}} & \cdots & \frac{a_{nn}}{\sum a_{in}} \end{bmatrix}$$

Figure 243: Normalization Procedure[131]

In figure 63 we can see how the second step of normalization procedure is made.

<u>“Synthesis of Weight and Consistency Test”.[132]</u>

This last step is divided in 4 sub-steps.

The first thing is required to do in order to obtain a global weight of the alternatives through the synthesis of local weights is to calculate C_i as the average and C_i as the average values of the row “i” of A*w matrix will be calculated for column vector *C*.

Once this is done, the second thing to do is to obtain the consistency vector. In order to obtain the vector, which it will be required to perform our consistency analysis, we have to multiply each row of matrix A for the column vector C. The result will be $x_{1,} x_2, \dots, x_n$, which is the consistency vector.

After having obtained the consistency vector we will use it to calculate λ_{max}.

λ_{max} is the eigenvalue of the comparison matrix, we can obtain it following this formula:

$\lambda_{max} = \sum_{i=1}^{n} \frac{x_1}{c_1}$.

Once we have obtained λ we can calculate the Consistency Index (CI).

CI = $\frac{\lambda_{max} - n}{n-1}$.

The Consistency Index will be then used in order to calculate the Consistency Ratio, which is the real indicator of how much our judgements have been consistent or not.

We can obtain the Consistency Ratio (CR) following this formula:

CR = $\frac{CI}{RI}$. In this equation RI is the Random Consistency Index, seen also in figure 62.

[131] Hannis Ansah R., Sorooshian S., Bin Mustafa S., “Analytic Hierarchy Process Decision Making Algorithm, Global Journal of Pure and Applied Mathematics. Number 4, pp. 2403-2410, 2015

[132] Hannis Ansah R., Sorooshian S., Bin Mustafa S., “Analytic Hierarchy Process Decision Making Algorithm, Global Journal of Pure and Applied Mathematics. Number 4, pp. 2403-2410, 2015

If the Consistency Ratio is below 10% the evaluation is consistent, conversely if the Consistency Ratio is above 10% evaluation is not consistent and therefore not acceptable.

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