POLITECNICO DI MILANO

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Master of Science Programme in Management Engineering

MULTIPRODUCT SUPPLY CHAIN ANALYSIS THROUGH BY SIMULATION WITH KANBAN AND EOQ SYSTEM

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I. Abstract

I.1. Original

This work reviews lean literature on the supply chain focused on the operational approach, from the lean management to the Kanban system.

But, the main issue of this work is to analyze the behavior of a lean supply chain using a Kanban system managing the planning in two different ways. The difference between both is related to the production order or sequence to follow: the product with fewer inventories in stock (the most critical to run out) or the one which requires less set-up time to optimize unproductive times.

The study the behavior of the supply chain, it would be done through simulation with many different scenarios: 5 different demands, each one with two coefficients of variance, 4 different batch sizes, 4 different compositions of production and process saturation and ensuring different service levels between 92% and 98%. To compare these supply chain models, an approach of the supply chain using the EOQ (Economic Order Quantity) system will be also simulated in the same conditions but with one batch size, the most economic one.

I.2. Italian

Questo lavoro recensisce la letteratura sulla lean e sulla supply chain con un approccio operativo, dal lean management al sistema Kanban.

Ma la questione principale di questo lavoro è quella di analizzare il comportamento di una filiera lean utilizzando un sistema Kanban di gestione della programmazione in due modi diversi. La differenza tra i due è legata alla sequenza di produzione: il prodotto con un minor numero di scorte in magazzino (il più critico che sta per esaurirsi) o quello che richiede meno tempo di set-up per ottimizzare i tempi non produttivi.

Lo studio del comportamento della supply chain viene fatto attraverso la simulazione usando diversi scenari: 5 domande, ognuna con due coefficienti di variazione diversi, 4 dimensioni dei lotti, 4 composizioni della saturazione di produzione e di processo e garantendo diversi livelli di servizio tra il 92% e 98%. Per confrontare questi modelli di supply chain, verrà anche simulato un approccio della filiera usando il sistema EOQ (Economic Order Quantity, ovvero il lotto economico) nelle stesse condizioni, ma con la dimensione del lotto che sia la più conveniente.

II. List of Acronyms, Abbreviations and Japanese words

Acronyms

ANP	Analytic Network Process
ConWIP	Constant Work-in-Progress
CPFR	Collaborative Planning Forecasting and Replenishment
CRM	Customer Relationship Management
CSM	Current State Map
ECR	Efficient Consumer Response
EDI	Electronic Data Interchange
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
FSM	Future State Map
FTL	Full Truck Load
GSCF	Global Supply Chain Forum
HRM	Human Resource Management
IT	Information Technology
JIT	Just-in-time
LTL	Less than Truck Load
MFC	Material Flow Control
MRI	Minimum Reasonable Inventory
MRP	Master Resource Planning
POLCA	Paired-cell Overlapping Loops of Cards with Authorization
POS	Point-of-Sale
PRM	Pattern Relationship Management
RFID	Radio Frequency Identification
SAP	Systems Applications and Products
SCM	Supply Chain Management
SMED	Single Minute Exchanges of Dies
SNM	Supplier Network Management
SPC	Statistical Process Control
SRM	Supplier Relationship Management
TPM	Total Productive Maintenance
TPS	Toyota Production System
TQC	Total Quality Control
TQM	Total Quality Management
VBA	Visual Basic for Applications
VMI	Vendor Managed Inventory
VSM	Value Stream Mapping
WIP	Work-in-Progress

Abbreviations

CR	Criticality dispatching rule
CV	Coefficient of Variance
DC	Decentralized Control
IB_D	Input Buffer Distributor

IB_PM	Input Buffer Primary Manufacturer
IB_SM	Input Buffer Secondary Manufacturer
LEAN_SU	Lean-Kanban model with Shortest Set-Up dispatching rule
LEAN_CR	Lean-Kanban model with Criticality dispatching rule
LI	Limited WIP
NVA	Non-Value Added
OB_PM	Output Buffer Primary Manufacturer
OB_SM	Output Buffer Secondary Manufacturer
PK	Production Kanban
PM	Primary Manufacturer
PP	Pull Production
ROP	Reorder Point
ROQ	Reorder Quantity
SM	Secondary Manufacturer
SSU	Shortest Set-Up dispatching rule
US	Use of two communication Signals
VA	Value Added
WK	Withdrawal Kanban

Japanese words

Kaizen: Continuous improvement.

Heijunka: Production smoothing.

Keiretsu: Grouping of enterprises, order of succession. It is a set of companies with interlocking business relationship and shareholding.

Muda: Wastefulness, uselessness.

German words

Takt (takt-time): Measure (measure time)

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1. Introduction

In recent years and under the global financial crisis in which all companies were engaged, a lean approach has become essential for many companies to continue leading the markets getting competitive advantages.

Lean strategy has been applied since the 1950s on the shop-floors at Toyota Motor Corporation and since the 1980s on the total supply chain of other companies with the final aim of reducing the wastes and consequently reducing the costs but always, without a reduction of the quality of the products and/or services. Lean approach is a philosophy based on zero wastes but also is a set of techniques to help achieve these goals.

These techniques are encompassed by the principle of material flow (and also the information flow) and quality. The material flow is based on the just-in-time (JIT) and Kanban system to reduce the inventories and work-in-process (WIP), aligned with this is the Total Productive Maintenance (TPM) with the aim of none stop of the machines or lines that stop the production and the material flow. In order to ensure the quality desired is aligned the Total Quality Management (TQM) pillar and the *kaizen* thinking that mean continuous improvement. The modern literature also includes other pillars such as the Human Resources Management (HRM) to align the whole organization in the same objective or even the Marketing and Innovation approach faced on lean.

This project analyze by simulation, using the Arena software, an entire supply chain with 24 different products and two different manufactories using a lean approach based on the Kanban system to demonstrate that is better than the Economic Order Quantity (EOQ) system in terms of inventory and transports needed, that is directly proportional to the costs. Furthermore, the lean approach has been analyzed using two different production logics: the product with less stock is the next one to be produced or the next product to be processed is the one which requires less set-up time, always if the number of pieces of these products is under a threshold.

The differences and saving between the three models will be evaluated depending on the variability of the demand, the saturation of the plants and the batch size.

2. Research Methodology

2.1. Scope of analysis

In this section, the literature related to Supply Chain Management (SCM) for planning and operations techniques is examined from the joint perspective of lean methodology applied and planning operations. A distinction between strategic and tactical approaches on the supply chain has been done. The strategic approach responses to how the supply chain is designed and the tactical or operative approach responses to how to manage the supply chain to achieve the objectives, e.g. to be more effective, efficient, robust, quicker, etc.

A viewpoint of lean and agile paradigms are analyzed as well as leagile paradigm that is a mixt between agile and lean, the firsts papers about leagile paradigm were written on the late 1990s (Naylor et al., 1999; Mason-Jones et al., 1999; Van Hoek, 2000). The decoupling point is the key to understand the difference between these paradigms and achieve the desired characteristics. The aim of this project is focused on the design of a lean supply chain and the analysis by simulations with different scenarios. So then, once the difference between lean, agile and leagile paradigm is clear, the literature review is focused on lean supply chain. More specifically, the literature review is focused on planning operations used on lean supply chains, e.g. kanban system, as well as on visibility.

To carry out the project and evaluate the results obtained when lean paradigm and visibility are applied, it is necessary to compare these results with any model, in that case, the results will be compared with Economic Order Quantity (EOQ) so some guidelines about the EOQ will be also described on the literature review.

2.2. Selection process

The literature was searched by terms text that have been found on article titles, abstracts and keywords using library databases, especially Scopus but also on Research Gate. The articles list was ordered by the number of citations in other papers in order to analyze the most important articles and verified by other authors. The publication age was also taken into account in some critical cases, when the time takes an important role in the content of the articles as in new technologies generally related to information technologies.

This method allows analyzing the most important papers and also the latest versions about some topics such as technology issues in major management, production and operational journals in the international level.

For this project, the main objectives of the literature review are to acquire more knowledge about all the issues that have been mentioned before (SCM, Lean principles and practices, differences between how to design and how to manage a supply chain, differences between lean and agile as well as their relation with leagile concept, sharing information, kanban, etc.).

In the beginning, some papers with the most general concepts were selected, papers with information about the SCM, lean management and lean supply chain considering and analyzing the differences on these issues with the tactical and strategic approach. After that, the selected articles were those which could explain clearly and allow us to understand the differences between agile, lean and leagile paradigm. Also, how to design and manage these paradigms as well as under which conditions their implementation is better. The selected papers were becoming more specific, going into detail on the practices of lean thinking, especially on kanban, as well as on visibility and information sharing and EOQ model.

2.3. Review method

There is a huge number of review methods used in previous papers, for this project the selected papers are classified based on: author, journal, year of publication, country in which first author's workplace is located, their content and finally, keywords used to find these articles on the library databases. This classification is very similar to Natarajarathinam et al., (2009) work but a little bit less complex. Some fields of Natarajarathinam et al., (2009) work are not really important for this project, since the supply chain analyzed through simulation is not real and the external factors have not been considered, this classification is summarized in table 1.

3. Summary of review and discussion

Aligned to the previous section, a summary of reviewed papers has been elaborated based on Natarajarathinam et al., (2009), the result can be seen in table 1. Papers selected are described according to their main characteristics: author, journal, year of publication and country in which the first author's workplace is located. Table 1 lists the papers analyzed in alphabetical order according to the journal and then, in alphabetical order according to the article's title. A total of 64 papers were analyzed from 30 different journals.

3.1. Reviewed characteristics

Continuing with Natarajarathinam et al., (2009), annex 1, table 34 show the number of contributions of each country considering the country where the first author works in and the number of papers from each journal. A total of 64 papers were analyzed from 30 different journals and 18 countries. Most of them, 24 papers (37%) were produced in United State and 15 of them (23%) in United Kingdom, the next country with more contributions is Taiwan with only 4. Therefore, United States and United Kingdom lead this list with a huge different over the other countries. If the continents are checked, the continent which has contributed more to the papers analyzed is Europe with 30 (46%) followed by North America with 25 (39%), Asia with 8 (12%) and South America with only 2 papers (3%).

The journals where papers have been taken can be seen in table 35, annex 1, annex 1. There are three journals with significantly more articles that are: International Journal of Production Economics, Journal of Operations Management and European Journal of Operational Research with 9, 9 and 7 articles respectively. These articles represent the 38% of the total papers analyzed and the followings journals with more contributions have 4 that are: International Journal of Operations and Production Management, International Journal of Physical Distribution and Logistics Management and International Journal of Production Research.

In the following table can be seen the paper analyzed for this work.

Table 1. Summary of the reviewed papers

No.	Authors	Year	Title	Journal	Country
1	Agarwal, A. et al.	2006	Modeling the metrics of lean, agile and leagile supply chain: An ANP-based approach	European Journal of Operational Research	India
2	Attaran, M.	2007	RFID: An enabler of supply chain operations	Supply Chain Management	United States
3	Barratt, M., Oke, A.	2007	Antecedents of supply chain visibility in retail supply chains: A resource-based theory perspective	Journal of Operations Management	United States
4	Ben Naylor, J. et al.	1999	Leagility: integrating the lean and agile manufacturing paradi gms in the total supply chain	International Journal of Production Economics	United Kingdom
5	Bitran et al.	1987	A Mathematical Programming Approach to a Deterministic Kanban System	Management Science	United States
6	Bonavia, T., Marin, J.A.	2006	An empirical study of lean production in the ceramic tile industry in Spain	International Journal of Operations and Production Management	Spain
7	Bruce, M. Et al.	2004	Lean or agile. A solution for supply chain management in the textiles and clothing industry?	International Journal of Operations and Production Management	United Kingdom
8	Brusset, X.	2016	Does supply chain visibility enhance agility?	International Journal of Production Economics	France
9	Caputo, A.C., Fratocchi, L., Pelagagge, P.M.	2006	A genetic approach for freight transportation planning	Industrial Management and Data Systems	Italy
10	Chang, C.T., Ouyang, L.Y., Teng, J.T.	2003	An EOQ model for deterioring items under supplier credits liked to ordering quantity	Applied Mathematical Modelling	Japan
11	Chang, S.C,.	1999	Fuzzy production inventory for fuzzy product quantity with triangular fuzzy number.	Fuzzy Sets and Systems	Taiwan
12	Chen, C.-T. et al.	2006	A fuzzy approach for supplier evaluation and selection in supply chain management	International Journal of Production Economics	Taiwan
13	Chen, I.J., Paulraj, A.	2004	Towards a theory of supply chain management: The constructs and measurements	Journal of Operations Management	United States

No.	Authors	Year	Title	Journal	Country
14	Chen, S.H., Wang, C.C., Chang, S.M.	2007	Fuzzy economic production quantity model for items with imperfect quality	International Journal of Innovative Computing, Information and Control	Taiwan
15	Christopher, M., Lee, H.	2004	Mitigating supply chain risk through improved confidence	International Journal of Physical Distribution and Logistics Management	United Kingdom
16	Christopher, M., Towill, d.	2001	An Integrated Model for the Design of Agile Supply Chain	International Journal of Physical Distribution and Logistics Management	United Kingdom
17	Christopher, M., Towill, D.	2001	An integrated model for the design of agile supply chains	International Journal of Physical Distribution and Logistics Management	United Kingdom
18	Dallery, Y., Liberopoulos, G.	2000	Extended kanban control system: Combining kanban and base stock	IIE Transactions (Institute of Industrial Engineers)	France
19	Deleersnyder, J.L. et al.	1989	Kanban Controlled Pull Systems, an analytic aproach	Management Science	Belgium
20	Delen, D. et al.	2007	RFID for better supply chain management through enhanced information visibility	Production and Operations Management	United States
21	Erlenkotter, D.	2014	Ford Whitman Harris's economical lot size model	International Journal Production Economics	United states
22	Frohlich, M.T., Westbrook, R.	2001	Arcs of integration: An international study of supply chain strategies	Journal of Operations Management	United Kingdom
23	Fullerton, R.R. et al.	2003	An examination of the relationships between JIT and financial performance	Journal of Operations Management	United States
24	Gargeya, V.B., Brady, C.	2005	Success and failure factors of adopting SAP in ERP system implementation	Business Process Management Journal	United States
25	Gunasekaran, A. et al.	2004	A framework for supply chain performance measurement	International Journal of Production Economics	United States
26	Gunasekaran, A., Ngai, E.	2004	Information systems in supply chain integration and management	European Journal of Operational Research	United States
27	Harris, F.W.	1913	How many parts to make at once	Factory, the Magazine of Management	United states

No.	Authors	Year	Title	Journal	Country
28	Hines, P. et al.	2004	Learning to evolve: A review of contemporary lean thinking	International Journal of Operations and Production Management	United Kingdom
29	Holweg, M.	2007	The genealogy of lean production	Journal of Operations Management	United Kingdom
30	James P. Womack, Daniel T. Jones	1996	Banishing Waste and Create Wealth in Your Corporation	Journal of Operational Research Society	United states
31	Jayaram, J. et al.	2008	Relationship building, lean strategy and firm performance: An exploratory study in the automotive supplier industry	International Journal of Production Research	United States
32	Jonsson, P., Holmström, J.	2016	Future of supply chain planning: closing the gaps between practice and promise	International Journal of Physical Distribution and Logistics Management	Sweden
33	Karaesmen, F., Dallery, Y.	2000	A performance comprison of pull type control mechanisms for multi-stage manufacturing	International Journal of Production Economics	France
34	Kumar, C.S., Panneerselvam, R.	2007	Literature review of JIT-KANBAN system	International Journal of Advanced Manufacturing Technology	India
35	Lage, M., Godinho, M.	2010	Variations of kanban system: Literature review and classification	International Journal of Production Economics	Brazil
36	Lambert, D.M., Cooper, M.C.	2000	Issues in supply chain management	Industrial Marketing Management	United States
37	Li, S. et al.	2005	Development and validation of a measurement instrument for studying supply chain management practices	Journal of Operations Management	United States
38	Liberopoulos, G., Dallery, Y.	2000	A unified framework for pull control mechanisms in multi-stage manufacturing systems	Annals of Operations Research	Greace
39	Mason-Jones, R. et al.	2000	Lean, agile or league? Matching your supply chain to the marketplace	International Journal of Production Research	United Kingdom
40	McCullen, P., Towill, D.	2001	Achieving lean supply through agile manufacturing	Computer Integrated Manufacturing Systems	United Kingdom
41	Meiling, J. et al.	2012	Managing for continuous improvement in off-site construction: Evaluation of lean management principle	Engineering, Construction and Architectural Management	Sweden

No.	Authors	Year	Title	Journal	Country
42	Melo, M.T. et al.	2009	Facility location and supply chain management - A review	European Journal of Operational Research	Germany
43	Metter, T., Rohner	2009	Supplier Relationship Management: A Case Study in the Context of Health Care	Journal of Theorical and Applied Electronic Commerce Research	Switzeland
44	Mistry, J.J.	2005	Origins of profitability through JIT processes in the supply chain	Industrial Management and Data Systems	United States
45	Naim, M., Barlow, J.	2003	An innovative supply chain strategy for customized housing	Construction Management and Economics	United Kingdom
46	Ng, D., Vail, G., Thomas, S., Schmidt, N.	2010	Applying the Lean principles of the Toyota Production System to reduce wait times in the emergency department	Canadian Journal of Emergency Medicine	Canada
47	Richard Lamming	1996	Squaring lean supply with supply chain management	International Journal of Operations and Production Management	United Kingdom
48	Riezebos, J. et al.	2009	Lean Production and information technology: Connection or contradiction?	Computers in Industry	Netherlands
49	Schwarz, L.B.	2008	The Economic Order Quantity (EOQ) Model	Operations Management Models and Principles	United states
50	Seuring, S., Müller, M.	2008	From a literature review to a conceptual framework for sustainable supply chain management	Journal of Cleaner Production	Germany
51	Shah, R., Ward, P.T.	2007	Defining and developing measures of lean production	Journal of Operations Management	United States
52	Shah, R., Ward, P.T.	2003	Lean manufacturing: Context, practice bundles, and performance	Journal of Operations Management	United States
53	Stevenson, M. et al.	2005	A review of production planning and control: The applicability of key concepts to the make-to-order industry	International Journal of Production Research	United Kingdom
54	Stevenson, M. et al.	2005	A review of production planning and control: The applicability of key concepts to the make-to-order industry	International Journal of Production Research	United Kingdom
55	Stratton, R., Warburton, R.D.H.	2003	The strategic integration of agile and lean supply	International Journal of Production Economics	United Kingdom
56	Sylwia Konecka	2010	Lean and agile supply chain management concepts in the aspect of risk management	Electronic Scientific Journal of Logistics	Poland

No.	Authors	Year	Title	Journal	Country
57	Takahashi, K. et al.	2005	Comparing CONWIP, synchronized CONWIP, and Kanban in complex supply chains	International Journal of Production Economics	Japan
58	Tardif, V., Maaseidvaag, L.	2001	An adaptive approach to controlling kanban system	European Journal of Operational Research	United States
59	Thomas, D.J., Griffin, P.M.	1996	Coordinated supply chain management	European Journal of Operational Research	United States
60	Van Dun, D. Et al.	2016	Values and behaviors of effective lean managers: Mixed-methods exploratory research	European Management Journal	Netherlands
61	Vidal, C.J., Goetschalckx, M.	1997	Strategic production-distribution models: A critical review with emphasis on global supply chain models	European Journal of Operational Research	Colombia
62	Wang, S., Sarker, B.R.	2006	Optimal models for a multi-stage supply chain system controlled by kanban under just-in-time philosophy	European Journal of Operational Research	United States
63	Wee, H.M., Wu, S.	2009	Lean supply chain and its effect on product cost and quality: A case study on Ford Motor Company	Supply Chain Management	Taiwan
64	Womack, J., Jones, D.	1997	Lean Thinking: Banish waste and create wealth in your comporation	Journal of the Operational Research Society	United States

4. Analysis of the current literature

4.1. Lean Management

Lean management is an approach to running an organization that supports the concept of continuous improvement. It is an ongoing effort to improve products, services, or processes, which require incremental improvement over time in order to increase efficiency and quality focusing on waste elimination (Lamming, 1996). Lean management is the approach of lean thinking implementation in the whole organization enhancing customer value through the elimination of non-value adding steps from work processes; it is do more with less.

The concept of lean originated in 1920s, when Henry ford applied the concept of “continuous flow” to the assembly-line process. This practice focused on cost reduction by improving quality and throughput. But it was three decades later when lean thinking took more importance and competitive advantage in the manufacturing with the Toyota Production System (TPS) during the 1950s (Ohno, 1988) with a clear emphasis on eliminating excess, muda (Japanese term that means “waste”) and unevenness in the supply chain in order to reduce costs and increase de value.

The first TPS can be found on the shop-floors of Toyota Motor Company during the 1950s (Shingo, 1981 and 1988; Monden 1983; Ohno 1988) with the implementation of just-in-time production system, the pull production managed with a kanban system and the high level of employees responsibility. During the next decade, 1960s, lean operations were extended to the vehicle assembly and the wider supply chain on the 1970s.

On this period, 1970s, the firsts papers about the lean concept applied on manufactures were produced in Japanese but it was not until the next decade when the first English literature was available (Shingo 1981 and 1988; Schonberger 1982; Hall 1983; Monden 1983; Ohno 1988, Sandras 1989). During these years, TPS has evolve to lean production in the 80s (Womack et al., 1990) and lean thinking in the 90s (Womack and Jones, 1996).

Lean is a systematic approach to enhancing value to the customer by identifying and eliminating waste through continuous improvement, by flowing the product at the pull of the customer, in pursuit of perfection. Taiichi Ohno identified seven types of waste, activities that add cost but no value, found in any process that will be discussed on the following sections.

Womack and Jones (1996) argue that a lean way of thinking allows companies to "specify value, line up value creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively." This statement leads to the five principles of lean thinking: value, value stream, flow, pull and perfection.

- **Specify Value:** Value can be defined only by the ultimate customer. Value is distorted by pre-existing organizations, especially engineers and experts. They add complexity of no interest to the customer.
- **Identify the Value Stream:** The Value Stream is all the actions needed to bring a product to the customer.
- **Flow:** Make the value-creating steps flow. Eliminate departments that execute a single-task process on large batches.
- **Pull:** Let the customer pull the product from you. Sell, one. Make one.
- **Pursue Perfection:** There is no end to the process of reducing time, space, cost and mistakes.

Figure 1. 5 Lean Principles (Womack and Jones, 1996)

In order to achieve lean objectives (improving efficiency, eliminating waste and enhancing customer value) and follow the lean principles (value, value stream, flow, pull and perfection) there are some techniques to apply that will be discussed on later sections. According to Shah and Ward (2003), lean techniques can be grouped in just-in-time (JIT), Total Productive Maintenance (TPM), Total Quality Management (TQM) and also, as Osterman (1995) and McDuffie (1995) introduced, in Human Resource Management (HRM).

4.2. Strategic and Tactical Lean Supply Chain Management

Before going further in detail about lean practices and techniques, the difference between strategic and tactical approach is discussed.

As it has been seen in section 2.1. Scope of analysis, the tactical approach is the way to achieve strategic decisions. In the supply chain framework, the strategic approach responses to how the supply chain is designed meanwhile the tactical approach is the way on how to manage this supply chain to achieve the desired design. Lean technics such as kanban, 5S, JIT or pull are placed in the tactical framework in order to achieve the strategic purposes.

Lean exists at two levels: strategic and operational. The customer-centred strategic thinking applies everywhere, whereas the shop-floor tools do not. Lean production must be used for the shop-floor tools following TPS, and lean thinking for the strategic value chain dimension (Argyris and Schon, 1978).

From a strategic point of view, many approaches and techniques can be applied without contradicting the core objective of lean – to provide customer value (Hines et al., 2004). Any concept that provides customer value can be in line with a lean strategy, even if lean production tools on the shop-floor, such as kanban, level scheduling, or take time, are not used.

To design a supply chain, many issues have to be taken into account besides from the physical design, the supply chain members, including the number of suppliers and customers at each level, the number of factories and warehouses. The design goes beyond that, the key decisions identified by members of the GSCF1 (Global Supply Chain Forum) are:

- **Customer relationship management (CRM):** How to manage and analyze customer interactions and data throughout the customer lifecycle, with the goal of improving business relationships with customers, assisting in customer retention and driving sales growth.
- **Customer service management:** How to provide the source of customer information. It becomes the key point of contact for administering the product/service agreement. Customer service provides the customer with real-time information on promised shipping dates and product availability.
- **Demand management:** How to balance the customer requirements with the firm's supply capabilities, forecast what and when customers will purchase
- **Order fulfilment:** How to integrate the firm's manufacturing, distribution and transportations plans. How to develop a continuous process from the suppliers to the organizations and from the organization to the customers.
- **Manufacturing flow management:** How the materials and the information flows through the company. In this section, it will be decided which kind of manufacturing management is going to be adopted: lean, agile or leagile (Stratton and Warburton, 2003). It will be also decided the Information Technology (IT) adopted.
- **Procurement process:** How to manage the relationship with the suppliers, log-term or short-term alliances, tiers of suppliers – a term taken from the Japanese *keiretsu* –, supplier organizations, strategic plans with suppliers to support the manufacturing flow management and developing new products.
- **Product development and commercialization:** It specially relates which kind of product should be developed and successfully launched to the market in order to remain competitive or open new marketplace

[1] The Global Supply Chain Forum (GSCF) is a group of non-competing firms and a team of academic researchers, they have meetings regularly with the objective to improve the theory and practice of SCM (Lambert and Cooper, 2000).

- **Returns process:** How to manage the returns generated by the supply chain. In some cases it could be an environmental issue, but not always, and it could contribute also to achieve competitive advantage.

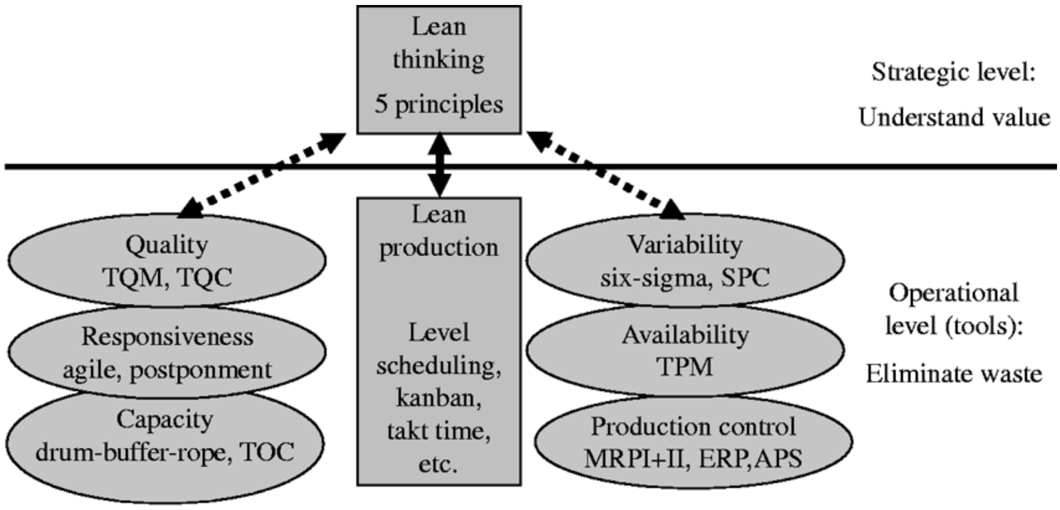
All of these decisions (Lambert and Cooper, 2000) are included on the strategic approach. The way to achieve these desires would be grouped in the tactical approach, operations are located on the tactical approach.

The phenomena of dependency and fluctuation are always present in any operating system (Goldratt, 1990) and they define the fundamental characteristics of production flow. These phenomena produce variation in the system and consequently, waste. With the aim to eliminate variation in the system and enabling flow, Toyota Production System is applied on lean supply chains improving customer services and efficiency.

There are a lot of lean techniques and it is not easy to elaborate a list since some of them are very global, others very specific and the scope is very wide.

There is a range of complimentary approaches that can be used in conjunction with lean. Hines et at. (2004) refers to the concepts considering production capacity, quality, responsiveness of the manufacturing system, demand variability, availability of production resources, and production control approaches. These concepts are not part of the lean production methodology, but can be used in support of a wider lean strategy appling lean techniques.

Figure 2. Lean - A framework. (Hines et al., 2004)



Beside of lean tools proposed by Hines et al. (2004) there are others proposed by Paul Myerson (2012) on the "Lean Supply Chain and Logistics Management" book: Single Minute Exchanges of Dies (SMED), Standardized work, 5S, JIT, continuous flow production, cross-docking, full truck load (FTL), pull system, kanban, Value Stream Mapping (VSM), Continue improvement or "kaizen", cellular manufacturing, Efficient Consumer Response (ECR), Electronic Data Interchange (EDI), Human Resource Management (HRM), cross functional work, production smoothing or heijunka in Japanese, etc.

4.3. Supply Chain Management Planning

4.3.1. Visibility Practices

Today's marketplace is characterized by turbulence and uncertainty. Consequently, the demand has become more volatile. During the last years, many companies have experienced a change in their supply chain due to changes in business strategies. It is caused by the globalization of the market, shorter and shorter product and technology life cycles, and the increased use of partners (manufacturing, distribution and logistics) resulting in complex international supply chain network. All these changes and uncertainties have contributed to the risk appearance, and a key element in any strategy designed to mitigate the risk is improved end-to-end visibility (Christopher et al., 2002). The only way to break the spiral of risk is to increase the confidence in the supply chain between partners.

A cornerstone to improve the supply chain visibility is by sharing information among supply chain members. Thanks to this, all members of the supply chain will have detailed knowledge of what goes on in other parts of the chain. As a consequence, the confidence in the supply chain work will increase.

If the information between supply chain members is shared, uncertainty is reduced and thus, the amount of safety stock is reduced (Christopher and Lee, 2004). Shared information is possible due to Information Technology (IT) which enhance inter-organizational integration and coordination through information systems (Patterson et al., 2003; White et al., 2005; Lin et al., 2006; Agarwal et al., 2007; Faisal et al., 2007; Liu et al., 2013; Rajaguru and Matanda, 2013). It promotes the practice of a collaborative supply chain through information system and continuous adjustments to the product lineup, sales reports and inventories (Qrunfleh and Tarafdar, 2012).

Figure 3. Cooperation relationship types (Mettler and Rohner, 2009)

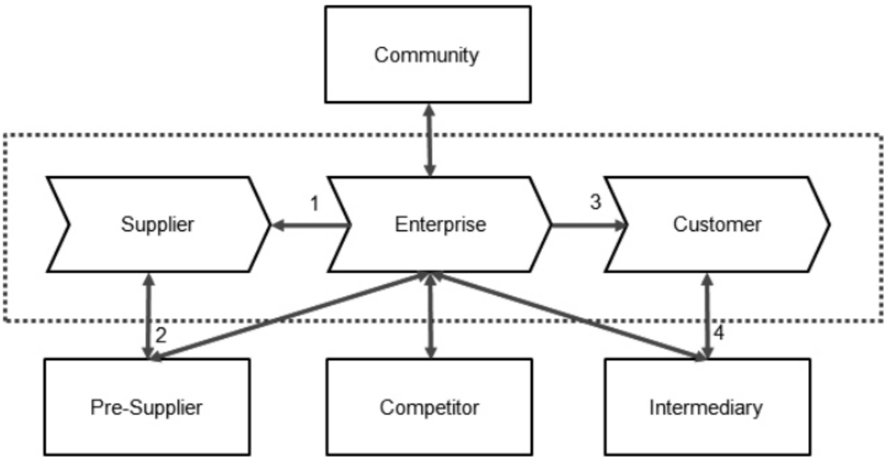


Figure 3 shows the relationship management approaches between customers and suppliers. Relation 1 and 2 are referred to the suppliers, if they are tier 1, the relation is known as Supplier Relationship Management (SRM) and otherwise as Supplier Network Management (SNM). Relations with customers are called Customer Relationship Management (CRM) if customers are tier 1 and their extensions are known as Pattern Relationship Management (PRM).

All these relations define how a company interacts with its suppliers and consumers. The objective is a common frame of reference to enable effective communication between an enterprise and suppliers who may use quite different business practices. As a result, these relations increase the efficiency of processes associated with acquiring goods and services, managing inventory and processing materials. The desired outcome is a win-win relationship where both parties get benefits (Mettler and Rohner, 2009).

Variability also depends on the supplier firms and it effects is transmitted downstream, when suppliers fail to deliver the right quantity or right quality at the right time or the right place. This variability can be managed by creating a dependable and involved supplier base that consists of a few key suppliers with long term contracts or partnerships. Common practices to limit supplier variability include providing regular feedback on quality and delivery performance and providing training and development for further improvement (Shah and Ward, 2007). To apply these practices is necessary an important and reliable confidence with these partners and usually CRM and SRM are applied to get more visibility of all the process, inventories, orders, costs, etc.

Information flow is closely related on developments in information technology that have provided new opportunities to improve the control of logistics by enable information shared between partners easily, without wastes and reliable. A collaborative platform provides a real time information exchange (Benjamin et al., 1990; Boyson et al., 2003) that allows for greater control over operations within the chain being able to see real demand (Barratt and Oliviera, 2001; Aviv, 2002; Croson and Donohue, 2003), how much inventory a customer is holding (Barratt and Oliveira, 2001; Aviv, 2002; Karkkainen, 2003; Petersen et al., 2005) or the movement of the products through the supply chain (Karkkainen, 2003; Prater et al. 2005) using for example, Radio Frequency Identification (RFID) - an e-tagging technology that can be used to provide electronic identity to any object -. All of this visibility between supply chain partners is possible using Electronic Data Interchange (EDI) that improves buyer-supplier relations.

There are some specific tools for enabling information sharing, which require IT services. To ensure a good quality of information flowing is essential to reach a good level of service and material flow with a focus on the final customer. Examples of it could be Efficient Consumer Response (ECR), Vendor Managed Inventory (VMI), Co-Managed Inventory, sharing Point-of-Sale (POS) data using a Collaborative Planning Forecasting and Replenishment (CPFR) (Lamming, 1996; Barratt and Oliveira, 2001; Aviv, 2002; Holmstrom et al., 2002). Partners collaborate with retailers using these techniques that allow enhancing close operation among autonomous partners engaged in joint efforts to meet end-customer needs (Faisal et al., 2007; Derrouiche et al., 2008).

CRM and SRM imply the use of IT to ensure the correct flow of information that has to be holistic, reliable and at the same time specific, the amount of information not needed is also consider a waste. It also implies focus the product on the final consumer (applying CRM) and their associated practices such as efficient or continuous replenishment to raise the product value. If these strategies are carried out with the practices discussed in this section, visibility will produce benefits on the supply chain. These benefits include improving responsiveness (Patterson et al., 2004), planning and replenishment capabilities (Karkkainen, 2003; Mentzer et al., 2004), improvements in marketing decisions (Kent and Mentzer 2003) and improving the quality of products (Armistead and Mapes, 1993).

4.3.2. Economic Order Quantity

Economic Order Quantity (EOQ) is a model to obtain the most economical quantity to be made or to purchase of each lot of a product so as to meet a demand that continuous over time at a rate constant to reduce the costs at minimum taking into account holding costs, ordering costs and purchase or production costs per unit. The production or purchase cost do not vary in function of the quantity ordered but the cost of carrying inventory increases with the lot size and otherwise, the average set-up cost per unit decrease with larger lots. Hence, the fundamental issue on EOQ models is the balancing of these two cost components (Schwarz, 2008; Erlenkotter, 2014).

Harris (1913) introduced the EOQ basic formula more than 100 years ago. Since then, a large number of papers have been written describing numerous variations of the basic EOQ model introducing new hypothesis and variables. Some examples can be the introduction of the uncertainty demand (Chang, 1999), imperfect products (Salameh et al., 2000; Mohamed, 2002; Lin et al., 2003; Chung et al., 2003; Lee, 2005; Chen et al., 2007) or the introduction of a delay in payments (Goyal, 1985; Aggarwal and Jaggi, 1995; Jamal et al., 1997; Liao et al., 2000; Chang et al., 2003; Mahata and Mahata, 2009). For a further review of variations of the basic EOQ model, see Brahimi et al (2006).

Harris (1913) presented a formula to calculate the whole cost per unit, the interest charge per piece plus the set up cost per piece plus the unit cost per piece:

$$Y(X) = C + \frac{S}{X} + \frac{1}{2 \cdot 12 \cdot M} \cdot (C \cdot X + S) \cdot I$$

Where:

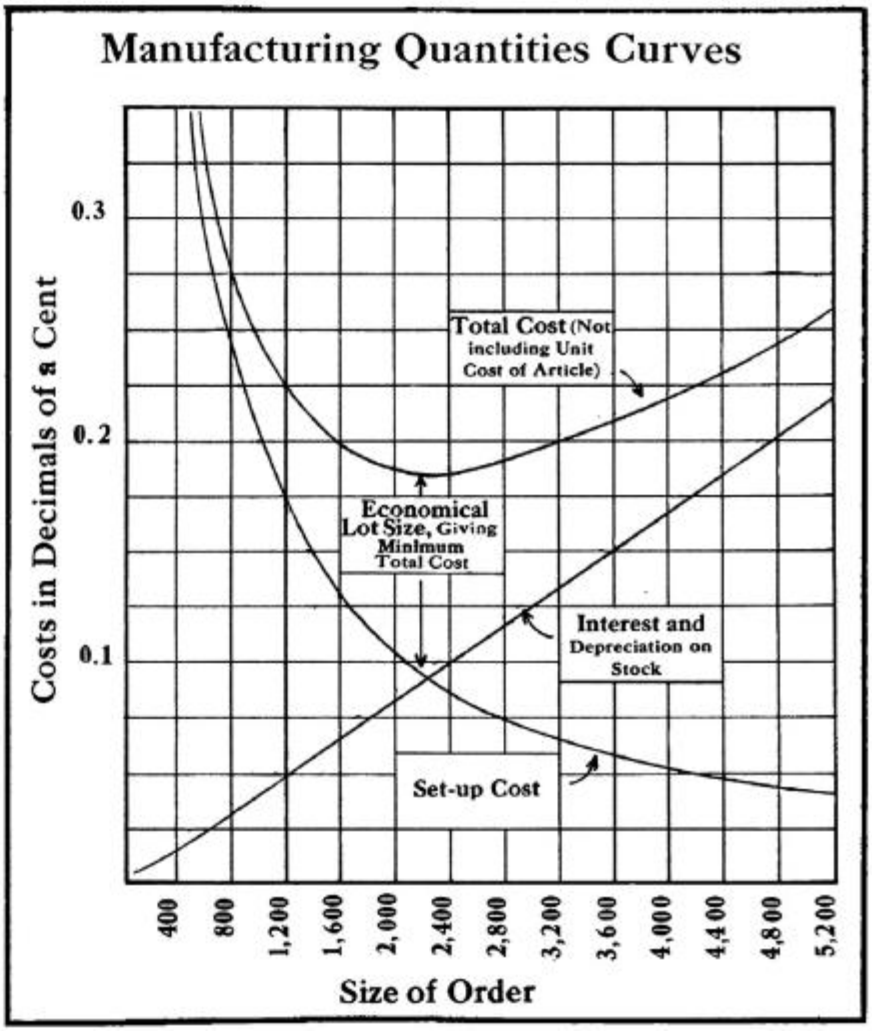
- $Y(X)$ = Whole cost per unit depends on the X.
- X = Size of order, lot size.
- C = Unit cost. Cost per unit of output under continuous production, without considering the set-up or the cost of carrying the stock after it is made.
- S = Set-up cost. Cost of getting the materials and tools ready to start work on an order, the cost of handling the order in the office and throughout the factory.
- M = Movement. Number of units used per month.
- I = Interest and depreciation on stock. Carrying a large stock means a lot of money tied up and a heavy depreciation.

Therefore, to find the value for X (lot size) that will give the minimum value to Y (cost per unit) is as simple as derivate the equation and balance it to zero getting:

$$X = \sqrt[2]{\frac{2 \cdot 12 \cdot M}{C \cdot I}}$$

As it can be seen in the equation to calculate the most economical lot size, the unit cost does not affect to the result and therefore, we could omit this variable as it was done on the figure 4.

Figure 4. Manufacturing Quantities Curves (Harris, 1913)



An increase in the size of the order results in an increased interest charge and a decreased set-up cost per unit and otherwise. There is only one possible solution to get the minimum cost on the EOQ model and coincide with the intersection between the interest and depreciation cost on stock and the set-up cost function.

On the basis of this work and equations extracted, other similar equation have been developed adding new variables for more complicated environments or just to change the meaning of the variables used for others. Many authors tend to use a variable which indicates the cost of storing one unit for a period time (Wang et al., 2007; Chang, 1999; Chang et al., 2003; Chen et al., 2007; Schwarz, 2008) that is simply the cost of production and getting one unit of production multiplied by the interest and depreciation on stock of the items.

$$h = \left(C + \frac{S}{X}\right) \cdot I$$

Where:

- h = Cost of storing one unit per unit time.

In addition, instead of using the concept of movement that is the monthly demand, we will use the variable of demand per year.

$$12 \cdot M = D$$

Where:

- D = Total demand quantity per year.

Other common differences with more recently literature are the abbreviation of some variables. The lot size is to tend to be named as Q instead of X to represent the quantity of units to produce or purchase per order. As well as, the set-up cost will be named as K instead of S.

Applying these two changes, the equation of cost per unit will be:

$$Y_{unit}(Q) = C + \frac{K}{Q} + \frac{h \cdot Q}{2 \cdot D}$$

And the total cost per ear is as simple as multiply the previous equation by the yearly demand:

$$Y_{total\ year}(Q) = C \cdot D + \frac{K \cdot D}{Q} + \frac{h \cdot Q}{2}$$

To apply the EOQ basic model, many unrealistic assumptions must be made. The most unrealistic of thee is that the demand rate is known and constant over the time period analyzed. Others assumptions not at all realistic are estimate the value of the fixed order cost (K) and the inventory holding costs (h), or what is equivalent, the interests and depreciation cost (I) (Schwarz, 2008). As more we are able to control these parameters as constant and know, the better are the results obtained with the EOQ model.

4.4. Lean Supply Chain Planning

4.4.1. Lean, Agile and Leagile Supply Chain

According to Stratton and Warburton (2003), lean supply is closely with enabling flow and the elimination of wasteful variation within the supply chain. However, lean operations depend on level scheduling and the growing need to accommodate variety and demand uncertainty has resulted in the emergence of the concept of agility.

The terms lean and agile supply have emerged to reflect the distinctions between stable functional products competing on price (lean) and volatile fashion or innovative products dependent on fast response (agile) (Fisher, 1997; Feitzinger and Lee, 1997). Various hybrids systems have been defined to clarify means and ways of, at least partially, satisfying the conflicting requirements of low cost and fast response (Mason-Jones et al., 2000; Christopher and Towill, 2000). Lean and agile paradigms can be and have been combined within successfully designed and operated total supply chains. Agility and leanness depend upon the total supply chain strategy, particularly by considering market knowledge and positioning of the decoupling point (Naylor et al. 1999).

The effect of dependency and fluctuation on lean and agile supply chains

In any operating system, there exists the phenomena of dependency and fluctuation (Goldratt, 1990) and when these are combined in delivery system, they define the fundamental characteristics of production flow, which may be viewed at the factory or supply chain level. There is always variation in the system due to various factors, such as machines failures, set-up delays, process adjustment, quality problems, etc. If we now acknowledge the existence of these fluctuations, not only will the disruption directly affect the event concerned, but more importantly, there will also be a knock-on effect down the line of dependency.

The traditional means of overcoming this is to place inventory between each process, so effectively decoupling the impact of the fluctuations. An alternative to investing in inventory to protect the flow under these conditions is investing in additional capacity (Stratton and Warburton, 2003).

Once introduced the dependency, fluctuation, capacity and inventory concepts, we will relate them to lean and agile strategies.

With lean manufacturing, the excess inventory level is viewed as a waste and it is reduced to the point where the remaining inventory levels act to smooth out the effect of various source of fluctuations. The target is detected and eliminate as much as possible the sources of fluctuations. If we are capable to control wasteful system fluctuations in the form of process variation, set-up delays, plant reliability, etc., the inventory will faced only to prevent the impact of demand variation on the supply chain (Stratton and Warburton, 2003). Figure 5 illustrates the lean system operating with low levels of variation and internal inventory, but potential high inventory levels of final goods to react to variations in market demands.

Figure 5. Lean supply viewed in terms of dependency, fluctuation, protective capacity (PC) and protective inventory (PI). (Stratton and Warburton, 2003)

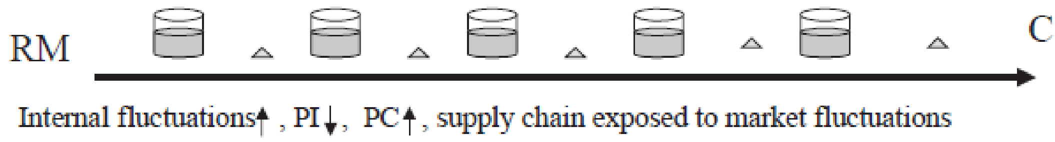
Agile manufacturing represents a broad business concept which may be defines by Gould (1997) as “the ability of an enterprise to thrive in an environment of rapid and unpredictable change”. In the case of agile supply chain, there are two major distinctions (Stratton and Warburton, 2003) which are represented in table 2.

(1) The non-standard nature of the product will inherently result in higher levels of internal fluctuation. It is common with low volume, high variety manufacture, which is inevitably more susceptible to internal variation and a mixture of protective inventory and protective capacity enables flow.

(2) The unstable nature of market demand precludes the effective use of finished stock inventory to decouple the supply system. It limits the effective use of inventory and hence emphasizes the role of protective capacity.

In this case, the reaction in front of demand variations is done managing the capacity level, the wastes are higher because the supply chain is not working at full capacity but the reaction is more instantaneous and the production can follow demand requirements.

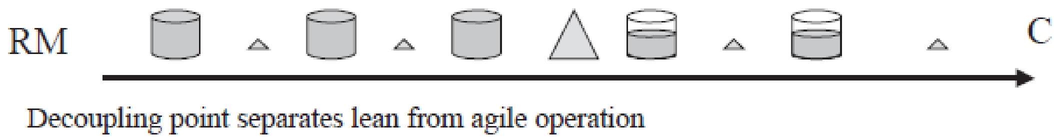
Figure 6. Agile supply viewed in terms of dependency, fluctuation, protective capacity (PC) and protective inventory (PI). (Stratton and Warburton, 2003)



The agile manufacturing paradigm is best suited to satisfying a fluctuating demand (in terms of volume and variety) and lean manufacturing requires, and promotes, a level schedule (Naylor et al. 1999).

Finally, another possibility is integrating lean and agile strategies on the same supply chain, this concept is known as leagile. The decoupling point separated two parts of the organization, one of them applying lean manufacturing upstream with common components, or modules and the other one downstream applying agile manufacturing achieving product differentiation desired by the customers.

Figure 7. Leagile supply viewed in terms of dependency, fluctuation, protective capacity (PC) and protective inventory (PI). (Stratton and Warburton, 2003)



Once we know the differences between lean and agile paradigms, we will discuss about how to build them as well as leagile one. As it has been said in section *2.1. Scope of analysis*, key points related to this is the marketplace understanding and the position of the decoupling point.

Marketplace understanding for lean and agile paradigms

Customer satisfaction and marketplace understanding are crucial elements for consideration when attempting to establish a new supply chain strategy. Only when the constraints of the marketplace are understood can an enterprise attempt to develop a strategy that will meet the needs of both the supply chain and the end consumer (Mason-Hones et al., 2000).

Understanding the marketplace and fit the supply chain to the demand is closely related to forecasting the demand. There are some cases in which the forecasting demand is very accurate and reliable but not in other cases when the demand is very variable and unpredictable, forecast accuracy has an important role to decide which kind of strategy is more suitable to the supply chain. The accuracy forecasting the demand depends also on how in advance it must be calculated to begin production orders.

Agile supply is closely associated with quick response and it is focused on the need to deliver a variety of products with uncertainty demand, meanwhile lean supply is focused on eliminating waste and achieving low cost delivery (Mason-Hones et al., 2000; Stratton and Warburton, 2003).

If there are a wide variety of products an agile supply chain will be able to switch between the products easily. If there is a wide range of products then the demand will tend to become more variable at a disaggregate level. Due to these aims, agile is more appropriate to new, innovative and fashion products with unstable demand and short life cycles whereas lean strategy is more suitable for standard products with stable demand and large life cycles. However, in some situations it is advisable to utilize a different paradigm on either side of the decoupling point to enable a total supply chain strategy; this approach is known as leagile paradigm (Mason-Hones et al., 2000).

Depending on the company and their objectives, products offered and the marketplace stability, strategy lean or agile would be better or more suitable than the other.

Table 2. The demand-product matrix for agile and lean supply (Stratton and Yusuf, 2000).

		Demand	
		Volatile	Stable
Product	Special	**AGILE**	
	Standard		**LEAN**

The decoupling point on lean, agile and leagile supply chains

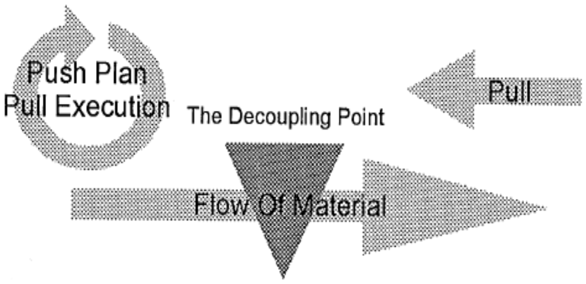
The use of lean and agile manufacturing has to be combined with a total supply chain particularly considering market knowledge as it was discussed in the section before and positioning of the decoupling point (Naylor et at. 1999).

The decoupling point separates the part of the organization oriented towards customer orders from the part of the organization based on planning (Hoekstra and Romme, 1992). The decoupling point is also the point at which strategic stock is often held as a buffer between smooth production output (lean) and fluctuating customer orders and/or product variety (agile). This fact is critical when considering when to adopt lean manufacturing upstream of the decoupling point and agile manufacturing downstream. The postponement of the decoupling point is interested in order to increase the efficiency of the supply chain by moving product differentiation closer to the end user and it also reduced the risk of being out of stock for long periods at the retailer and of holding too much stock of products that are not required (Naylor et at. 1999).

The decoupling point separates the part of the supply chain that responds directly to the customer from the part of the supply chain that uses forward planning and a strategic stock to buffer against the variability in the demand of the supply chain. Then, this process is push planned and pull executed (Berry, 1994). Downstream from the decoupling point all products are pulled by the end-user, that is, they are market driven.

The aim is to deliver standardized or functional products and systems to the decoupling point as sub-assemblies and to configure them as an when the customer order is received (Naim and Barlow, 2003).

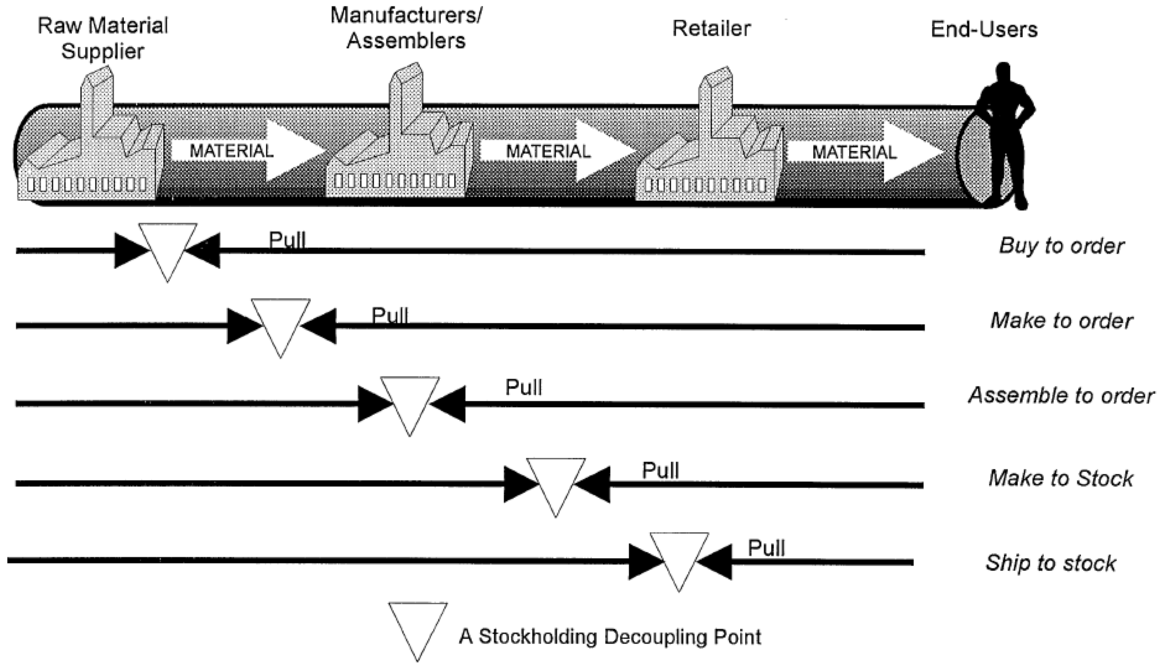
Figure 8. Managing at each side of the decoupling point (Naylor et al., 1999)



The positioning of the decoupling point depends upon the longest lead time an end-user is prepared to tolerate and the point at which variability in product demand dominates (Lehtonen et al., 1996).

Hoekstra and Romme (1992) identified five distinguishing classes of supply chain depending on the position of the decoupling point:

Figure 9. Supply chain strategies (Hoekstra and Romme, 1992)



The final two supply chain strategies represent cases where a standard product in provided from a defined range. The members of the supply chain must be able to forecast demand accurately if they adopt these two strategies. It is critical that they are aware how accurate their forecasts are and hold the correct level of stock to minimize the risk of stock-outs and overstocks (Fisher et al., 1994).

At the other extreme, we have the 'buy to order/make to order' supply chains, which are potential strategies for the customized product. There is no risk of stock obsolescence as the product is configured to customer requirements from the start of value adding operations undertaken on the raw materials. The major disadvantage is the potentially protracted lead-time before the consumer is in receipt of the finished goods (Nain and Barlow, 2003).

As it can be intuit, moving the decoupling point, supply chain can be more lean than agile or contrary. If the decoupling point is in the beginning of the supply chain, it is agile and otherwise, if the decoupling point is situated at the end of the supply chain, we are talking about a lean paradigm.

Figure 10. Effects of the decoupling point (Naylor et al., 1999)

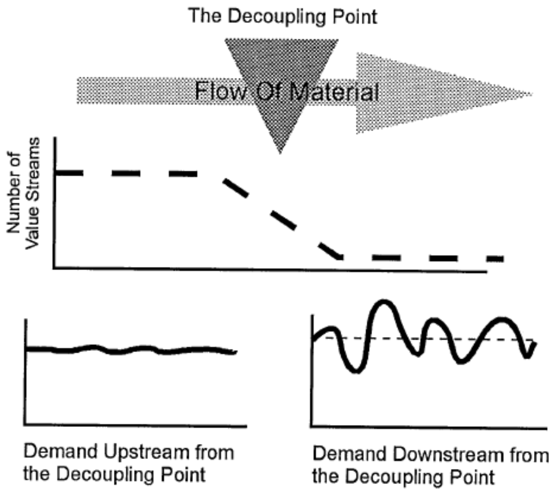


Figure 10 shows the demand variability at each side of the decoupling point as well as the number of value streams at each side. Lean paradigm can be applied upstream of the decoupling point as the demand is smooth, variety is reduced and standard products flow through a number of value streams. The agile paradigm must be applied downstream from the decoupling point as demand is variable with a large variety of products and the number of products flow through one value stream.

Differences between lean and agile supply chains

Based on the work of J.B. Naylor et al. (1999), three characteristics are the foundations for both lean and agile manufacturing, without which it will not be possible to develop either paradigm any further. These three foundations are:

- **Use of market knowledge:** All businesses in any supply chain must focus on the end-user and both paradigms emphasize this point (Kidd, 1995; Womack et al., 1990). The nature of the end-user or market sector as a whole will have a direct impact upon which paradigm will be the most suitable for any supply chain or part of a supply chain. If market knowledge is not exploited it can drive to high costs of overstocking or losing demand.
- **Integrated supply chain / value stream / virtual corporation:** Businesses must work together to form an integrated supply chain focusing on meeting the demands of the end-user or final customer of the supply chain no matter what paradigm is adopted (Towill, 1997). The goal of an integrated supply chain is

to remove all boundaries to simplify the flow of material, cash, resources and information, streamlined and optimized reducing waste and lead times.

- **Lead time compression:** Leanness calls for the elimination of all waste. This means the elimination of anything that is not adding value to a process or service and it includes waste time. Therefore, time compression is essential for lean manufacturing. Likewise agile manufacturing requires a responsive supply chain (Kidd, 1995). This also calls for lead time compression in terms of information flow as well as material flow (Mason-Jones and Towill, 1997).

There are other characteristics with similar importance for both paradigms but not the same:

- **Eliminate waste:** Lean manufacturing uses less, or the minimum, of everything required to produce a product or perform a service (Hayes and Pisano, 1994). Leanness achieves this by eliminating all non-value adding processes (Womack et al., 1990) to reduce the cost of the products. In a "pure" lean supply chain there would be no slack and zero inventory, a more realistic view would be to aim at a Minimum Reasonable Inventory (MRI) where any further attempts to decrease stocks would not be worthwhile (Grünwald and Fortuin, 1992) and the appropriate MRI level may be found by using market knowledge. Quite clearly the agile manufacturer would also aim to eliminate as many non-value adding activities as possible. However, in an agile system there will have to be a careful consideration of stock and/or capacity requirements to ensure the supply chain is robust to changes in the end users' requirements.
- **Rapid reconfiguration:** Agile manufacturing means that the production process must be able to respond quickly to changes in information from the market (Goldman et al., 1994). This requires lead time compression in terms of flow of information and material and the ability to change to a wide variety of products (Kidd, 1995). Therefore, the ability to rapidly reconfigure the production process is essential. In lean manufacturing the ability to change products quickly is also a cornerstone to avoid waste (*muda*) and therefore should be eliminated. However there must be a certain amount of leeway with respect to the production schedule and the forewarning of product changes in

order to eliminate waste (Harrison, 1995). Thus whilst it is highly desirable to have rapid reconfiguration it is not as essential as with agile manufacturing.

Agile manufacturing calls for a high level of rapid reconfiguration and will eliminate as much waste as possible but does not emphasize the elimination of all waste as a prerequisite. Lean manufacturing states that all non-value adding activities, or *muda*, must be eliminated. The supply chain will be as flexible as possible but flexibility is not a prerequisite to be lean.

Finally, two characteristics essentials for one of both paradigms and not important for the other:

- **Robustness:** An agile manufacturer must be able to withstand variations and disturbances and indeed must be in a position to take advantage of these fluctuations to maximize their profits. If a manufacturer needs to be as responsive as a truly agile manufacturer must be then it is inevitable that the demand for the product will not be stable.
- **Smooth demand / level scheduling:** Lean manufacturing avoids the requirement for robustness by calling for the demand to be stable through the use of market knowledge and information, and forward planning (Harrison, 1995). Lean manufacturing by its very nature tends to reduce demand variation by simplifying, optimizing and streamlining the supply chain (Stevens, 1989). Sudden variations in demand would lead to waste either in not producing near capacity or needing to keep larger buffer stocks.

Table 3 shows a resume of distinguishing attributes between agile and lean supply according to Mason-Jones et al., (2000) that have been seen in this section *4.4.1. Lean, Agile and Leagile Supply Chain*.

Table 3. Comparison of lean and agile supply. The distinguishing attributes (Mason-Jones et al., 2000)

Distinguishing attributes	Lean supply	Agile supply
Typical product	Commodities	Fashion goods
Marketplace demand	Predictable	Volatile
Product variety	Low	High
Product life cycle	Long	Short
Customer drivers	Cost	Availability
Profit margin	Low	High

Dominant costs	Physical costs	Marketability costs
Stock-out penalties	Long term contractual	Immediate and volatile
Purchasing policy	Buy goods	Assign capacity
Information enrichment	Highly desirable	Obligatory
Forecasting mechanism	Algorithmic	Consultative

4.4.2. Lean Supply Chain

Lean approach is generally described from two points of view, either from a philosophical perspective related to guiding principles and overarching goals (Womack and Jones, 1996; Spear and Bowen, 1999) or from a practical perspective of a set of managing practices, tools or techniques that can be observed directly (Shah and Ward, 2003; Li et al., 2005). Argyris and Schon (1978) therefore encourage the use of lean production for the shop-floor tools to increase business competiveness by systematically eliminating waste of all kinds (Callen et al. 2000) following Toyota's example, and lean thinking for the strategic value chain dimension. This section is focused on the practical perspective of lean applied to the whole supply chain.

This section deal with lean supply chain that consist on apply lean concept among the supply chain, not only on the manufacturing but also on the relations between suppliers and customers as well as the transportation and information flow.

General lean supply chain concepts

Lean supply chain is a network of entities (suppliers, carriers, manufacturing sites, distribution centers, retailers, and customers) linked directly upstream and downstream of the core business through which material and information flow continuously that work to reduce waste by efficiently pulling and reducing the effects of variability related to supply, processing time or demand through continuous improvement and enhancing value to the customer (Lummus and Alber, 1997; Shah and Ward, 2007).

Waste is as anything beyond the strict minimum needed by way of equipment, materials, components, effort, space or worker time in order to give added value to the goods produced (Marín and Delgado, 2000; Suzaki, 2000). In order to eliminate it, firms must know the importance of continuous improvement process, processing and set-up times and batch sizes. These actions are basic to the set of techniques that are known as "lean production". Furthermore, lean supply chains include not only lean production but also the activities of "lean product development, lean procurement and lean distribution (Jackson and Dyer, 1998; Karlsson and Ahlström, 1996; Martínez and Pérez, 2001).

In section 4.4.1 *Lean, Agile and Leagile Supply Chain*, subsection "*The effect of dependency and fluctuation on lean and agile supply chains"* has been seen the importance of variability and the best conditions to apply lean paradigm in terms of the marketplace.

Also, in section 4.4.1 *Lean, Agile and Leagile Supply Chain*, subsection "*Differences between lean and agile supply chains"*, lean characteristics were discussed such as the importance of the market knowledge, value stream, lead time compression, elimination of wastes and satisfy the level schedule.

Lean production or manufacturing

In order to implement lean manufacturing and maximizing value stream focused on customers, it is necessary to identify the sources of waste. Tichii Ohno defined seven common forms of waste, activities that add cost but no value: production of goods not yet ordered (overproduction); waiting; rectification of mistakes (defects); excess processing (processing or over-processing); excess movement (motion); excess transport (transportation); and excess stock (inventory). (Ng et al., 2010).

- **Overproduction:** creating more work than is required by the next step or making it too early. This is usually because of working with oversize batches, long lead times, poor supplier relations or bad forecasts.
- **Waiting:** time spent waiting for the next step in the process to occur. The waste of waiting disrupts flow which is one of the main principles of lean manufacturing. If there is waiting, the capability decrease.
- **Defects:** reworking or scrapping work that has already been done. Defective items require rework or replacement, it wastes resources and materials and it also can lead to lost customers.

- **Processing:** non-value added work step. One of the main principles of lean manufacturing is eliminate non-value added processes.
- **Motion:** extra steps for the worker or excessive machine movements. Then, the capability is not as higher as possible.
- **Transportation:** moving materials around unnecessary. Transportation does not add value to the products and consequently has to be minimized.
- **Inventory:** excessive stockpiling of materials. Raw materials, work in process and finished goods in stock have a cost associated to the warehousing, space is required and they can be damaged or even become obsolete.

As it was discussed previously, the main objective of lean production is to eliminate waste by reducing or minimizing variability related to supply, processing time, and demand to achieve lean production and minimize wastes (Hopp and Spearman, 2004; De Treville and Antonakis, 2006). Similarly, Shah and Ward (2007) proposed the following definition to capture the many facets of lean production:

“Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer and internal variability.”

On lean production three or four “bundles” associated with practices can be identified depending on the authors: JIT, TQM and TPM (Cua et al., 2001; Katayama and Bennett, 1996; Sakakibara et al., 1997) and also HRM or workforce management (Monden, 1983; Shah and Ward, 2003).

- **JIT:** The primary goal of just-in-time is the continuous reducing and ultimately elimination of all forms of waste (Sugimori et al., 1977). In this bundle are included all practices related to production flow in order to face on two major forms of waste such as work-in-progress (WIP), inventory, and unnecessary delays in flow time. WIP inventory can be reduced implementing practices related to production flow such as lot size reduction, cycling time reduction, kanban system and quick changeover techniques (the principle technique to change-over reduction is the SMED system) and otherwise implementing cellular layout, reengineering production processes and bottleneck removal to reduce unnecessary delays in the production process (Schonberger, 1986; Harrison, 1992; Shah and Ward, 2003).

- **TQM:** All practices related to continuous improvement and sustainability of quality products and process are included in the bundle of Total Quality Management. It includes practices such as quality management programs, formal continuous improvement program, Total Quality Control (TQC) (Shah and Ward, 2003) and tools such as Statistical Process Control (SPC), 5S, the 5 whys of Ishikawa and Six Sigma.
- **TPM:** Total Productive Maintenance bundle includes practices primarily designed to maximize equipment effectiveness through planned predictive and preventive maintenance of the equipment and using maintenance optimization techniques. More generally, emphasis on maintenance may also be reflected by the emphasis given to new process equipment or technology acquisition (Cua et al., 2001).
- **HRM:** The most commonly cited practices on Human Resource Management bundle are job rotation, job design, job enlargement, formal training programs, cross-training programs, work teams, problems solving groups, employee involvement and self-directed work teams (Ichniowski et al., 1994; McDuffie, 1995; Osterman, 1994).

Jackson and Dyer (1998) conclude on their job that JIT improves lead time and reduces inventories, whereas HRM, TQM and TPM improve quality and lead time. Ohno (1988) introduced kanban to maintain JIT production pulling materials from upstream stations managing product flow; pull system and specifically kanban system is one of the most essential techniques for all systems that follow TPS. Other critical components of JIT are production smoothing, set up reductions (Sugimori et al., 1977) and also quality improvement and employee involvement (Hall, 1987; McLachlin, 1997) and customer focus (Flynn et al., 1995).

Sources of variation internal to the supply chain are progressively reduced applying SPC, TPM and also standardize work reducing the need for the inventory previously used to protect the flow (Stratton and Warburton, 2003). Applying these practices, the system is controlled statistically and easily to identify abnormal behaviors, furthermore, the system becomes more robust and consequently the variations in the process decrease. There are also other practices and tools to minimize process time variability. For example, a stringent quality control reduces rework and results in less variability in process time or cross-trained employees are able to step in for absent employees without disrupting flow, quality, and quantity of work. To face on demand variability, takt-time tool is usually used in lean production, a measure of the time to produce on item depending on the amount of demand and production smoothing to adapt the changing demand producing intermediate goods at a constant rate (Monden, 1983).

As it has been said, the main principle in lean approach is the reduction, or elimination if possible, of all kinds of wastes and all that does not add-value to the product is known as waste. To achieve this propose the Value Stream Mapping (VSM) implementation is essential. It is a lean supply chain tool to identify wasteful and unnecessary activities classifying the activities into value added (VA) and non-value added (NVA) based on a Current State Map (CSM). Activities that do not add value to the product are considered waste in the value stream chain and consequently, they must be eliminated, the target to focus on and try to achieve is known as Future State Map (FSM) (Bicheno, 1991; Modaress et al. 2005; Wee and Wu, 2009).

As it has been discuss in this section, lean supply chain is a multi-dimensional approach that include a wide variety of tools and management practices. These practices can work synergistically to create a streamlined, high quality and high efficient system that produces finished goods at a production rate adjusted to the demand with little or no waste (Cua et al., 2001; White and Prybutok, 2001; Fullerton and McWatters, 2001; Shah and Ward, 2003;). Then, the benefits are higher when some lean practices are introduced at the same time or sequentially. Among the benefits most often mentioned are stock reduction, quality improvement, greater productivity and shorter lead time.

Lean measures focused on suppliers and customers' relationship

A supply chain is formed by a group of entities and activities that are usually independent of one other and linked through which material and information flow.

These autonomous activities create wastes on costs and time that have to be identified and eliminated by lean adopters of the supply chain working together in order to bring greater value. A lean supply chain should provide a flow of goods, services and technology from suppliers to customers and in the other direction if necessary as well as a good information flow in both directions (Lamming, 1996).

The physical part of these relationships is the transport and according to lean principles, non-value added activities must be eliminated to increase the efficiency and minimize costs. Logistics managers can usually choose between two different shipping models, full truck loads (FTL) or less than truck loads (LTL) (Crainic, 1999). Using FTL shipping, the quantity of goods to be delivered is near to the truck capacity and the truck capacity is actually saturated, this results in the lowest cost per tone or item. Otherwise, in LTL shipping, only a fraction of the truck is used for the transport of goods and the cost associated to each item is inversely proportionate to the amount of material transported (Caputo et al., 2006). If only transportation is taken into account, FTL shipment is more economically, the cost of transport is not related to the value of goods carried on the trucks, the cost of transport air is the same that the cost of transport materials. As more items are transported, lower cost is associated to each item. An activity associated with logistics and transport is the replenishment. This is another activity which takes part of the supply chain and it must be as efficient as possible reducing the waste if lean approach is applied. Some practices related to lean replenishment are aligned with visibility practices such as vendor managed inventory (VMI), co-managed inventory or point-of-sale (POS) to connect the costumer and the organization to achieve common benefits in terms of cost, these practices are efficient replenishment, continuous replenishment and cross-docking (Lamming, 1996) which is a practice of unloading materials from an incoming truck (or other vehicles) and loading these materials into outbound truck (or other vehicles) with little or no storage between in order to do not have inventory or minimize it. To be able to carry out these practices, the communication between both parts of the supply chain is essential.

Flows between the different entities of the supply chain depend on the relationship between both organizations affected by the level and type of power which one exercise to the other (Ramsay, 1995). There are evidences (Mason-Jones and Towill, 1997 and 1998) of benefits with close relationships between customers, suppliers and other relevant partners, sometimes called partnerships.

According to Shah and Ward (2007) conclusions and related to the customers and suppliers relationship, the measures to dictate how good a supply chain in terms of lean are:

- **Supplier feedback:** provide regular feedback to suppliers about their performance.
- **JIT delivery by suppliers:** ensures that suppliers deliver the right quantity at the right time.
- **Supplier development:** develop suppliers so they can be more involved in the production process of the focal firm.
- **Customer involvement:** focus on a firm's customers and their needs.

Using techniques described in section *4.3.2. Visibility Practices*, information flow is much more effective to apply the measures described above by Shah and Ward (2007) and consequently the wastes are reduced since the communication is more efficient using common information canals. Concretely, these are the aims of the lean approach, the reduction of wastes eliminating the different sources of variability as non-added value activities in order to increase the efficiency of the process.

4.4.3. Kanban System

The kanban system is a multi-stage production scheduling, supply components and inventory controlling system based on pulling and employed to assist in linking different production processes in a supply chain system to implement the scope of JIT to ensure that the delivery of necessary amount of material and parts at the appropriate time and place. It is a subsystem of the TPS and motivated by the concept of just-in-time production which aims to reducing the level of inventory to a minimum. In the same direction, Kanban system has become identified as one of the most characteristic element of just-in-time (Bitran, Chang, 1987; Deleersnyder et al., 1989; Tardif, Maaseidvaag, 2001; Wang, Sarker, 2004; Lage, Godinho, 2010).

Kanban plays an important role in the information and material flows in a supply chain system (Wang, Sarker, 2004) and according to Graves et al. (1995), kanban is a Material Flow Control (MFC) mechanism which controls the proper quantity and proper time of the production of necessary products.

It is originally designed by Toyota to realize JIT production to keep a tight control over inventory and specifically created for each company to fulfil specific needs to force the hidden problems to surface so that they can be identified and addressed directly, i.e. work effectively under specific production and market condition (Bitran, Chang, 1987; Lage, Godinho, 2010).

Kanban characteristics

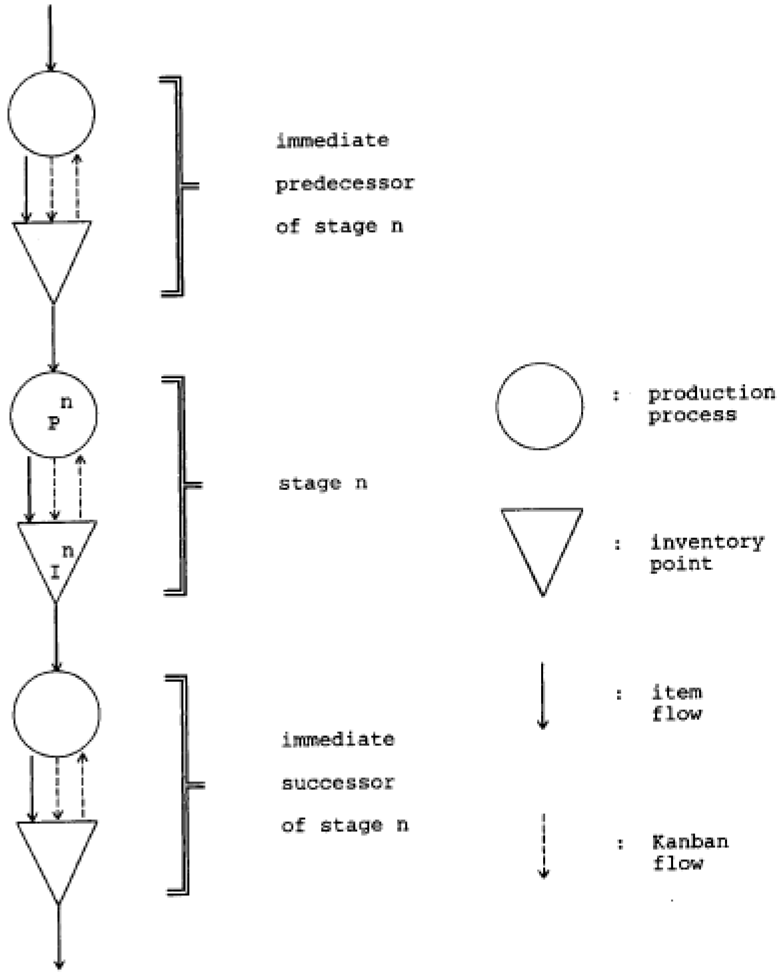
Kanban system is designed to use small transfer batches of standard size which create an efficient and regular flow of materials, hence to prevent problem about obsolete stock that cannot be sold (Burbidge, 1996; Riezebos et al., 2009).

The original Kanban characteristics based on the Kanban system used at Toyota Motor Company are US, PP, DC, LI:

- Use of two communication signals (US): production signals and transportation signals which authorize production or transportation respectively.
- Pull production (PP): the production is pulled based on the inventory level or the scheduling of the last station.
- Decentralized control (DC): the control of the production flow is performed through visual control by the employees of each step of the production process.
- Limited WIP (LI): the inventory level is limited in each workstation, which means, finite buffer capacity depending on the number of signals.

As it was said before, Kanban is a pull system where the order came from downstream to upstream while the products and goods go to the final consumption downstream.

Figure 11. A serial production model with flows of material, information and kanbans (Bitran and Chang, 1987)



According to Bitran and Chang (1987), the Kanban system tends to absorb and adapt to uncertainties, in demand and production, without requiring continued management intervention. In this work, four important issues regarding to the functionality of the Kanban system were found:

1. The total number of kanbans circulating on each loop between the production process and buffer or between the buffer and production process is unchanged over time.
2. The maximum inventory build-up in the inventory buffer depends on the number of kanbans circulating.
3. The movement of kanbans between the production stage and the buffer is triggered by the immediate successor inventory withdrawal.

4. All the stages in a production setting are chained together. Therefore, the production schedule of the final stage is transmitted back to all the upstream stages.

According to Sepheri (1986) and Deleersnyder et al. (1989), the shop floor must be a cellular layout with the aim to achieve flow lines operating around product families with good levels of utilization but with a minimal extra investment. One of the key issues to have exit on Kanban implementation is set a good flowline loading that involve the allocation of a viable number of work to each flowline in order to avoid bottlenecks developing.

The kanban function is to control the interaction between production and inventory levels. To achieve this control, the key variable is the number of kanbans to be used in each buffer-production and production-buffer loop (Deleersnyder et al., 1989). There are many papers focused on to study the behavior of the system depending on the number of kanbans and to find the most adequate number of kanbans in a system such as Bitran and Chang (1987), Deleersnyder et al. (1989), Berkley (1996), Yavuz and Satir (1995), Ohno et al. (1995), Chan (2001), Wang and Sarker (2004), Rabbani et al. (2009) or Hou and Hu (2011). Further details can be found on Monti and Paolo (2016).

Despite there are many studies in that direction, all of them can be agree that the number of kanbans needed to transport the batches in each stage can be determined considering the demand or the number of batches that has to be shipped by the kanbans and knowing the delivering time and loading/unloading time needed (Wang, Sarker, 2004). Similar to this, all of the authors are agree with the following formula proposed by Toyota to determine the number of kanbans needed:

$$nk = \frac{dem_{day} \cdot (t_w + t_{pc})}{k} \cdot s$$

Where:

- nk = number of kanbans
- dem_{day} = medium daily demand
- t_w = waiting time for the container

- t_{pc} = processing time of the pieces of one container
- k = batch size of the container
- s = security factor

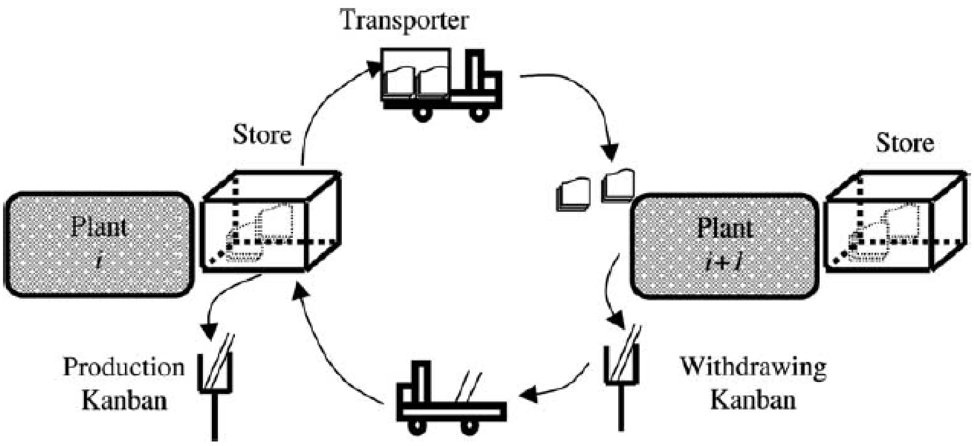
Since the number of kanbans in each loop is constant over time and Kanban system is created to fulfil specific needs of a company, the conditions are different for all organizations and it is difficult variate the conditions of the system. Therefore, Kanban has some variants than can be found at the end of this chapter and some restrictions to be implemented (Ohno, 1982; Monden, 1983; Aggarwal 1985; Grünwald et al., 1989; Sipper and Bulfin, 1997); it is not adequate in situations with unstable demand, processing time instability, non-standardized operations, long setup times, great variety of items neither with row material supply uncertainty.

How kanban works

Kanban is a Japanese word that means card, which control the flow of the containers with materials through the production process. Each container has a card or kanban attached with the necessary information to process their materials. This information usually includes item number and name, description of the item, container type, quantity of pieces per container, kanban identification number and preceding and succeeding stage (Bitran, Chang, 1987; Wang, Sarker, 2004).

The traditional Kanban system uses two communication signals, two different types of kanban, production kanban signal and transportation or withdrawal kanban signal. When finished products are needed at any stage, the production kanbans start to circulate upstream to enable the production of a fixed number of products. Otherwise, when row materials or products to be processed are needed at any stage, transportation signals authorizes the transportation of a fixed number of products from the previous stage to the next one to process these parts. (Lage and Godinho, 2010). Hence, the material flows downstream while the information flows upstream where the kanbans are sent downstream to be ready for sending new orders.

Figure 12. Operation of kanban production system (Wang and Sarker, 2004)



As Kanban system is a pull system, production is triggered by the demand to the final production stage and successively triggered to the previous production stage until the beginning stage using. These orders are transmitted using kanban signals: production and withdrawal signals. Production schedule is transmitted back to all the upstream. Thus, the production is controlled by demand of the succeeding stage that at the end of the process is the market, the final consumers. (Bitran and Chang, 1987; Wang and Sarker, 2004).

There are six rules for Kanban systems proposed by Toyota:

1. Downstream processes use items only in amounts specified by the kanban card.
2. Upstream processes produce items only in amounts specified by the kanban card.
3. Nothing is made, moved, or altered without a corresponding kanban card.
4. If an item is produced or shipped, it must have a corresponding kanban card.
5. Errors, defects, or shortages are never sent downstream.
6. The total number of kanban cards is limited to reduce inventory or WIP and reveal bottlenecks or other problems.

In lean production, the planner is responsible for setting the transfer batch size for kanban and for additional procedures such as level planning that aims to avoid unbalanced loading of different stages of production stages. The design of the planning system focuses upon determining the number of kanbans per products per cell. However, the decision to start the production of a batch is under the direct control of the shop floor employees (Riezebos, 2001).

Benefits

Benefit of pull systems and especially of Kanban system is that they are transparent and easy to understand since the workers can understand the status and requirements of production without having to access complex software in computerized approaches. They do not rely on computer technology to control the workflow. It also delegates control decisions to workers, rather than adopting centralized decisions and it contributes to increase the workers implication (Sugimori et al., 1977; Riezebos et al., 2009).

According to Sugimori et al. (1977), kanban system had various advantages over computerized approaches such as:

1. The cost of processing information was reduced.
2. It was better at recording and communicating information in a dynamic environment.
3. The demand for all items was synchronized.

Some papers show that Kanban pull systems achieve lower inventories and shorter throughput times limiting the WIP than others MRP (Master Resource Planning) push system (Sugimori et al., 1977; Schonberger, 1983; Krajewski et al., 1987).

Kanban system is a cyclical planning system since the cards circulate through the supply chain upstream and then being sent downstream to restart the same cycle. This contributes positively to the system providing (Hall, 1987):

- Improvement in supply chain co-ordination.
- Eliminating the causes of disturbances rather than reacting to them.
- Improving the introduction of engineering changes coordinated with the release of work orders.
- Increase consciousness of internal client/server relationships between successive cycles.

Since the Kanban system is allocated in the TPS and it is one of the most important pillars of JIT, it contributes to remain the inventory as lower as possible and to reduce wasted labor and waste materials (Deleersnyder, 1989; Wang and Sarker, 2004; Tardif and Maaseidvaag, 2001). Remember that Kanban system works with small lot sizes and limits the WIP producing only when the inventory is lower than a threshold.

Different systems based on cards

During the last decades, it has been a great globalization of the economy in the production and consumption system and a fast development in information technologies. The demand is changing and international competition is continually increasing due to globalization (Porter, 1990). The crescent customer sophistication and the demanding customers' requirements such as punctuality, variety, low cost, high quality and also flexibility perform a wide review about the different kinds of management control systems required within the production logic (Starr, 1988; Sipper and Bulfin, 1997; Veen-Dirks, 2005).

There are other production planning systems based on cards authorization and visual control systems such as ConWIP, POLCA that are also cyclical systems and explicitly limit the amount of WIP that can be in the system as well as many other variants of Kanban systems.

ConWIP

The ConWIP (constant Work-in-Progress) system is a product-anonymous card system in which the cards regulate the flow of work staying with a product or batch through the whole length of the process, making it a more manageable method when there is high variety (Stevenson et al., 2005). ConWIP is totally focused on control the WIP and it only requires the determination of one parameter for the whole system or routing that is a single level of WIP (Tardif and Maaseidvaag, 2001).

One of the most differences between ConWIP and Kanban is that ConWIP do not use intermediate stocks in production or the supply chain. Therefore, the inventory levels inside the system are not controlled individually and high inventories can appear in front of slow processes or when a machine breaks down. (Riezebos et al., 2009; Gaury et al., 2000)

ConWIP uses a combination of physical and virtual authorization mechanisms. On the one hand, the physical mechanism works also with cards or containers providing authority to the operators to release new orders. This physical system only indicates that a new order may be released, but does not limit the set of orders from which to choose. On the other hand, the virtual mechanism is needed to provide guidelines on which order to release to choose the item to produce. This virtual machine acts like a sequencing and scheduling module that determines which orders will be released in the system (Hopp and Spearman, 2001; Riezebos et al., 2009).

POLCA

POLCA (Paired-cell Overlapping Loops of Cards with Authorization) is a hybrid push-pull system emphasizing the reduction of lead times, cutting product costs, increasing delivery date adherence and cutting scrap and rework (Stevenson et al., 2005).

POLCA system also uses two types of authorization mechanisms. One of them uses to be a card that sets an upper limit to the amount of WIP on the shop floor to order to start the production. The second authorization mechanism is a release list based on the production plan that enables the planner to control the progress of orders by having planned release dates for each order. Then, the decision on which items to produce depends on this second authorization mechanism. Cards are cell-specific operating between pairs of cells staying with a job on its journey between them. The card identifies the first two work cells that an order has to visit, but not the type of product; the same card may be attached to totally different orders as long as these orders subsequently visit the same combination of cells. POLCA cards are therefore not product-specific but route-specific. The mix of orders balances WIP with respect to routings (Riezebos et al., 2009; Stevenson et al., 2005).

In Riezebos et al. (2009) work there is a comparison of different systems analyzed so far.

Table 4. Kanban, ConWIP and POLCA system comparison (Riezebos et al. 2009)

Characteristics	Kanban	ConWIP	POLCA
Visual pull system	+	±	++
Autonomation	++	+	+
Production environment	Make-to-stock	Make-to-stock Make-to-order	Make-to-stock Make-to-order Engineer-to-order
Number of parameters	Has to be set for each product	Has to be set for each routing	Has to be set for each combination of two cells
Progress control by planner	No influence	Release sequence for whole order	Release dates per cell
Workload balancing capability	Not present	Not present	Present

All of these control systems uses visual signaling, but POLCA used to using visual cards that include color-coding (both cells receive a different color on the card) which increases the information content.

Ohno (1988) introduced the “autonomation” term which means automation with a human touch where the employees have a greater role in the design and adaptation of these systems. Above all, in the Kanban system due to the shorter loops taken by Kanban cards while the loops on the other system are longer as they cover several cells.

As the cards are product specific on Kanban system, the implementations of this system are mainly found in make-to-stock environments. ConWIP implementations are also mainly found in make-to-stock environments but easily cope with make-to-order situations since the cards are product-anonymous (Framinan et al., 2003). POLCA is even more flexible than the others systems as it only requires the current and next cell to be identified when releasing an order and then, it can be found also in engineer-to-order environment (Riezebos, 2001).

The number of parameters to determine in a Kanban system depends on the number of different products while in a ConWIP system on the number of routings and in a POLCA system on the number of pairs of cells in the routing set. Hence, the system which requires a minimum number of parameters varies according to the particular production system (Tardif and Maaseidvaag, 2001).

In terms of the control of the planner, it is focused upon generating a level scheduling with a limited control with shop floor in the case of Kanban system. A planner using a POLCA system can influence the choice of orders in a cell by taking authorization decisions and using a ConWIP system, the planner is allowed for release lists per order but it has no separate authorizations per cell or operation.

Finally, the workload balancing capability indicates the ability to reduce throughput times avoiding large WIP buffers before a bottleneck or avoiding bottlenecks though the intelligent release of orders. POLCA clearly outperforms the other mechanisms in this regard as it is the one that has more leeway to act on the system.

Different Kanban systems

Due to the difficulty in using the kanban system in its original concept in such diverse situations, variations (or adaptations) to the system different from the ''original'' were created to adapt properly to companies' specific reality.

According to the work of Lage and Godinho (2010), the most common operational differences in relation to the original kanban system are:

1. Variable maximum inventory level: during the same production period, the quantity of inventory allowed can vary.
2. Signals use modification.
   2.1. Signal transferring rule: Characterized by the use of norms to withdraw or transfer a signal that is different from the original kanban system.
   2.2. Physical attributes to the signal: the system does not use cards as signal.
   2.3. Signal type: the system modifies the original concept of using two signals.
3. Gathering and using information: variations that gather and apply information related to inventory level and demand, for example, differently from the original system that uses visual control.
4. Functioning: includes all systems which propose significant modifications in the original functioning concept, so the adaption is quite different from the kanban introduced by Toyota.
5. Materials release: all variations that modify the way or the rule to release parts both within a workstation and in between workstations.

Lage and Godinho (2010) made a list of 32 different Kanban versions that were compared with the original Kanban system described above on *"Kanban characteristics"* and characterized depending on the operational differences described above.

Table 5. Different modalities of Kanban system

Year	Variant Kanban	Common Characteristics	Operational Differences
-	E-kanban	3(PP, DC, LI)	2.2, 2.3, 3
-	Simultaneous kanban Control System (SKCS)	3(PP, DC, LI)	2.1, 2.3
-	Independent kanban Control System (IKCS)	3(PP, DC, LI)	2.1, 2.3
1985	Periodic Pull System (PPS)	3(DC, LI, US)	1, 2.2, 3
1987	Dynamically Adjusting kanban	3(PP, DC, LI)	1, 2.3
1988	Regenerative Pull Control System (RPCS)	3(PP, LI, US)	1, 2.2, 3
1988	Job-Shop kanban	3(PP, DC, LI)	2.3
1988	Minimal Blocking	3(DC, LI, US)	1
1989	Generalized kanban Control System (GKCS)	3(PP, DC, LI)	2.1, 2.3
1989	Modified kanban System (MKS)	3(DC, LI, US)	2.1, 2.3
1990	Auto-Adaptive kanban	3(PP, DC, LI)	2.1, 2.2, 2.3
1993	Concurrent Ordering System	3(DC, LI, US)	2.1, 3
1996	Modified Concurrent Ordering System	3(DC, LI, US)	2.1, 3
1994	Generic kanban System (GKS)	3(PP, DC, LI)	2.1, 2.3
1997	Flexible kanban System (FKS)	3(PP, DC, US)	1, 2.1, 3
1998	Push-Pull Approach (PPA)	3(DC, LI, US)	2.1, 4
1998	Decentralized Reactive kanban (DRK)	3(PP, DC, US)	1, 3
2000	Extended kanban Control System (EKCS)	3(PP, DC, LI)	2.1, 2.3
2000	Simultaneous Extended kanban Control System (SEKCS)	3(PP, DC, LI)	2.1, 2.3
2000	Independent Extended kanban Control System (IEKCS)	3(PP, DC, LI)	2.1, 2.3
2001	Adaptive kanban	3(PP, DC, LI)	1, 2.1, 2.3, 3, 5
2003	Reconfigurable kanban System (RKS)	3(PP, DC, US)	1
2003	Inventory Based System	3(DC, LI, US)	1
1988	Fake Pull Control System (FPCS)	0	4
1991	Hybrid Push/Pull	2(PP, LI)	1, 2.3, 5
1997	Bar-Coding kanban	1(LI)	1, 2.2, 2.3, 3
1998	CPM kanban System	1(PP)	1, 2.3, 4
1999	MRP/ SFX-Shop Floor Extension	1(LI)	1, 2.3, 3
2000	Virtual kanban (VK)	2(LI, US)	2.1, 2.3
2001	Customized Type 5	2(DC, LI)	2.1, 2.3, 3, 4, 5

2001	Customized Type 10	2(DC, LI)	2.1, 2.3, 3, 4, 5
2002	Gated Max WIP	1(LI)	2.2, 3, 4, 5

Further details of all of these particular kanban systems can be found on Lage and Godinho (2010) literature.

5. Research Objectives

The objective of this thesis is analyze the behavior of a multi-product supply chain with two different systems to manage the planning and control of the production and, with two dispatching rules for one of these planning and control systems. Then, the analysis has been done with three different rules for production planning. More specifically, there are two aims in this thesis.

1. The first one is verify that pull systems, in this case using a traditional kanban system, are better than EOQ systems in terms of cost. The cost will not be calculated in any case but there it is related with the amount of inventory and transports needed ensuring the same service level.
2. The second objective is to find relevant differences in terms of transportation, inventory amount and saturation level dispatching the products in a kanban system in two different manners. In this thesis, the products can be produced following two rules:
    a. Criticality: The product which accomplishes the production condition with fewer pieces in stock (that is, the product with more production kanban cards on the board) is the most critical and therefore, the next to be produced.
    b. Shortest set up time: The next product to be produced will be the one which accomplishes the production condition and need less set up time.

    The production condition is that the number of production kanban cards is higher than the ROQ (Reorder Quantity).

All of these comparisons will be done and analyzed in different conditions and the objective is also related to under which conditions one model is better than the other and why. The goal is to be able to identify proper conditions (in terms of demand variability, batch size and service level) to apply the different models analyzed.

6. Description of the working methodology

6.1. Work development

With the goal of analyzing a supply chain behavior with some modifications to compare different scheduling and processing models such as EOQ and kanban with two dispatching rules in the case of using kanban model and, in addition, check the behavior with up to 8 different demands, the best option to extract conclusions and be able to analyze each model is using simulation.

The simulation program used in this work is Arena Simulation Software. Arena is the most used Discrete Event Simulation Software in the word and its flowcharting tool allows us to understand quickly and easily simulation concepts as well as to build a strong foundation in discrete event simulation that applies to real world situations. In addition, Arena uses Visual Basic for Applications (VBA) language that is built into most Microsoft Office applications such as in Microsoft Excel and allows very easily the communication between these programs since Microsoft Excel is used to analyze the Arena results.

The simulation model used in this work is based to the simulation model developed in the works of Monti and Paolo (2016) and previously started by Rosini and Franzoni (2014) and also developed by Carbò (2015).

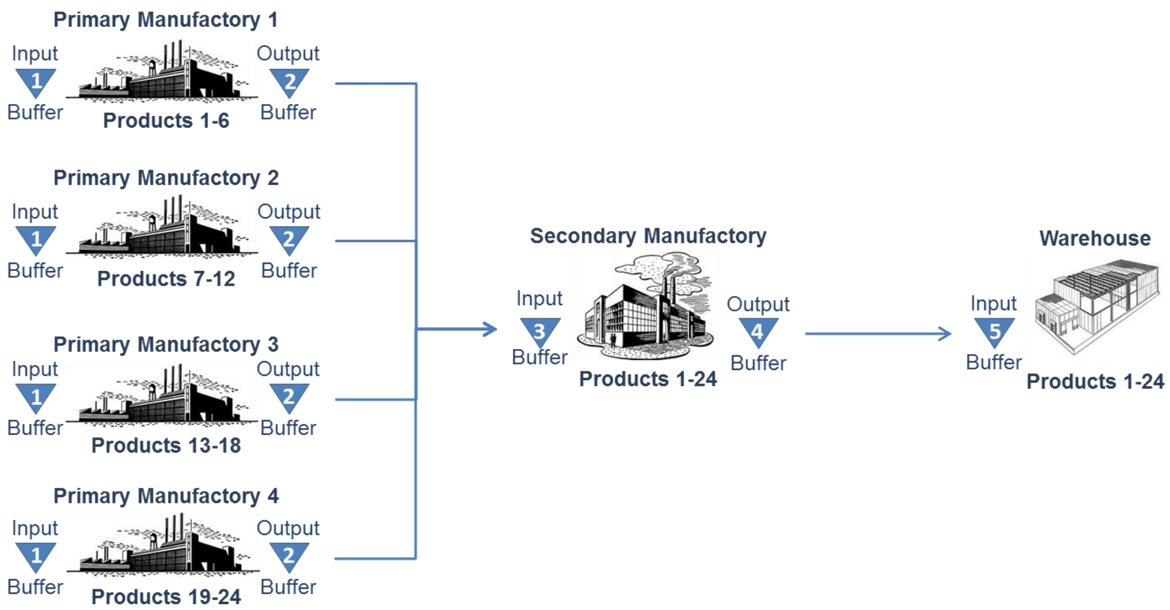
6.2. The model description

The model represented to simulate and extract conclusions about the supply chain behavior consist on two fabrication levels and one distribution center at the end of the chain, it is represented in figure 13. The first production level is composed of four factories and the secondary is composed only for one. Each factory has an input and output buffer as well as another input buffer that represents the distribution center or warehouse which is located downstream. The transportation is also represented in the model, from each primary manufacturer to the secondary as well as the transportation from this point to the warehouse.

In terms of products developed in the supply chain, there are 24 different products divided in 4 families which flow through the chain. Each primary manufactory (PM) hold the production of one family composed by 6 products and all of them are shipped to the secondary manufactory (SM) to be finished and get finished good that will be send to the warehouse. The first primary manufacturer holds the first family products (products from 1 to 6), the second holds the products from 7 to 12, the third holds the products from 13 to 18 and finally, the fourth primary manufacturer holds the last family of products (products from 19 to 24).

The image bellow shows schematically the representation of the supply chain analyzed:

Figure 13. Schematic representation of the supply chain analyzed



The secondary manufacturer works 8 hours per day while the primaries work less time due to they need less time to complete the production required. All primaries manufactories work the 65% of the time of the secondary that it is equal to 5 hours and 12 minutes per day.

Input buffers of the PM store raw materials necessaries to produce each product and the capacity of them is supposed infinite as well as the availability of raw materials so there will be always enough materials to produce on the PM. Once the products have been processed, they are stored on the output buffer waiting to be transported to the next stage, to the input buffer on the SM. Once there, the products will be handled getting final goods and stored on the output buffer since to be transported to the last stage. It is an input buffer that represents the warehouse were the products are directly in contact with the consumers to satisfy the demand that is 16 units daily of each product.

According to the demand, the capacity of the secondary manufacturer must be, at least, 384 products per day (16 units daily per 24 products). While the capacity of the PM must be 16 units daily per 6 products, at least, that is 64 products per day to satisfy the customers' demand.

There are four different scenarios in terms of saturation levels. The production saturation is composed of (is the sum of) the process saturation and the set up saturation. The process saturation is the percentage time that the machines are working to produce out of the total time available of the manufacturer. Then, the saturation set up is the percentage of time spent doing the set up out of the total time available of the manufacturer.

The scenarios used in this studio are with a production saturation of 80% and 90% with 10% and 20% of set up saturation for both cases. The four scenarios used are:

- Process 60% + Set Up 20% = Production Saturation 80%
- Process 70% + Set Up 10% = Production Saturation 80%
- Process 70% + Set Up 20% = Production Saturation 90%
- Process 80% + Set Up 10% = Production Saturation 90%

The set up time not only depends of the next product to be processed but also of the product that is processing before and it is zero if the products are the same. Then, the set up time can be represented in a square matrix that is not symmetric with zeros on the diagonal where the set up time is different if the production sequence is 13 – 21 or 21 – 13.

On the supply chain there are two phases of transport, to carry the products from the PM to the SM and the other one from PM to the warehouse. In both cases, the transportation is carried out by trucks but with different capacity. In the first stage of transport (from PM to SM), the trucks capacity is 150 units and the trucks capacity is 450 units from the SM to the warehouse.

There are some modalities of transport as it was discuss in section *4.4.2. Lean Supply Chain* subsection *"Lean measures focused on suppliers and customers'* *relationship".* For this thesis, the modality adopted is based on FTL but with some details to consider.

The transport modality is always FTL unless there has not been any truck full to be shipped in one day from any output buffer. In that case, the truck can be shipped in condition of LTL. Therefore, if at least one truck has been shipped during the day, the products in the next truck that is not full at the end of the day will remain on the output buffer to collect the products processed the next day until the truck is full or until finish the day.

6.3. Model variations

In order to satisfy the objectives of this project and be able to verify how much better are lean supply chains using kanban systems in comparison to supply chains managed by EOQ (Economic Order Quantity) systems, two different models have had to be analyzed: Economic Order Quantity model and Kanban model.

6.3.1. Economic Order Quantity model

In this model, the production management is performed by Economic Order Quantity (EOQ) system. Using this policy, production orders are sent when the stock of the next stage falls below of a threshold called ROP (Reorder Point) and the batch size of PM and SM is fixed and it never changes.

There are two key variables to identify when EOQ is applied, one of them is the ROP and the other is the batch size, also called ROQ (Reorder Quantity).

- The objective of EOQ is to calculate the ROQ in order to minimize the costs associated with inventory management: holding costs, ordering cost and purchase or production cost.
- The threshold value of the ROP is the leverage parameters that are changed during the simulations to obtain different levels of service needed for data collection.

Now, we are going to see how to manage these key variables:

- When the inventory of the buffer i falls below the position of a certain ROP, a production order is sent upstream to the previous buffer i-1.

The relation between inventory level and ROP is checked every 10 minutes and denominated as period t. The inventory of each buffer i for each product j is calculated according to:

$$IP_{i,j,t} = SC_{i,j,t} - back_{i,j,,t} + OR_{\,i,j,t-1}$$
$$i = 1,2 \ldots 5; \qquad j = 1,2 \ldots 24; \qquad t = 1,2 \ldots 96\,000$$

Where:

- $IP_{i,j,t}$ = Inventory position of the buffer i, product j and period t.
- $SC_{i,j,t}$ = Stock level of the buffer i, product j and period t.
- $back_{i,j,,t}$ = Backlog of the buffer i, product j and period t.
- $OR_{\,i,j,t-1}$ = Orders sent by the buffer i at the upstream stage i-1 for the product j at period t.
- i = buffers, 5 buffers are considered although there are 11 physical buffers. There are 4 input and 4 output buffers, one for each factory and product family that can be considered as 1 input and 1 output buffer with capacity for all 24 products.
  Then, i = 1 and j = 15 correspond to the input buffer of the third PM and product 15.
- j = products. There are 24 different products to process on the supply chain
- t = period to check the inventory levels. The simulation reproduce 2 000 days, each one has 8 hour of work, then, each simulation reproduce 960 000 minutes. As it was said before, the simulation check the inventories levels every 10 minutes therefore, there are a total of 96 000 periods of time.

- The batch size, EOQ or ROQ for each buffer i from 2 to 5, we must remember that buffer 1 has infinity capacity and there are always row materials, has been calculated using the following equation:

$$EOQ_i = \sqrt{\frac{2 * D * S}{I * C}} \qquad \forall\, product\ j = 1,2 \ldots 24$$

Where:

- D = Annual demand (units). The demand is 16 units of each product per day that is equal to 3 520 annual units for each product since manufactories work 220 days per year.
- S = Cost per order (€).
- I = Annual holding costs, percentage of purchase or production cost (%).
- C = Production cost per unit (€/unit).
- i = buffers, 5 buffers are considered although there are 11 physical buffers. There are 4 input and 4 output buffers, one for each factory and product family that can be considered as 1 input and 1 output buffer with capacity for all 24 products.

  Then, i = 1 and j = 15 correspond to the input buffer of the third PM and product 15.
- j = products. There are 24 different products to process on the supply chain.

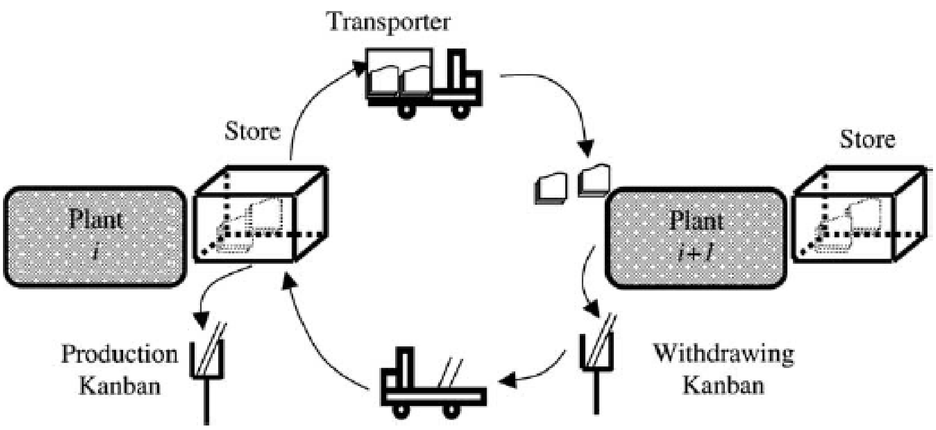
Batches sizes are set as initial values of this work, continuing the work of Monti and Paolo (2016), and many combinations of C, S and I values are possible to find them. EOQ for the input buffer at the distribution center (IB_D) is 54 units, for the output buffer at the secondary manufacturer (OB_SM) is 91 units, for the input buffer of the secondary (IB_SM) is 131 units and finally, for the output buffer of the primary manufacturer (OB_PM) is 195 units. In the case of the input buffer for the primary (IB_PM), the buffer always contains row materials and then, no requirements of materials are needed. These values are fixed during the simulation and never change.

6.3.2. Kanban model and dispatching rules

In this model, the logistics operations follow a pull system with a sequence of orders from downstream to upstream, the production and transfer of materials are only authorized when there is a downstream consumption and the level of kanban is higher than a threshold.

In this supply chain analyzed, each product has associate one kanban card that contains information about the product and signals about the movements or production orders that must be executed. Kanban cards have two signals, one for movement called withdrawal kanban (WK) and the other about production order called production kanban (PK).

Figure 14. Operation of kanban production system. Output buffers with PK and input buffers with WK. (Wang and Sarker, 2004)



As it can be seen in the figure above, production kanbans flow through the production process and withdrawal kanbans flow through the transportation system.

Some concepts that must be clear to understand the kanban system:

- Each buffer has a table with as many columns as different products they stock. In this case, 5 buffers have been considered with 24 products on each one.
- The kanban cards are placed one below the other on the corresponding column.
- Input buffers (IB_D, IB_SM and IB_PM) have a table related to withdrawals kanbans (WK) because the products are shipped (moved) from the output buffer of the previous stage to these input buffers. Therefore, the orders are related to movement.
- Output buffers (OB_SM and OB_PM) have a table related to production kanbans (PK) since to receive products; they must be produced between the previous buffer and these output buffers. Therefore, the orders are related to production.

Kanban follows pull system, then, the orders go from downstream to upstream on the supply chain. We are going to see how kanban system works starting from the distributor or warehouse and finishing on the PM:

- As products are consumed at the distribution center by the demand, WK cards are detached from the container (or product) and put into the kanban board WK.

Figure 15. Withdrawal kanban example for IB_D after some demand was delivered

	WITHDRAWAL KANBAN BOARD (IB_D)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0																								
1																								
2																								
3																								

- When there are any withdrawal kanban cards of any product, which is the same as the number of any WK kanban of any product is higher than zero, all kanban cards are detached from the withdrawal kanban board and sent to the previous stage, in that case, to the output buffer of the secondary manufacturer. They are sent following the order of criticality, the product with more WK on the board is the product with fewer pieces in stock and then, the most critical. (Cells with "**O**" represent the kanban cards detached on this step).

Figure 16. Withdrawal kanban example for IB_D after to send movement orders to OB_SM

	WITHDRAWAL KANBAN BOARD (IB_D)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0																								
1							O			O									O					O
2										O														O
3																								

- WK are received on the output buffer of the secondary manufacturer where detach PK of the products that are put into the kanban board PK and attach WK received by IB_D. (Cells with "**X**" represent the kanban cards added on this step).

Figure 17. Production kanban example for OB_SM with ROQ equal to 91 units

	PRODUCTION KANBAN BOARD (OB_SM)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1																								
2																								
.																								
.																								
.																			X					
90																								
91																								X
92										X														X
93										X														
94							X																	

- When the number of production kanban cards for any product is higher than the ROQ, in the case of OB_SM higher than 91 units, means that the stock of these products is too low and more products should be processed to increase the inventory. We can call these as “possible products to process”.
  If the production system of the stage before is free, in that case, if SM is free, all PK cards of one “possible product to process” are detached from the production kanban board and sent to the previous stage IB_SM. With this, the production order is send upstream to process as many products as PK cards have been sent.
  Depending on the dispatching rules described at the end of this section *6.3.2. Kanban model* one product or other will be selected to produce between the ones which are “possible products to produce”.

Figure 18. Production kanban example for OB_SM after to send production orders to IB_SM

	PRODUCTION KANBAN BOARD (OB_SM)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1										O														
2										O														
.										O														
.										O														
.										O														
90										O														
91										O														
92										O														
93										O														

94																								

- SM receives production orders and produces the necessary products for the output buffer. Before that, WK cards associated to the products on the IB_SM that will be processed are detached and PK cards are attached to these products.
  WK cards detached from the products are then put into the withdrawal kanban board of the input buffer of the secondary manufacturer.

Figure 19. Withdrawal kanban example for IB_PM after process products 10 and 24 on the SM

	WITHDRAWAL KANBAN BOARD (IB_SM)																							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
0										X														
1										X														
·										X														
·										X														
·										X														
92										X														
93										X														
94																								

- The same loop is repeated between the primary and secondary manufacturer with the movement of WK and PK cards and the shipment of transport and production orders.

The inventory on each buffer can be known in function of the kanbans following the next expression:

$$IP_{i,j,t} = KBbuffer_{i,j,t} + KBback_{i-1,j,,t} + KBtransp_{\,i,j,t} - KBback_{\,i,j,t}$$

$$i = 1,2 \dots 5; \qquad j = 1,2 \dots 24; \qquad t = 1,2 \dots 96\,000$$

Where:

- $IP_{i,j,t}$ = Inventory position of the buffer i, product j and period t.
- $KBbuffer_{i,j,t}$ = Number of kanbans stored of the buffer i, product j and period t.
- $KBback_{i,j,t}$ = Number of kanbans related to the backlog delivery of the buffer i (to the next stage), product j and period t.

- $KBtransp_{i,j,,t}$ = Number of kanbans in transportation to the buffer i, product j and period t.
- i = buffers, 5 buffers are considered although there are 11 physical buffers. There are 4 input and 4 output buffers, one for each factory and product family that can be considered as 1 input and 1 output buffer with capacity for all 24 products.

  Then, i = 1 and j = 15 correspond to the input buffer of the third PM and product 15.
- j = products. There are 24 different products to process on the supply chain.
- t = period to check the inventory levels. The simulation reproduce 2 000 days, each one has 8 hour of work, then, each simulation reproduce 960 000 minutes. As it was said before, the simulation check the inventories levels every 10 minutes therefore, there are a total of 96 000 periods of time.

Dispatching rules for the production system

Every 10 minutes, there is a check on the system, if the manufacturer (primary or secondary) is not working, it can receive a production order from downstream. Production orders are only when the number of production kanban cards on the PK board is higher than a threshold that is the ROQ on the output buffer (primary or secondary).

When there are more production kanban cards of more than one product on the PK board than the ROQ value, means that more than one type of product must be processed but, what about the order of processing? Which type of product is the next to be processed?

There are different options to decide the order of production between different products. In this work, two options described above are proposed and analyzed: criticality and shortest set up dispatching rule.

To explain these options, we will use the case used before to explain how kanban system works, this is the production kanban board on the output buffer of the secondary manufacturer:

Figure 20. Production kanban example for OB_SM with ROQ equal to 91 to explain dispatching rules

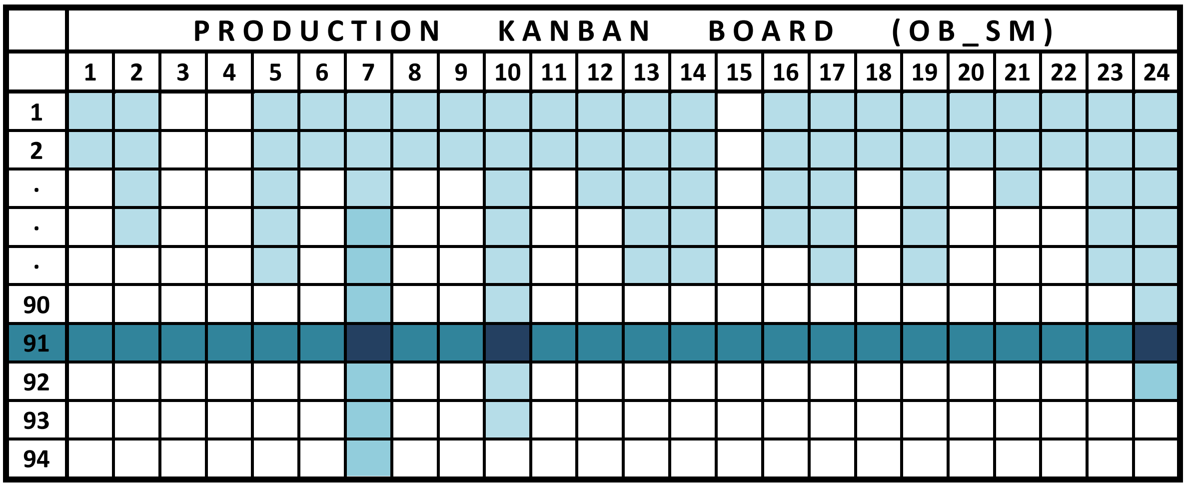


Table 6. Set up times example to explain dispatching rules

Set up time needed (min) Product processed before: 4th	**Product 7**	**Product 10**	**Product 24**
	10,78	8,88	40,67

There are three products with more PK cards than the ROQ (that is 91 units), then, there are three "possible products to produce", depending on the dispatching rule, one or other will be selected to produce.

Criticality dispatching rule

Using this dispatching rule, the order to produce corresponds to the product with more production kanban cards on the PK boards.

The product with more PK cards on the board is the one with fewer inventories in stock and therefore the most critical to run out thus it is the most necessary product to process to do not have backlog.

In the example proposed before in the figure 20, the most critical product is the 7th. Hence, the PK cards of the 7th product must be detached from this board and be sent to the production system of the second manufacturer.

Using the dispatching rule of criticality, the next product to process must be the product 7.

Shortest set up dispatching rule

In this modality, the next product to process in the one which needs less set up time to start the production. In this way, it is assumed risk to have backlog but the system needs less time to prepare the production and the saturation is lower that means that more products could be produced in case the demand increase.

In the example proposed before, the product processed before was the 4th. Between the three products selected as "possible products to produce", the one which needs less time to prepare its production is the product 10. Hence, the PK cards of the 10th product must be detached from this board and be sent to the production system of the second manufacturer.

The next product to process using shortest set up time dispatching rule is the product 10.

6.4. Procedure description

Once the model is described with all its variants and the objectives are known, the way to obtain the results with different variables of saturation, demands and demand variability is explained in this section.

There are two main variants on the supply chain model: EOQ and Kanban, and two dispatching rules for the kanban variant in function of criticality or set up time. Hence, there are three models variants to simulate and extract conclusions with different variables of saturation, demands and demand variability to evaluate which model is better in different conditions.

- Saturation: Explained in section 6.2. The model description. Four saturation combinations are simulated:
  - Process 60% + Set Up 20% = Production Saturation 80%
  - Process 70% + Set Up 10% = Production Saturation 80%
  - Process 70% + Set Up 20% = Production Saturation 90%
  - Process 80% + Set Up 10% = Production Saturation 90%
- Demand: There are 5 different demands, all of them with the same mean of 16 units per day.
- Demand variability: There are two different coefficients of variability used to simulate the supply chain and analyze the behavior depending on demand

variability. Two standard deviations are used for each demand: $\sigma = 12{,}8$ and $\sigma = 6{,}4$ that means a coefficient of variability equal to 0,8 and 0,4 respectively since the mean is equal to 16 units.

Therefore, 4 different combinations of saturation, 5 different demands with 2 coefficients of variability make 40 simulations for each model variant. As it is said before, there are 3 models variants and then, 120 simulations will be done to carry out this project.

7. Results Obtained and Analysis

To make clear and easily understanding the different scenarios analyzed on this work, all of them can be seen on the following table with an "X" for each scenario simulated:

Table 7. Scenarios analyzed by simulation.

Kanban-Lean*																Economic Order Quantity							
Criticality								Shortest Set-Up								Criticality							
CV = 0,8				CV = 0,4				CV = 0,8				CV = 0,4				CV = 0,8				CV = 0,4			
D1	60	70	80	D1	60	70	80	D1	60	70	80	D1	60	70	80	D1	60	70	80	D1	60	70	80
90		X	X	90		X	X	90		X	X	90		X	X	90		X	X	90		X	X
80	X	X		80	X	X		80	X	X		80	X	X		80	X	X		80	X	X	
D2	60	70	80	D2	60	70	80	D2	60	70	80	D2	60	70	80	D2	60	70	80	D2	60	70	80
90		X	X	90		X	X	90		X	X	90		X	X	90		X	X	90		X	X
80	X	X		80	X	X		80	X	X		80	X	X		80	X	X		80	X	X	
D3	60	70	80	D3	60	70	80	D3	60	70	80	D3	60	70	80	D3	60	70	80	D3	60	70	80
90		X	X	90		X	X	90		X	X	90		X	X	90		X	X	90		X	X
80	X	X		80	X	X		80	X	X		80	X	X		80	X	X		80	X	X	
D4	60	70	80	D4	60	70	80	D4	60	70	80	D4	60	70	80	D4	60	70	80	D4	60	70	80
90		X	X	90		X	X	90		X	X	90		X	X	90		X	X	90		X	X
80	X	X		80	X	X		80	X	X		80	X	X		80	X	X		80	X	X	
D5	60	70	80	D5	60	70	80	D5	60	70	80	D5	60	70	80	D5	60	70	80	D5	60	70	80
90		X	X	90		X	X	90		X	X	90		X	X	90		X	X	90		X	X
80	X	X		80	X	X		80	X	X		80	X	X		80	X	X		80	X	X	
* In lean approach, each scenario has been released with 4 different batch sizes																							

As it is commented in the table 7, each scenario in lean approach has been analyzed with 4 different batch sizes that are the batch size set in the beginning and a reduction of 20%, 40% and 60% of that.

To name each scenario, we will use the following code:

- Model: Kanban-Lean (LEAN) or Economic Order Quantity (EOQ).
- Dispatching rule for Kanban-Lean: Critically (CR) or Shortest Set-Up (SSU).
- Coefficient of variability (CV): It can be 0,8 or 0,4.
- Demand: There are 5 demands, each one assigned with a number from 1 to 5.
- Production saturation (ProdSat): It can be 80% (80) or 90% (90).

- Process saturation (ProcSat): It can be 60% (60), 70% (70) or 80% (80).

Only for Kanban model and if it is necessary:

- Factor of batch reduce (BatchRed): It can be 1 if no reduction in applied, 0,8 (reduction of 20%), 0,6 (reduction of 40%) and 0,4 (reduction of 60%).

And the way to name each scenario will be:

Model_DispatchingRule_CV_Demand_ProdSat_ProcSat_BatchRed

Then, the scenario with a process saturation of 70% and a production saturation of 80% simulated with the demand 4 using a coefficient of variance equal to 0,4 and applying the criticality dispatching rule for the Kanban or lean model with no reduction in the batch size is named as:

LEAN_CR_0,4_4_80_70_1

It is important to note that although there are two different models one of them was simulated using two dispatching rules, we will consider the three scenarios in a same comparison level comparing all three in the same situations. Therefore, from now on we will consider three supply chain models:

- EOQ: Economic Order Quantity.
- LEAN_SSU: Kanban-Lean model with shortest set-up dispatching rule.
- LEAN_CR: Kanban-Lean model with criticality dispatching rule.

7.1. Inventory Analysis

7.1.1. Related to the Service Level

The higher the service level, the higher the inventory necessary to satisfy the customers demand as it can be seen in graph 1.

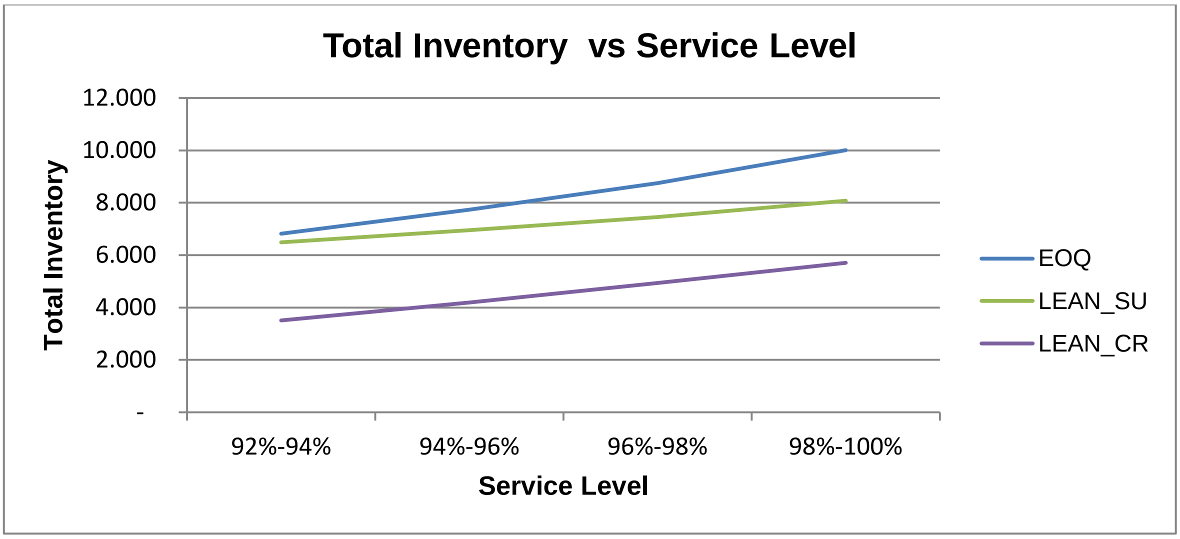
The service level provided depends on the available inventory to delivery to the next stage of the supply chain as well as to the final consumer. Hence, as higher the inventory level, the greater the change of not running out of pieces and be able to deliver products to the next stage increasing the service level.

As shown in graph 1, the EOQ system is the one which more inventory needs to satisfy the customers' demands for any service level and otherwise, the Kanban system using the criticality dispatching rule in the one which requires less stock for any service level.

Table 8. Inventory level depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR
92%-94%	6.815	6.487	3.503
94%-96%	7.732	6.955	4.187
96%-98%	8.749	7.458	4.931
98%-100%	10.013	8.077	5.703

Graph 1. Inventory level depending on the service level for each model



It can also be seen that the difference in inventory level using the shortest set-up dispatching rule compared with the EOQ system is very small around the 93% of service level and greater as higher the service level.

For a more detailed analysis, graph 2 shows the difference in inventory level comparing both lean approaches to the EOQ.

Graph 2 and table 9 show that the differences in level inventory are greater as higher the service levels for the shortest set-up and criticality approach. Then, the higher the service level, the higher the improvement in inventory level using Kanban systems.

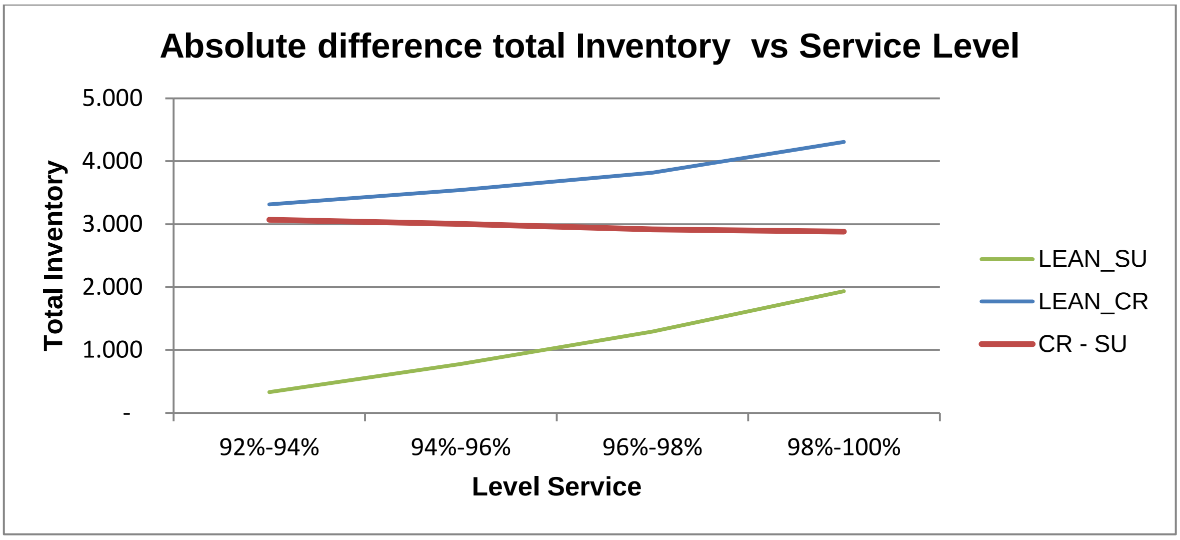
It must be stressed that we do not know what happens if the service level is lower than 93% due to the system analyzed has a condition to provide a higher service level but it seems that the inventory level for lower services levels can be worse using the kanban system with the shortest set-up dispatching rule than the EOQ system.

The differences in inventory level between the EOQ model and Kanban models increase as higher is the service level as we can see in table 9 and graph 2. If we compare the inventories between both Kanban models, we can observe that the difference is smaller as higher the service level but very similar in any case.

Table 9. Absolute inventory differences with EOQ system and between Kanban models depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR		SSU – CR
92%-94%	-	-328	-3.312		3.071
94%-96%	-	-777	-3.545		3.005
96%-98%	-	-1.291	-3.819		2.915
98%-100%	-	-1.935	-4.310		2.880

Graph 2. Absolute inventory differences with EOQ system and between Kanban models depending on the service level

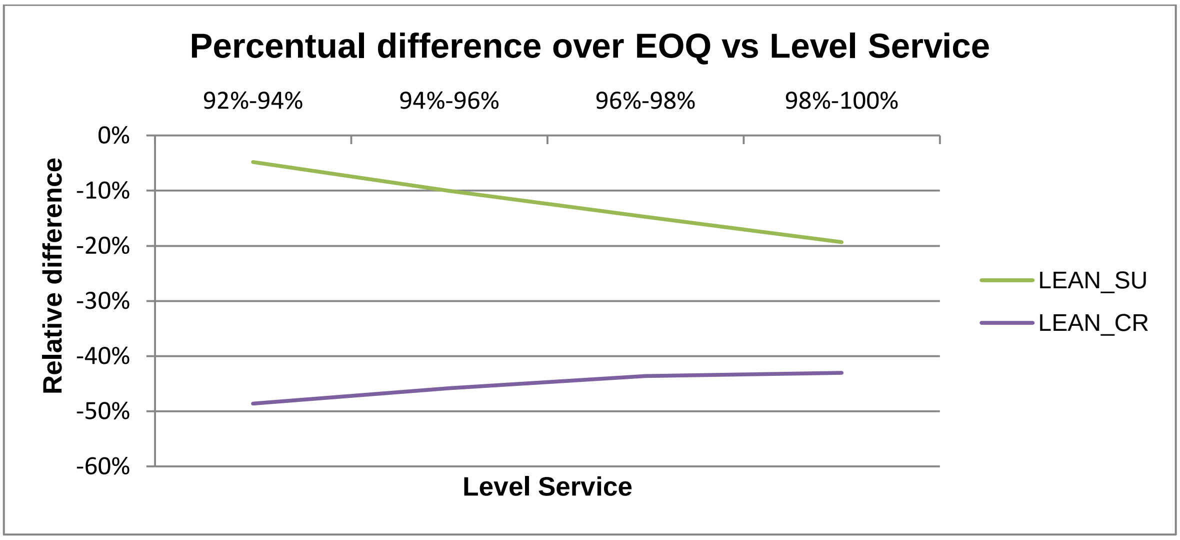


The relative differences are shown on table 10 and graph 3. The Kanban model with the shortest set-up dispatching rule significantly increments the relative difference with the EOQ model. It means that the improvement in inventory level is more representative as higher the service level. However, this improvement is equally representative for any service level or even a little less as higher the level of service as shown in table 10 and graph 3.

Table 10. Relative inventory differences with EOQ system depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR
92%-94%	-	-4,8%	-48,6%
94%-96%	-	-10,0%	-45,9%
96%-98%	-	-14,8%	-43,6%
98%-100%	-	-19,3%	-43,0%

Graph 3. Relative inventory differences with EOQ system depending on the service level



Criticality dispatching rule

Going more in deep and analyzing the results depending also on the batch size according to the criticality dispatching rule. The next table show how the inventory level significantly improves as lower the batch size since its 60% and then the improvement lose a little bit of ground maintaining similar levels.

It can also be seen that the improvement in inventory is greater as lower the service level for any batch size.

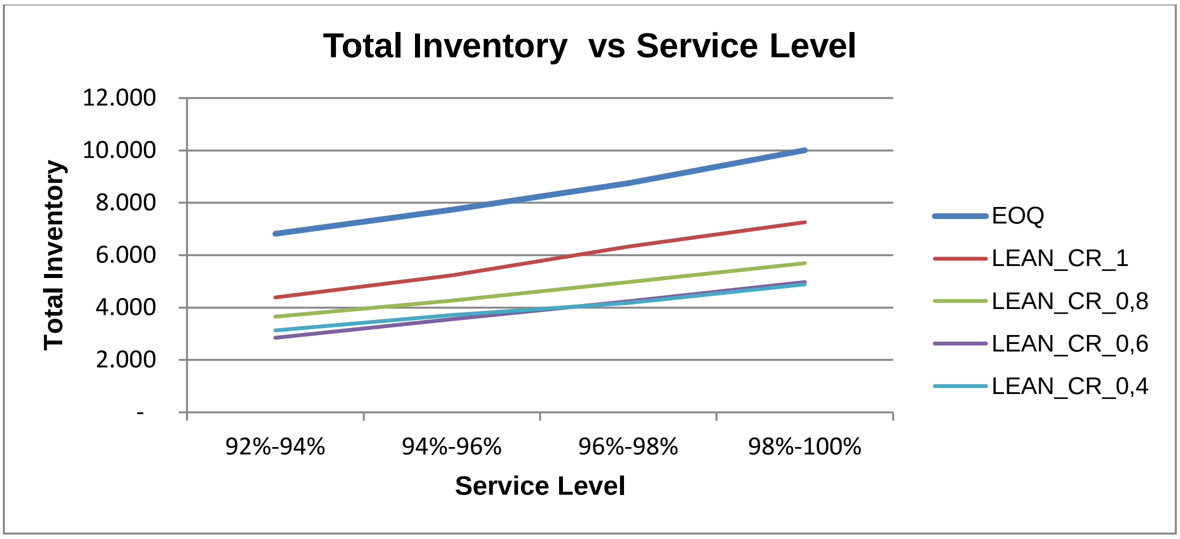
The greater improvement on inventory level using the criticality dispatching rule is corresponded with a batch size of 0,6 for the lowest service levels. In spite of this, for uncertainties on the service level, the batch size reduction recommended to use is 0,6.

Table 11. Inventory reduction for each batch reduction using criticality dispatching rule depending on the service level

Service Level	LEAN_CR_1	LEAN_CR_0,8	LEAN_CR_0,6	LEAN_CR_0,4
92%-94%	-35,6%	-46,5%	-58,3%	-54,0%

94%-96%	-32,4%	-44,9%	-54,1%	-52,0%
96%-98%	-27,6%	-43,2%	-51,6%	-52,2%
98%-100%	-27,5%	-43,2%	-50,3%	-51,2%
Mean	**-30,8%**	**-44,4%**	**-53,6%**	**-52,4%**

Graph 4. Inventory level depending on the service level for each batch reduction using criticality dispatching rule



Shortest Set-Up dispatching rule

According to the shortest set-up dispatching rule and the batch sizes, it is clear that the results are better as lower the batch size as shows table 12 and also as higher the service level for any batch size.

Then, the best option using this model is reduce at the minimum the batch size and increase the service level to decrease the total inventory stock.

The Kanban system using the shortest set-up dispatching rule does not ensure lower inventories than the EOQ model for any case. Using no reduction in batch, the inventory level is higher than using the EOQ model for levels of service lowers than 95%. In all other cases, the inventory needed is lower than the inventory required for the EOQ system.

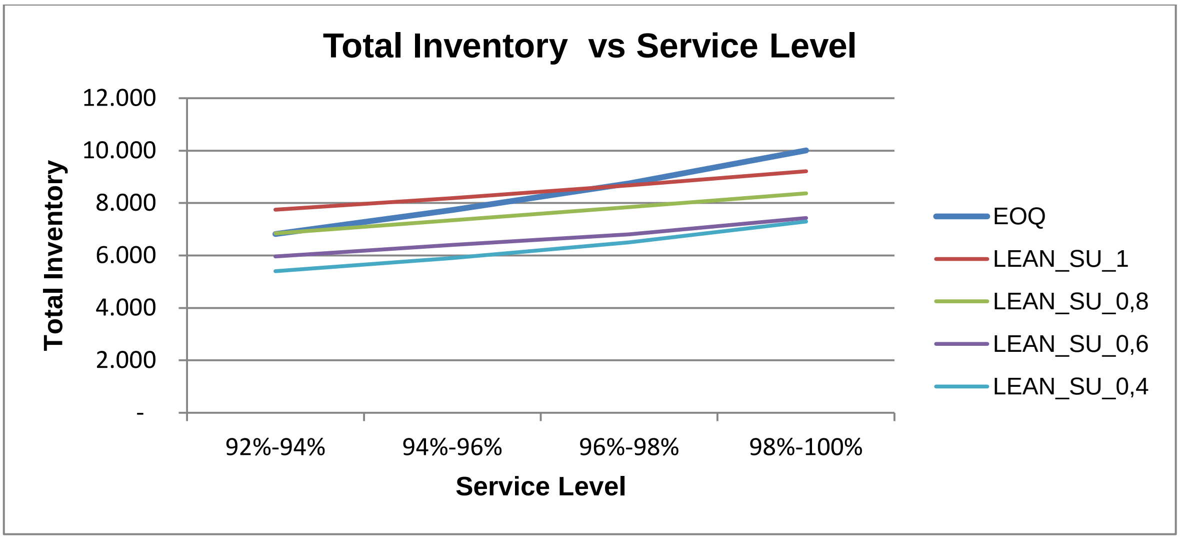
Table 12. Inventory reduction for each batch reduction using shortest set-up dispatching rule depending on the service level

Level Service	LEAN_SSU_1	LEAN_SSU_0,8	LEAN_SSU_0,6	LEAN_SSU_0,4
92%-94%	13,6%	0,4%	-12,5%	-20,7%
94%-96%	5,8%	-5,1%	-17,2%	-23,7%

96%-98%	-0,9%	-10,3%	-22,3%	-25,6%
98%-100%	-8,0%	-16,4%	-25,8%	-27,1%
Mean	**2,6%**	**-7,9%**	**-19,4%**	**-24,3%**

The shortest set-up model is more stable than the EOQ model since the inventory level variations are lower in function of the service level as shown in graph 5. For this reason, it can be that the most suitable model, with a fixed batch size, to ensure a lower inventory level depends on the service level.

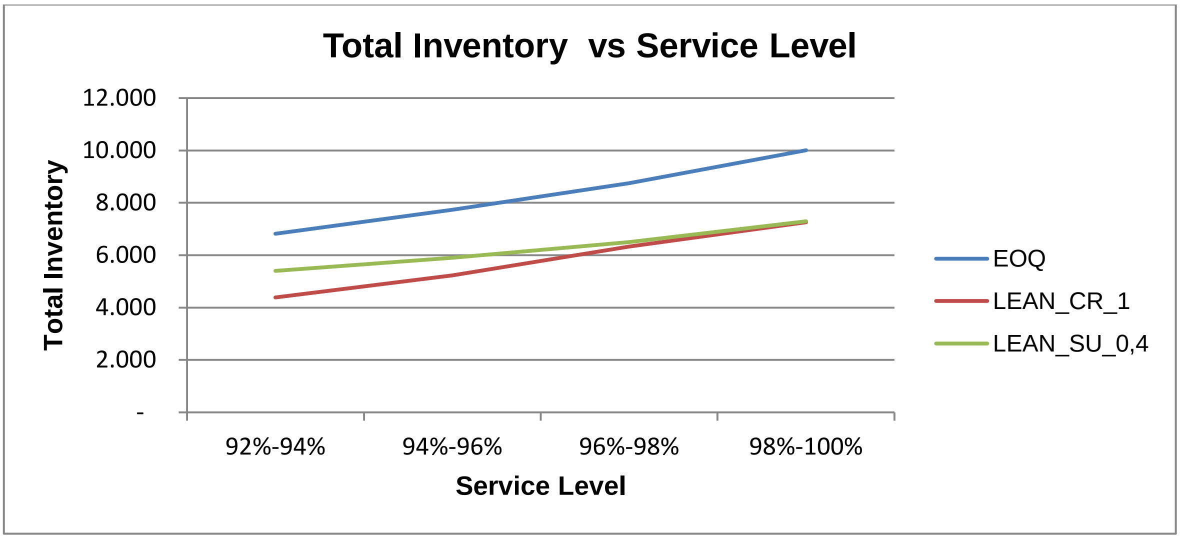
Graph 5. Inventory level depending on the service level for each batch reduction using shortest set-up dispatching rule



Criticality and Shortest Set-Up dispatching rule

Now, we will compare the best scenarios to minimize the inventory level using the shortest set-up and the two worse using the criticality dispatching rule.

Graph 6. Best and worse results for shortest set-up and criticality dispatching rule respectively depending on service level



As shown in graph 6, the worse scenario using the criticality model (LEAN_CR_1) is better than the best scenario using the shortest set-up model (LEAN_SSU_0,4) for services levels lower than 96% and very similar for higher services levels. If we also consider the second worse scenario for the criticality model, we can see how it is much better than the best of the shortest set-up dispatching rule according always to the inventory in stock.

From this section, we can conclude that the most suitable model to minimize the inventory level is the use of the Kanban model using the criticality dispatching rule with a batch reduction of 40%.

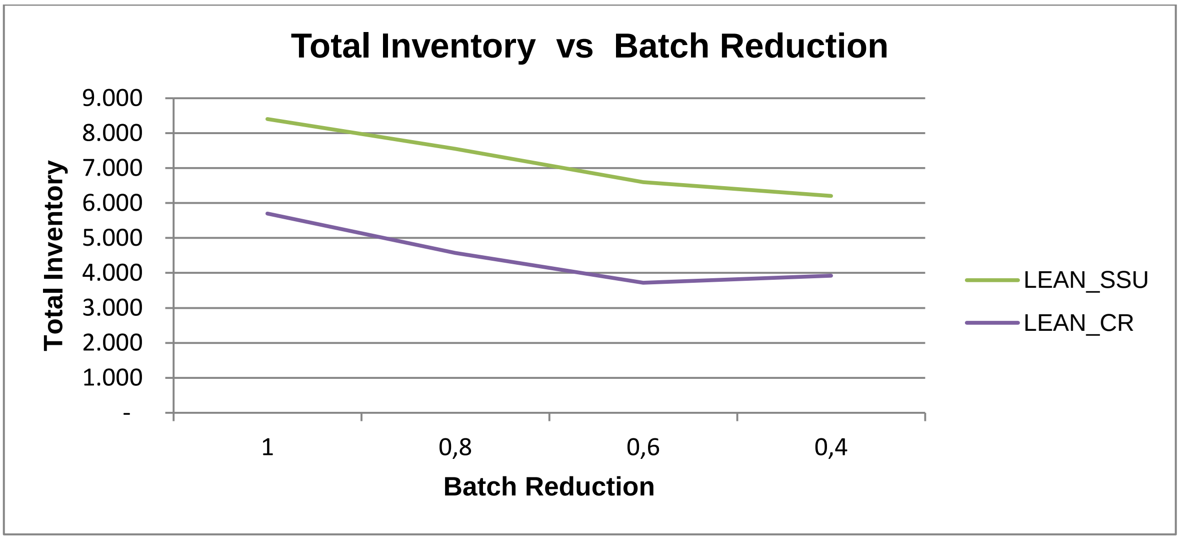
7.1.2. Related to the Batch Size

Analyzing the inventory level in function of the batch size for any service level, we can observe again that the criticality rule ensure less stock than the shortest set-up rule for any batch size.

Table 13. Inventory level depending on the batch size for Kanban models

Batch Reduction	LEAN_SSU	LEAN_CR
1	8.402	5.704
0,8	7.548	4.572
0,6	6.597	3.720
0,4	6.208	3.917

Graph 7. Inventory level depending on the batch size for Kanban models



As shown in graph 7, using small batch, the inventory tends to be lower to a point where the reduction in inventory is not possible for the criticality model. This point, corresponds with a batch reduction of 40% (LEAN_CR_0,6). According to the shortest set-up dispatching rule, from this point, the reduction in inventory continues to be significant but with a lower slope.

7.1.3. Related to the Saturation Scenarios

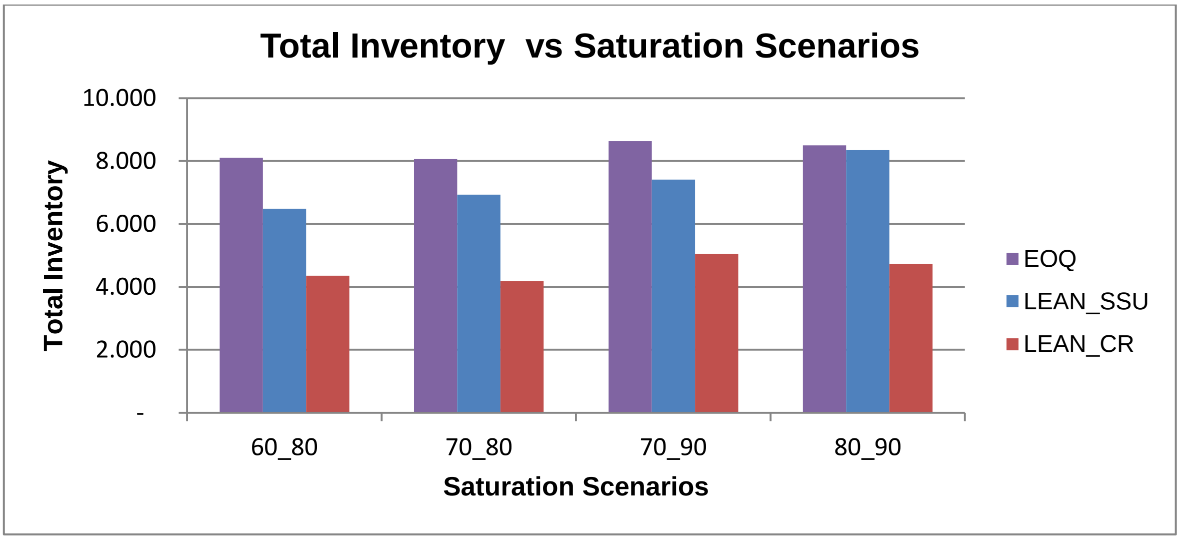
In this section, we will analyze the behavior of the inventory level for different levels of saturation. As it can be seen in the next tables and graphs, it also depends on the saturation of the process.

We can obverse in table 14 and graph 8 that for any saturation case, the best model to apply in terms of inventory level is tha Kanban using the criticality dispatching rule and the worse one for any saturation level is the EOQ model. It is important remark that the higher the saturation level the worse the shortest set-up model in front of the others.

Table 14. Inventory level depending on the saturation scenarios

Saturation	EOQ	LEAN_SSU	LEAN_CR
60_80	8.104	6.487	4.357
70_80	8.064	6.934	4.181
70_90	8.636	7.408	5.049
80_90	8.505	8.354	4.745

Graph 8. Inventory level depending on the saturation scenarios for each model



To continue, the stability in the level of inventory by saturation production will be analyzed beyond that the higher the saturation of production, the higher the inventory level.

Table 15. Inventory level depending on the production saturation

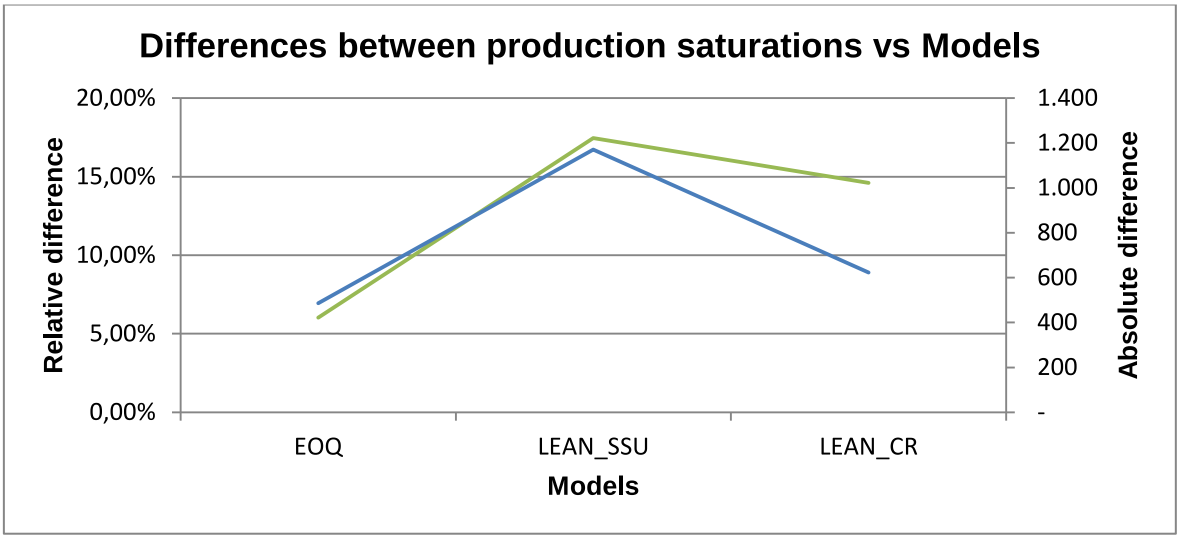
Saturation	EOQ	LEAN_SSU	LEAN_CR
X_80	8.084	6.710	4.269
X_90	8.570	7.881	4.892

As shown in table 16 and graph 9, the model which is more stable in front of variations in the saturation production is the EOQ system. The variation of the others systems is between 2 and 3 times higher than the EOQ systems variation, according to the saturation in production. Comparing the stability between both Kanban systems in percentage is very similar but in the amount of inventory is much higher in the shortest set-up dispatching rule.

Table 16. Increase of inventory level according to the increase of production saturation

Models	Relative	Absolut
EOQ	6,02%	486
LEAN_SSU	17,45%	1.171
LEAN_CR	14,60%	623

Graph 9. Relative and absolute increase of inventory level according to the increase of production saturation



To analyze the inventory level according to the process saturation, we will divide the scenarios analyzed into high and low difference between process and production saturation.

- High difference: Scenarios 60_80 and 70_90
- Low difference: Scenarios 70_80 and 80_90

It must be stressed that the difference between the process and production saturation is called set-up saturation due to the time required to process the items plus the time required for the set-up is equal to the total production time.

Table 17. Inventory level depending on the process saturation

Difference	EOQ	LEAN_SSU	LEAN_CR
High	8.370	6.948	4.703
Low	8.285	7.644	4.458

The results in table 18 shown again that the most stable system is the EOQ due to its variation is the lowest one even in absolutes term when this system is the one with highest inventory.

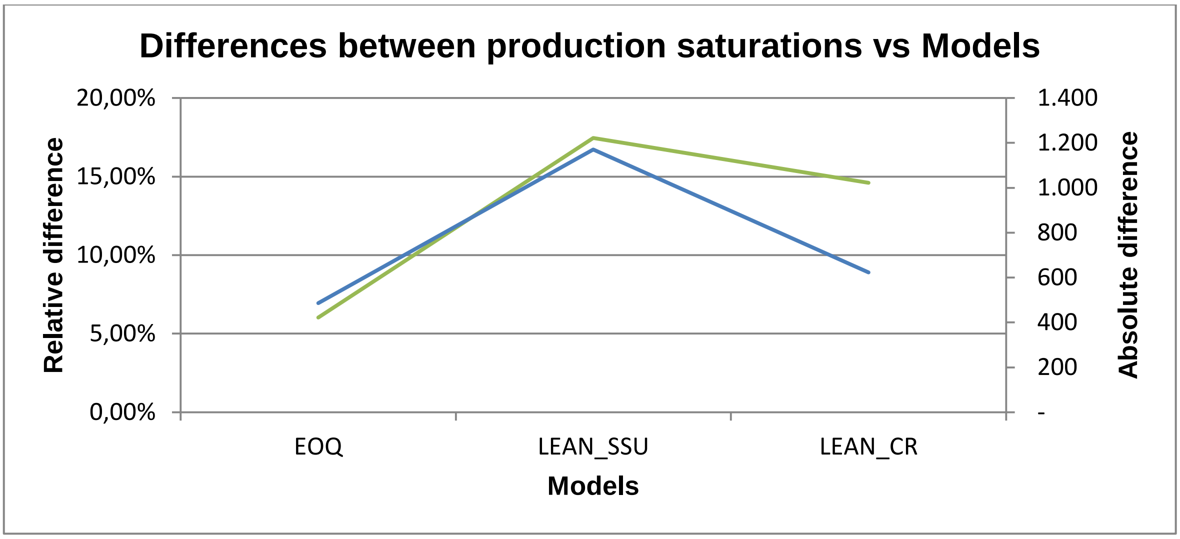
Table 18. Variation inventory level according to the reduction of set-up saturation

Models	Relative	Absolute
EOQ	-1,01%	-85
LEAN_SSU	10,02%	696

LEAN_CR	-5,21%	-245

We should remark that high differences between process and production saturation are favorable for the Kanban system applying criticality dispatching rule and unfavorable for the one which use the shortest set-up dispatching rule.

Graph 10. Relative and absolute variation inventory level according to the reduction of set-up saturation



To know how much better each model is compared to the others for any saturation scenario, we will compare the inventory level of the Kanban models for each saturation scenario to the EOQ system.

As it was said before, the best model for any saturation scenario is the Lean model using a the criticality dispatching rule. Using this model, the inventory in stock saved is around the 50%-55% of the available stock using the EOQ model.

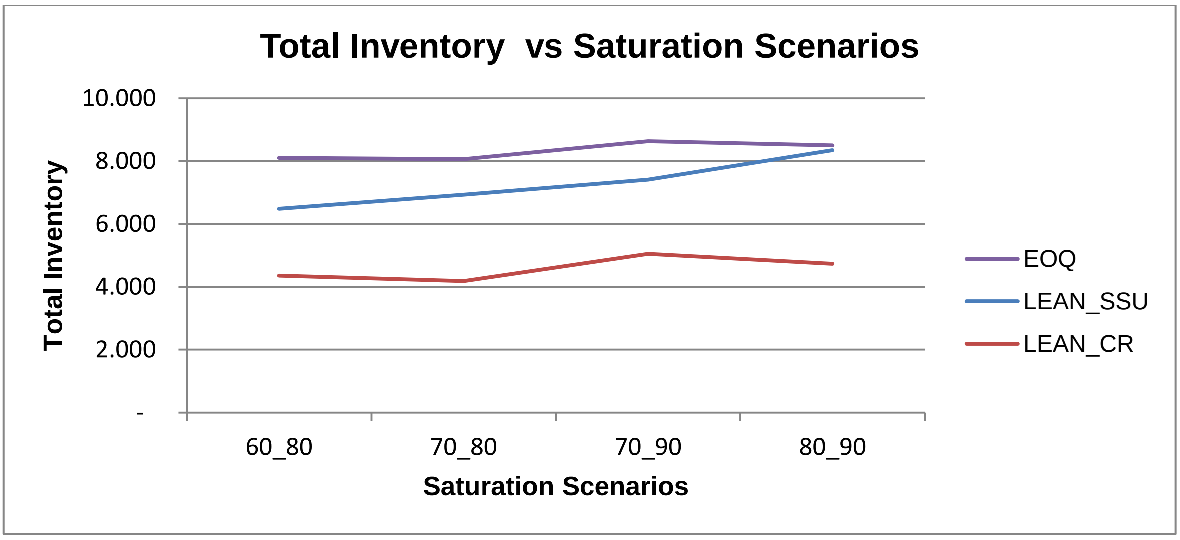
But, if we compare the EOQ model with the Kanban with shortest set-up, we can observe in table 19 and graph 11 that the higher the saturation, the better the EOQ system compared to Kanban with shortest set-up dispatching rule. Despite of this, the shortest set-up model is better that the EOQ system for any saturation scenario.

Table 19. Percentage of inventory items related to the EOQ inventory depending on the saturation scenarios

Saturations	EOQ	LEAN_SSU	LEAN_CR
60_80	100%	80,1%	53,8%
70_80	100%	86,0%	51,8%
70_90	100%	85,8%	58,5%

80_90	100%	98,2%	55,7%

Graph 11. Percentage of inventory items related to the EOQ inventory depending on the saturation scenarios



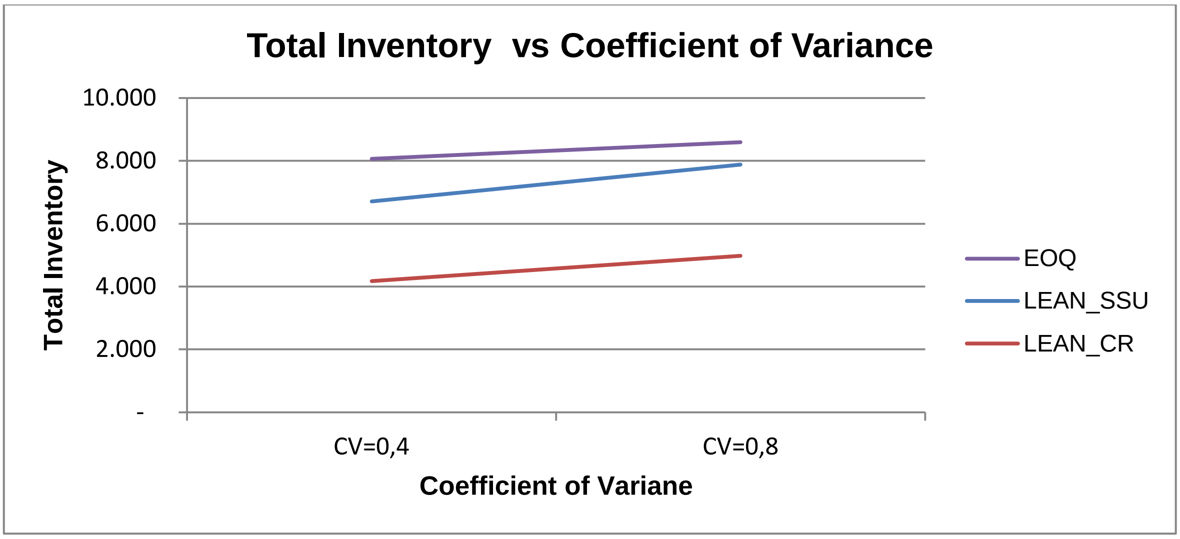
7.1.4. Related to the Coefficient of Variance

The coefficient of variance has an important effect to the inventory level. As is obvious, the greater the demand variation the higher the inventory level necessary to ensure the quality service required for any model. This statement is corroborated on the following table and graph.

Table 20. Inventory level depending on the demand variability

CV	EOQ	LEAN_SSU	LEAN_CR
0,4	8.062	6.710	4.178
0,8	8.592	7.882	4.983

Graph 12. Inventory level depending on the demand variability



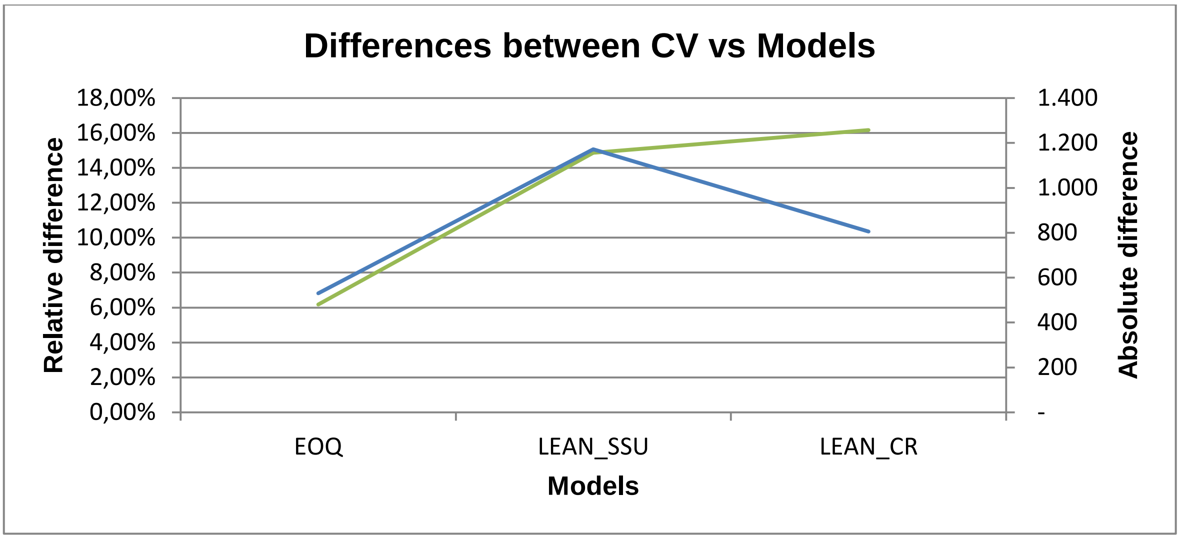
But the most important to analyze in this section, is the behavior of the different models in front of the demand variability. Which one presents less variance in inventory level for stable and unstable demands?

Comparing the inventory in stock with demands with high variability (coefficient of variance equal to 0,8) and low variability (coefficient of variance equal to 0,4), it can be observed as shown in table 21 and graph 13 that the EOQ system is the one bears better the changes in demands. For this system, is easy to adapt to changes in the demand stability and the one which bears worse these kinds of changes is the Kanban model using the criticality dispatching rule.

Table 21. Increase of inventory level according to the increase of demand variability

Models	Relative	Absolut
EOQ	6,17%	530
LEAN_SSU	14,87%	1.172
LEAN_CR	16,17%	806

Graph 13. Relative and absolute increase of inventory level according to the increase of demand variability



Even this, Kanban systems and specially the one which use the criticality dispatching rule need much less stock than the EOQ system for both coefficients of variance.

7.2. Transportation Analysis

The trucks with capacity to transport 450 units of any products are shipped from one manufactory to the next stage with products and then, they are returned empty to be filled again on the manufactory and start the same route. Then, each truck is able to release many routes during the 2.000 days simulated.

In this section, when it is talked about trucks, the real meaning is routes. When we talk about a full truck load, we are talking about one route with a full truck and the same when it is talked about non-full or less than truck load.

7.2.1. Related to the Service level

Total transport from PM to SM and from SM to retailers

As shown in table 22 and graph 14 the system which requires more trucks is the Kanban model using the criticality dispatching rule although both Kanban systems require similar number of trucks and the one which needs less trucks is the EOQ system. In this graph, all trucks of the supply chain have been taken into account, full and non-full trucks from the PM to the SM and also from the SC to the retailers.

It seems that the number of trucks provides variations depending on the service level required for the Kanban models and also for the EOQ system. The higher the service level, the lower the trucks required for the EOQ system and the Kanban system with criticality dispatching rule. It is related to the backlog, if a higher service level is requires, a lower backlog level is necessary and less pieces have to be sent later with another transport to satisfy the delay.

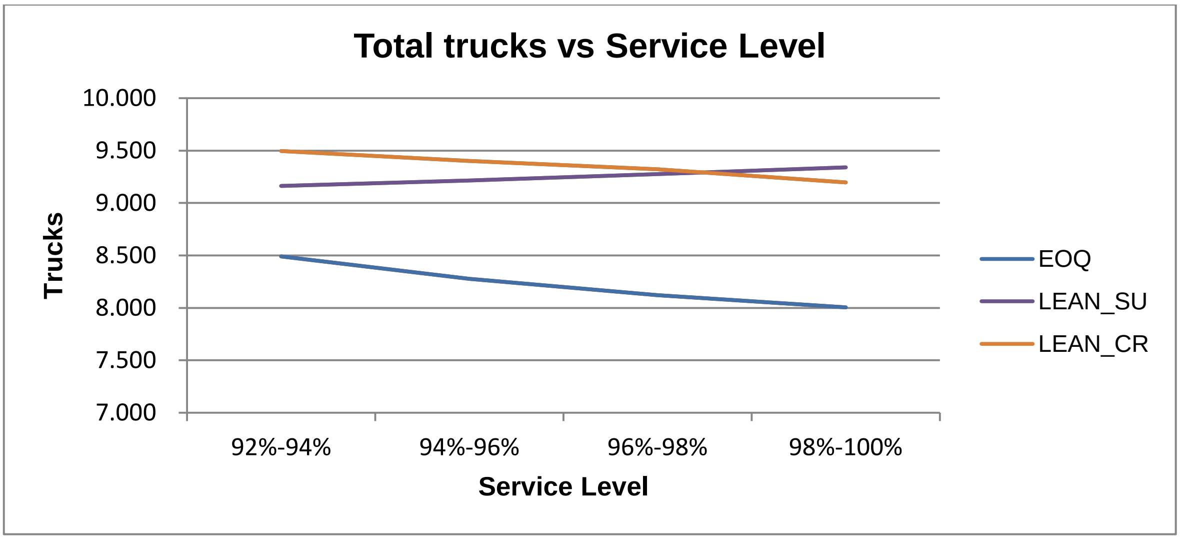
Otherwise, in the case of the Kanban system using the shortest set-up dispatching rule, the higher the service level the higher the trucks needed to carry the products to the next stage. It is because of the risk of being run out of products that is much higher in the shortest set-up model since the aim of the criticality model is minimize the backlog.

Using the Kanban system, the shortest set-up dispatching rule needs less trucks than the criticality model for services levels lowers than 98% and in the other way for higher levels of service.

Table 22. Trucks depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR
92%-94%	8.490	9.164	9.497
94%-96%	8.276	9.216	9.400
96%-98%	8.121	9.275	9.323
98%-100%	8.006	9.339	9.198

Graph 14. Trucks depending on the service level for each model



It can also be seen that the difference in trucks level using the shortest set-up dispatching rule compared with the criticality rule is very small for high service levels and greater as lower the service level.

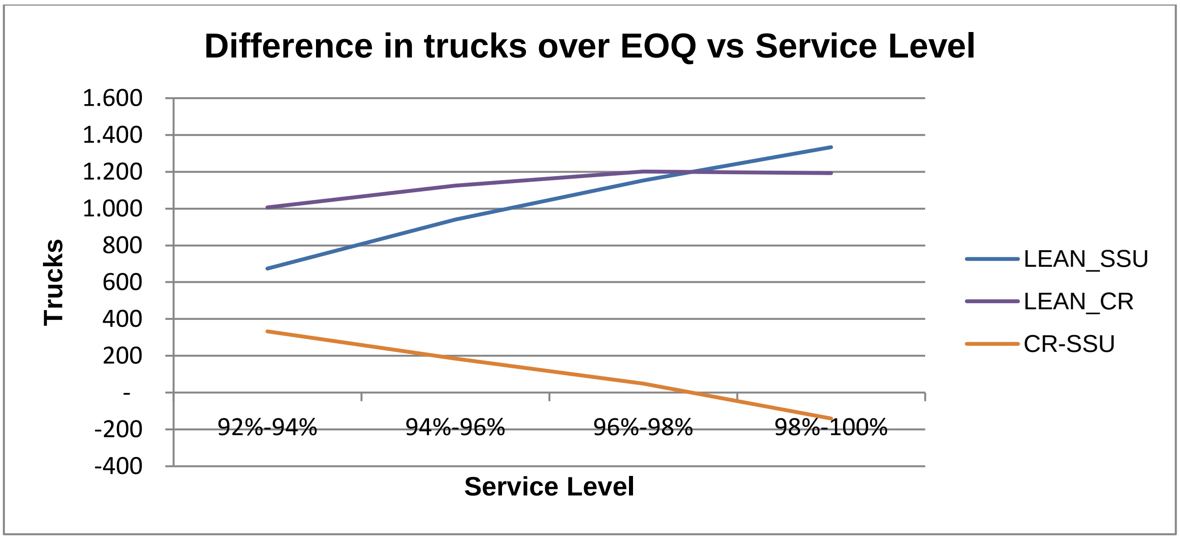
In the following graph 15 and table 23, it can be seen the difference in routes done comparing both lean approaches to the EOQ.

Graph 15 and table 23 show that the differences in trucks number are greater as higher the service levels for both Kanban models, especially for the shortest set-up model. With this statement, we can conclude that the higher the service level, the worse the Kanban models since the difference in transports is higher. If we compare the trucks needed between both Kanban models, we can observe that the difference favorable to the shortest set-up dispatching rule is smaller as higher the service level and the criticality model is even better, in terms of transports, than the shortest set-up mode for levels of service higher than 98%

Table 23. Absolute trucks differences with EOQ system and between Kanban models depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR		CR - SSU
92%-94%	-	674	1.007		333
94%-96%	-	940	1.124		184
96%-98%	-	1.153	1.202		49
98%-100%	-	1.333	1.192		-141

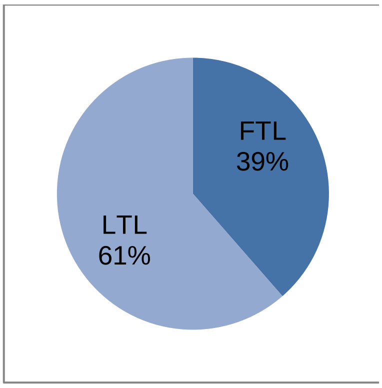
Graph 15. Absolute trucks differences with EOQ system and between Kanban models depending on the service level



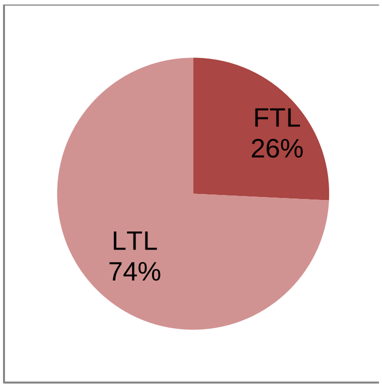
Now, we will distinguish between the number of FTL and LTL shipped through the supply chain depending also on the batch size.

For all of these three models, the conditions in demand are exactly the same and hence, the same products have to be delivered from the PM to the SM and then, from the SM to the retailers. The number of transports will depend on the batch size of these transports that is related to the capacity of the trucks. Since the capacity of the trucks is always the same, the system which fill more trucks and send them in FLT condition will requires less routes to satisfy the demand. And this is exactly what has happened, more FTL equals to less routes to do.

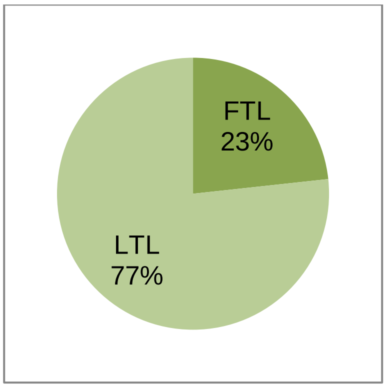
Graph 16. EOQ model



Graph 17. Lean_SSU model



Graph 18. Lean_CR model



In the following table, we can observe the percentage of full trucks used to carry the products to the next stages. Using the EOQ system, it is clear that the higher is the service level required the higher the percentage of full trucks in front of LTL and around the 37%-40% of the routes are done with FTL.

The model of Kanban approach also varies in function of the service level. It can be appreciated that as higher the service level, the higher the percentage of FTL using the criticality dispatching rule and otherwise for the shortest set up dispatching rule. Using the shortest set-up model, between the 28% and 25% of the routes are carried out with FTL for any service level and between the 21% and 24% are done with FTL using the criticality dispatching rule.

Table 24. Percentage of FTL depending on the service level

Service Level	EOQ	LEAN_SSU	LEAN_CR
92%-94%	37,9%	28,1%	21,9%
94%-96%	38,6%	26,8%	22,9%
96%-98%	39,0%	25,1%	24,0%

98%-100%	39,9%	23,2%	24,3%
Mean	**38,8%**	**25,8%**	**23,3%**

To continue, we will analyze how the percentages of FLT evolve in function not only the service level but also the batch size. The table 25 and 26 show us these percentages.

Table 25. Percentage of FTL depending on the service level and batch size for shortest set-up model

Service level	LEAN_SSU_1	LEAN_SSU_0,8	LEAN_SSU_0,6	LEAN_SSU_0,4
92%-94%	34,0%	31,4%	26,0%	21,4%
94%-96%	32,7%	30,1%	24,6%	20,2%
96%-98%	31,1%	28,6%	22,6%	18,6%
98%-100%	29,5%	26,5%	20,7%	16,7%
Mean	**31,8%**	**29,2%**	**23,5%**	**19,2%**

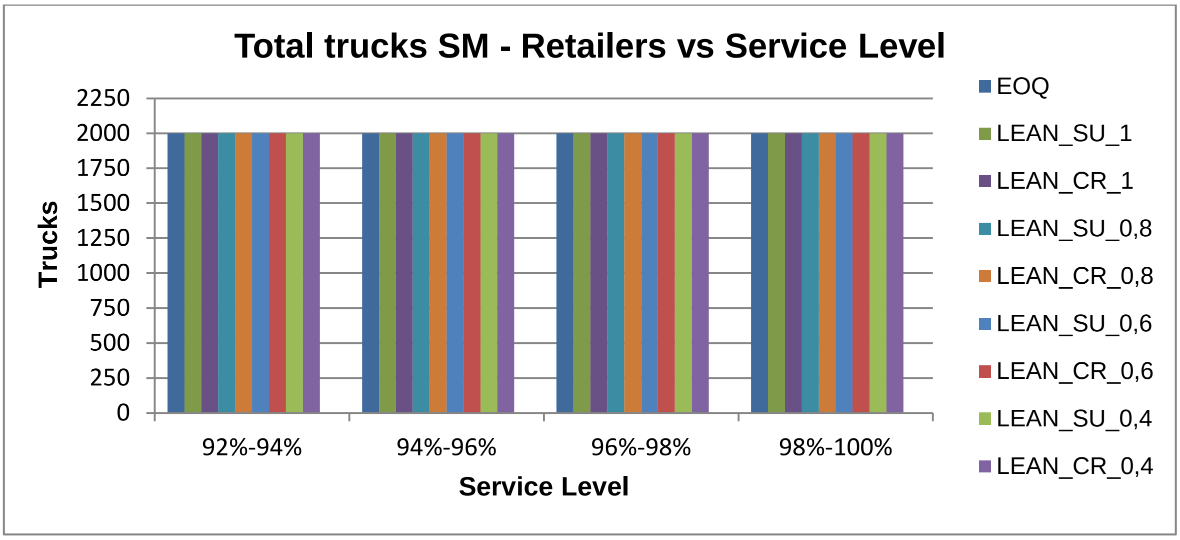
Table 26. Percentage of FTL depending on the service level and batch size for criticality model

Service level	LEAN_CR_1	LEAN_CR_0,8	LEAN_CR_0,6	LEAN_CR_0,4
92%-94%	26,9%	23,2%	19,4%	18,3%
94%-96%	28,0%	25,3%	19,9%	18,6%
96%-98%	29,5%	28,0%	20,4%	18,5%
98%-100%	30,4%	27,5%	20,9%	18,9%
Mean	**28,7%**	**26,0%**	**20,1%**	**18,6%**

The behavior comparing the percentage of FTL in front of the total trucks with the batch reduction is also very similar. The greater the batch size, the higher the proportion of FTL and hence, the lower the waste due to the trucks capacity when it is not full. In the shortest set-up model can be appreciated a higher difference in the percentage of FTL than applying the criticality rule for dispatching products when the batch size increases. Hence, the improvement in waste of trucks capacity increasing the batch size is more relevant using the shortest set-up dispatching rule.

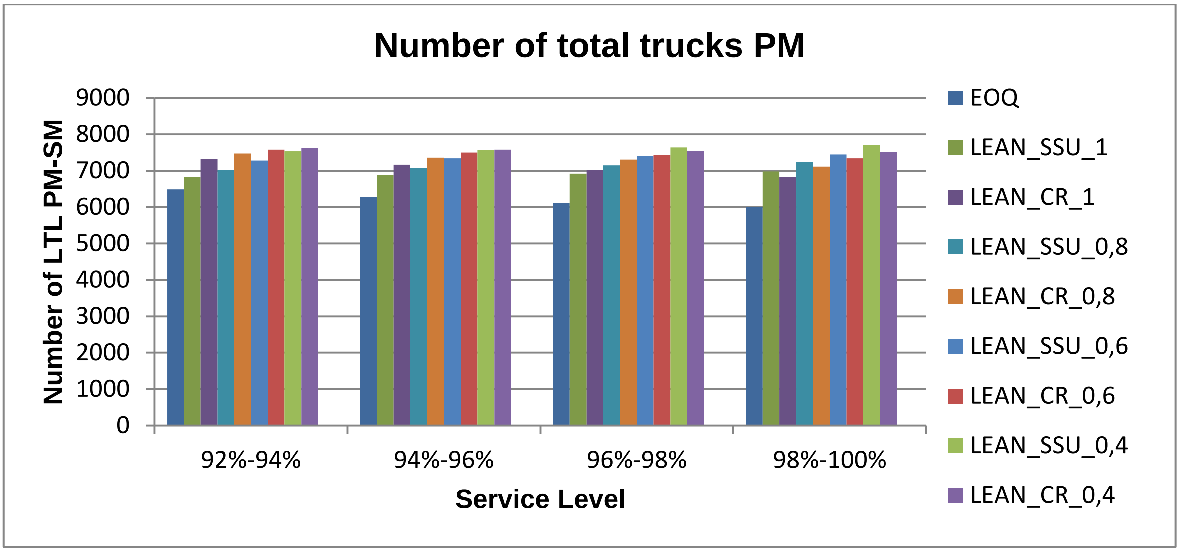
In the transport between the second manufactory and the retailers the total transport always remain equal to 2000 since one transport per day is obligated since there is at least one piece of any kind produced and stocked. There is not any day with more than one truck shipped because the daily production is not enough to fill more than one complete truck daily.

Graph 19. Total trucks from the SM to the retailers depending on the service level for each model and batch size.



In terms of the transport from the primaries manufactories to the secondary, the number of trucks shipped is not always 1 per day from each primary manufactory. As shown in graph 19, there is not any situation in which the trucks needed are equal to 8.000 that would be the same as 1 truck shipped per day from each PM (there are 4 PMs and 2.000 days simulated). Each primary manufactory runs only 6 kinds of products and the time available to produce is less than the available time of the SM. Hence, the orders to the PMs come less frequently and it is possible that some days no trucks are shipped.

Graph 20. Total trucks from the PM to SM depending on the service level for each model and batch size.



As we said before, the EOQ system is the one which makes fewer trips, we will compare how worse are the Kanban models for each service level and batch reduction in terms of number of trucks needed.

Table 27. Relative difference in number of trucks needed depending on the service level and batch size for criticality model

Service level	LEAN_CR_1	LEAN_CR_0,8	LEAN_CR_0,6	LEAN_CR_0,4
92%-94%	9,8%	11,5%	12,8%	13,4%
94%-96%	10,7%	13,1%	14,8%	15,8%
96%-98%	11,0%	14,6%	16,1%	17,5%
98%-100%	10,3%	13,8%	16,7%	18,7%
Mean	**10,5%**	**13,3%**	**15,1%**	**16,3%**

Graph 21. Relative difference in number of trucks needed depending on the service level for each batch size for criticality model

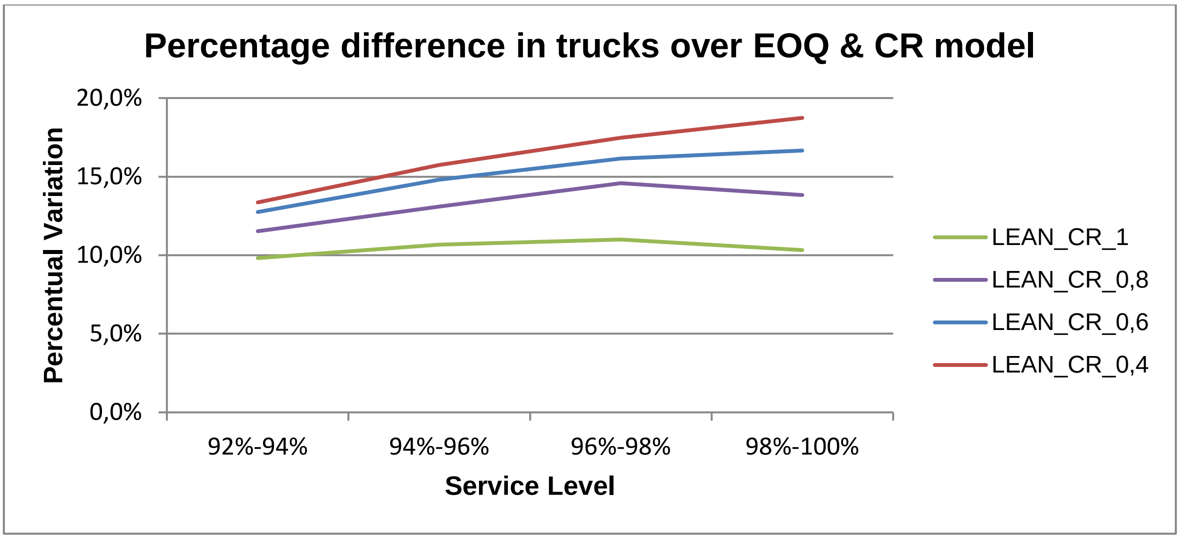
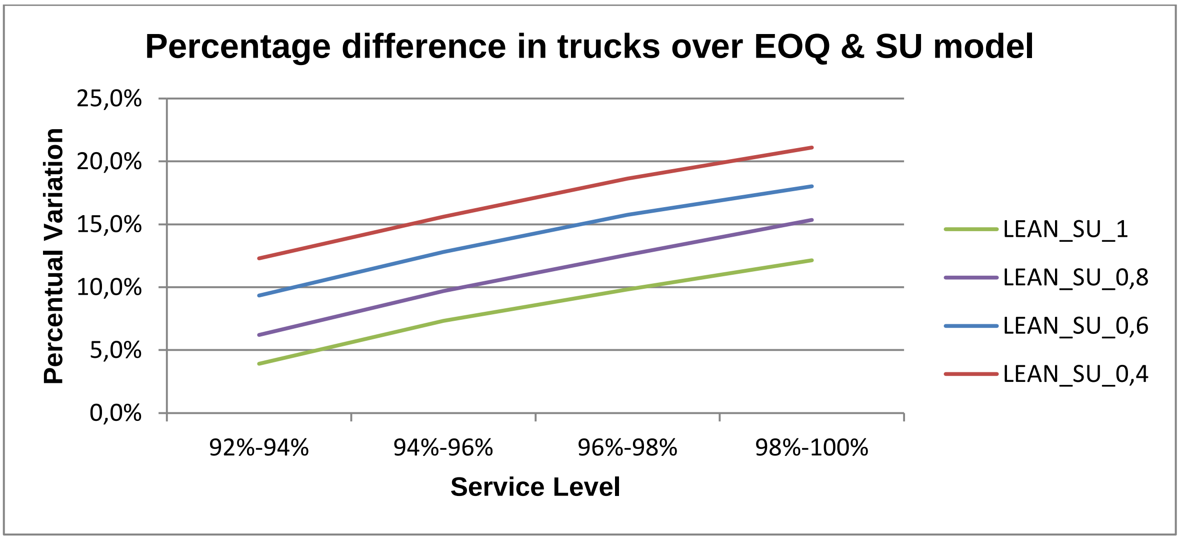


Table 28. Relative difference in number of trucks needed depending on the service level and batch size for shortest set-up model

Service level	LEAN_SSU_1	LEAN_SSU_0,8	LEAN_SSU_0,6	LEAN_SSU_0,4
92%-94%	3,9%	6,2%	9,3%	12,3%
94%-96%	7,3%	9,7%	12,8%	15,6%
96%-98%	9,8%	12,6%	15,7%	18,6%
98%-100%	12,1%	15,3%	18,0%	21,1%
Mean	**8,3%**	**11,0%**	**14,0%**	**16,9%**

Graph 22. Relative difference in number of trucks needed depending on the service level for each batch size for shortest set-up model



Both Kanban models needs more trucks to ensure the service level required than the EOQ system. Both of them have the same behavior in front of the service level and batch size. The higher the service level and the lower the batch size, the worse the Kanban models compared to the EOQ.

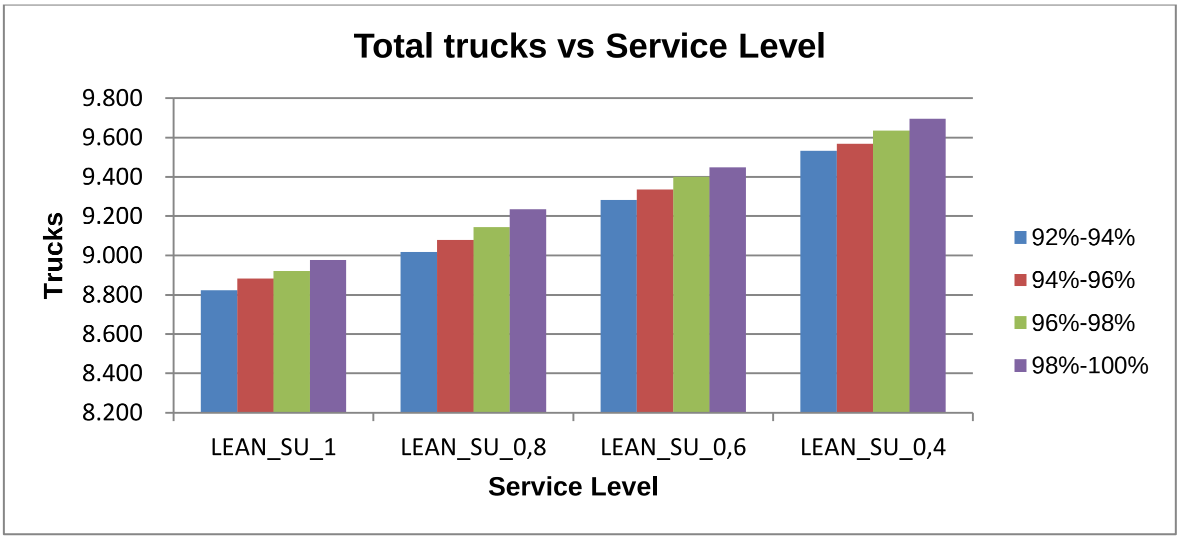
The main difference between both Kanban models is that the shortest set-up model has much greater variations depending on the batch reduction and the criticality model present much greater variation in function of the service level. One is more stable for the service level and the other is more stable for variations in the batch size, always comparing them to the EOQ model.

7.2.2. Related to the Batch Size

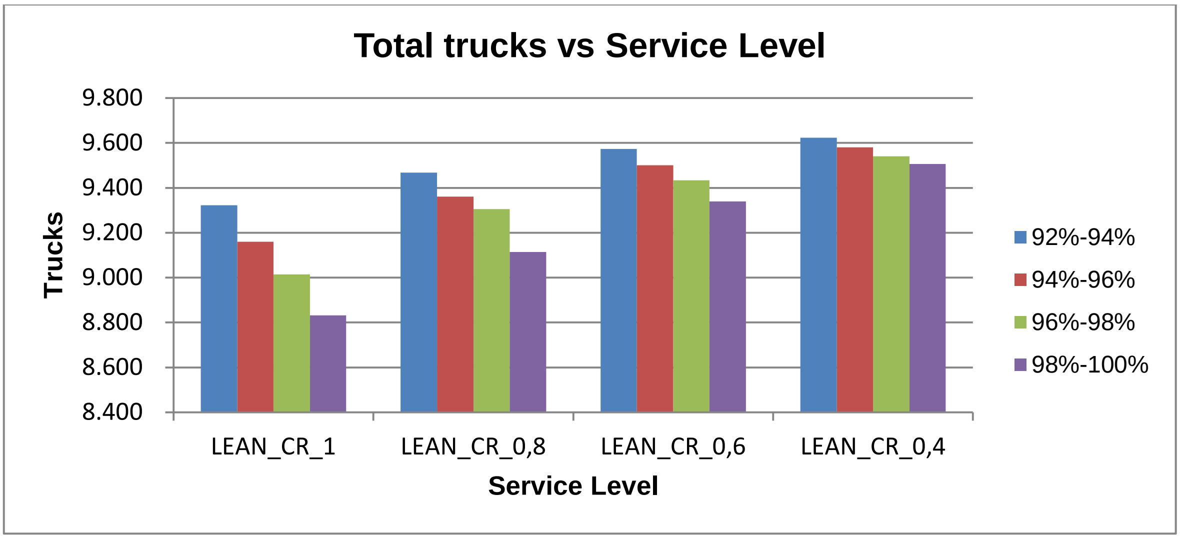
The lower the batch size the higher the number of trucks required to satisfy the demand ensuring a determined service level for both Kanban systems.

Considering the differences related to the service level for a fixed batch size, the Kanban system with the shortest set-up dispatching rule needs more trucks as higher the service level and the one which uses the criticality dispatching rule requires less trucks as higher the service level. This difference is due to the backlog level (the higher the backlog, the higher the amount of pieces to send later with another transport) and the rule of shortest set-up has much more risk to be run out of products than the criticality rule which aim is minimize the backlog.

Graph 23. Trucks depending on the batch size for each service level and shortest set-up dispatching rule



Graph 24. Trucks depending on the batch size for each service level and criticality dispatching rule



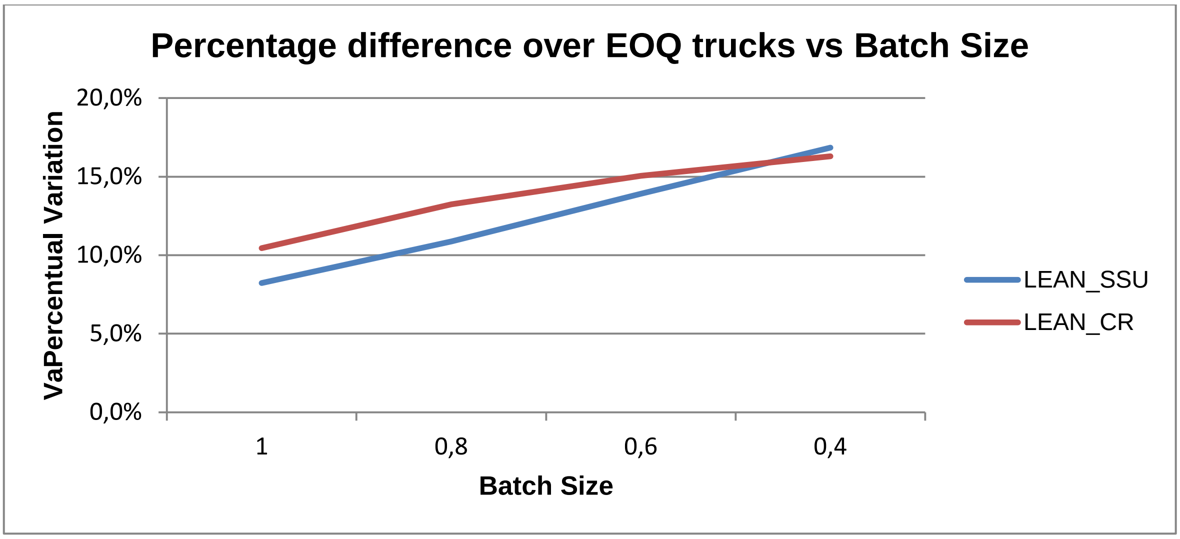
The differences in number of trucks is only related to the trucks that are moved from the PM to the SM due to the trucks shipped from the SM is always one per day, 2.000 in the whole simulation for all cases.

It was said in the previous section that in the PM not always one truck is sent to the SM and it is proportional to the frequency of the orders. The higher the frequency of new production orders, the higher the days with production and hence, the higher the days with a truck sent to the next stage. Related to this statement is the behavior of the number of trucks necessaries in function of the batch size. The lower the batch size, the higher the orders frequency and hence, the higher the trucks required to send products to the next stage.

Comparing the relative difference between both Kanban models and EOQ model, it can be observed that the higher the reduction in batch, the higher the difference and hence, the worse the models in comparison with the EOQ system.

In general, the system with shortest set-up rule requires less trucks that the one which uses the criticality dispatching rule but the higher the batch reduction, the lower the difference favorable to the shortest set-up model since the point where with a batch reduction of the 60% (coefficient of 0,4), the system with criticality rule the best of both Kanban systems related to the trucks needed.

Graph 25. Percentage of additional trucks needed for Kanban models depending on the batch size



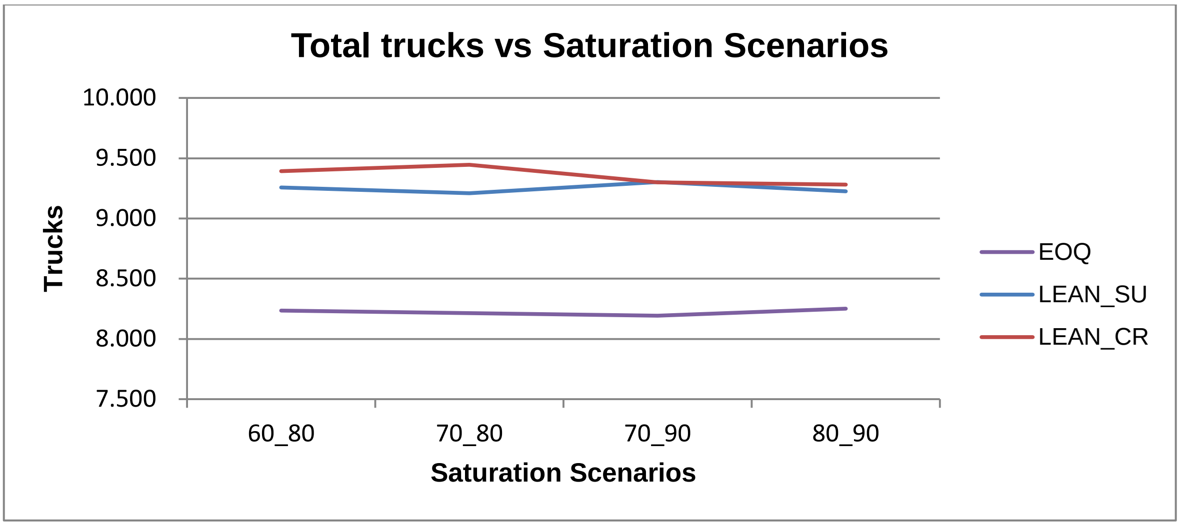
7.2.3. Related to the Saturation Scenarios

The EOQ system and shortest set-up model does not present differences in the number of trucks necessaries to carry the materials from one stage to the next one varying the system saturations. However, the Kanban system with the dispatching rule of criticality present few variations on the amount of trucks needed depending on the production saturation.

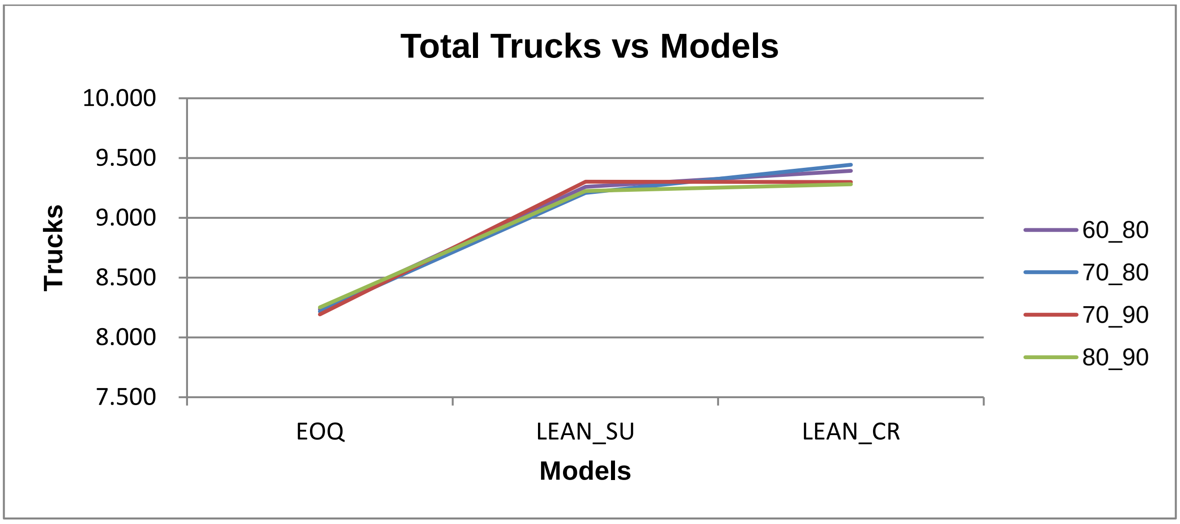
Table 29. Total trucks depending on the saturation scenarios

Saturation	EOQ	LEAN_SSU	LEAN_CR
60_80	8.235	9.258	9.394
70_80	8.215	9.209	9.445
70_90	8.192	9.302	9.299
80_90	8.251	9.225	9.280

Graph 26. Total trucks depending on the saturation scenarios for each model



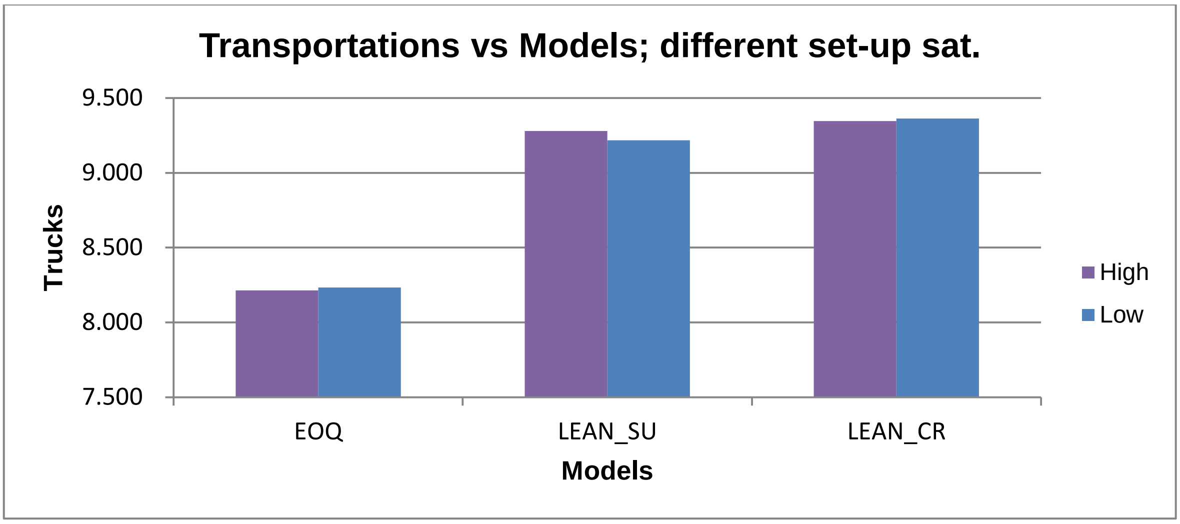
Graph 27. Total trucks depending on the model for each saturation scenario



The graph 27 shows that the EOQ and shortest set-up model does not present variances for different saturations but the criticality model does. This difference is present when varies the production saturation (graph 29) that can be 80% or 90% regardless of the process saturation, hence, it does not depends on the set-up saturation as shown in graph 28.

It must be stressed that the difference between the process and production saturation is called set-up saturation that is 10% or 20% for each production saturation that is 80% and 90%.

Graph 28. Total trucks depending on the model for each set-up saturation



Graph 29. Total trucks depending on the model for each production saturation

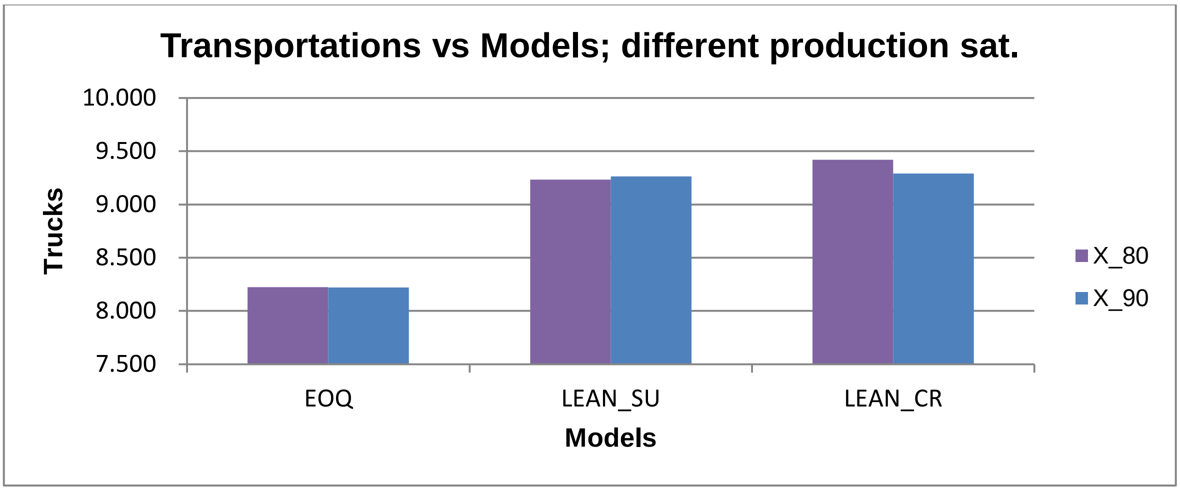
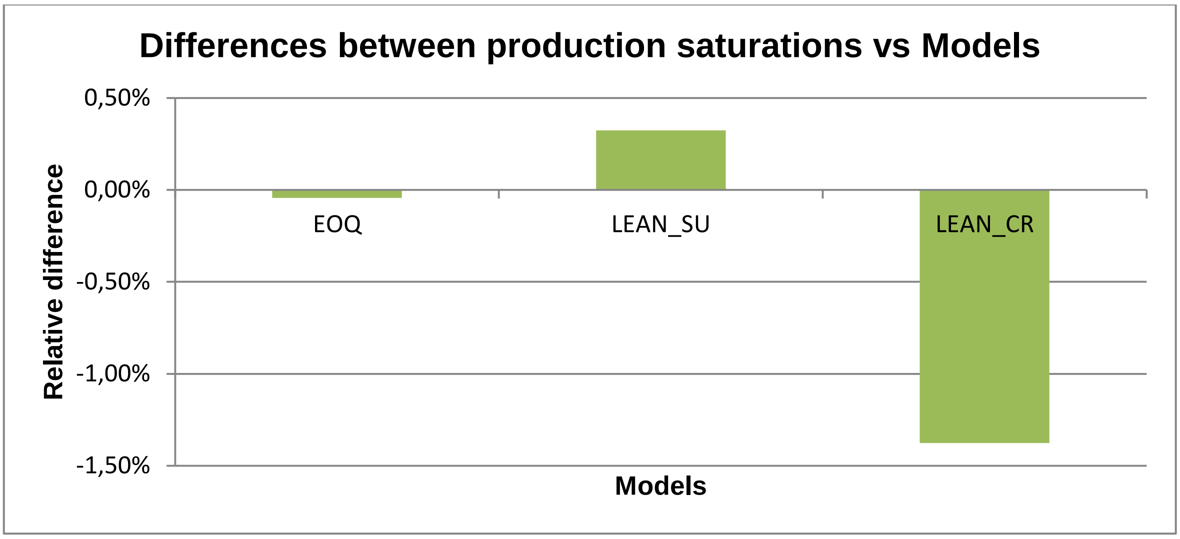


Table 30. Relative and Absolute difference between production saturations

Model	Relative	Absolut
EOQ	-0,04%	-4
LEAN_SSU	0,32%	30
LEAN_CR	-1,38%	-130

As we can see in the table 30, the differences in trucks needed are not very high varying the production saturation. Hence, all three systems are very stable varying the saturations that is the same that they are stable for different demand rates that implies more or less saturation in the supply chain.

Graph 30. Relative difference between production saturations



As shown in graph 30, even though all of them are very stable, there is a huge different between the variance of the Kanban system using the criticality dispatching rule and the others models being this one the less stable.

7.2.4. Related to the Coefficient of Variance

The coefficient of variance does not have an important effect to the trucks needed to transport the pieces as we can see in table 31 and graphs 31 and 32.

Graph 31. Trucks depending on the model for each coefficient of variance

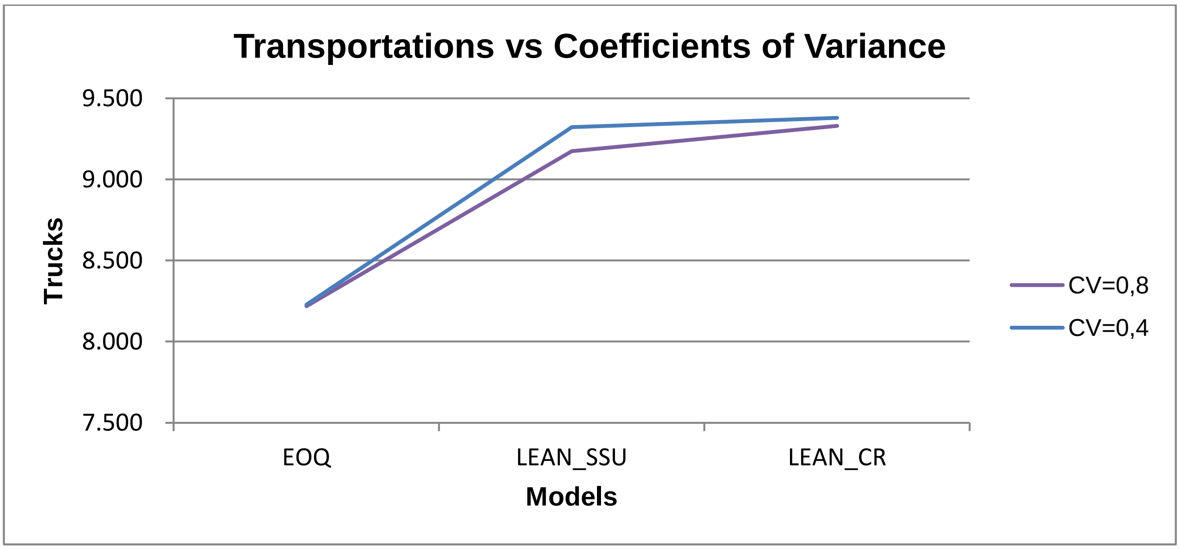
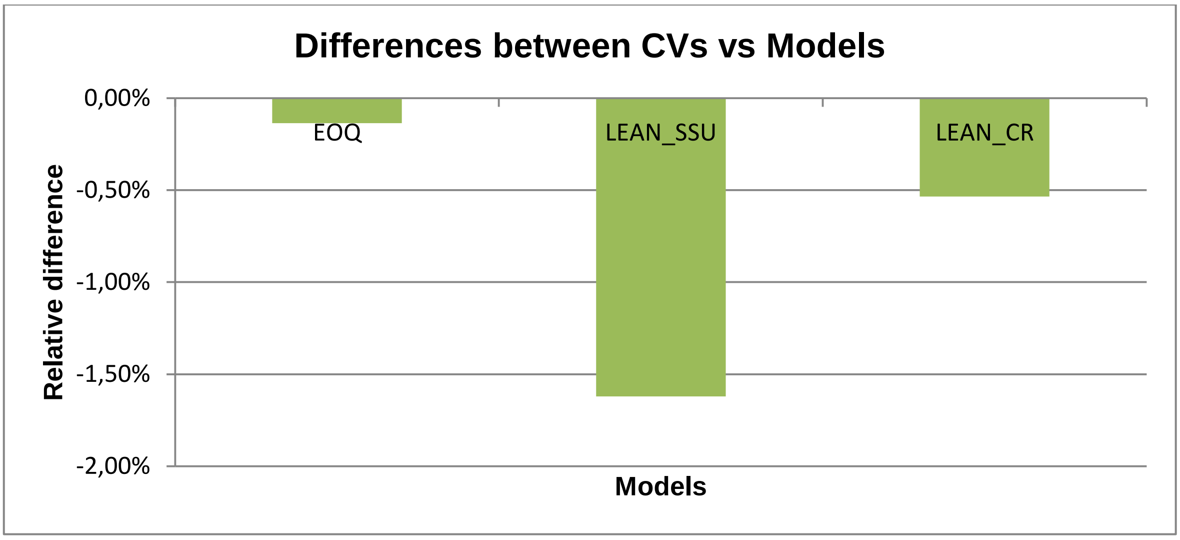


Table 31. Relative and absolute difference between CV

Model	Relative	Absolut
EOQ	-0,14%	-11

LEAN_SSU	-1,62%	-149
LEAN_CR	-0,53%	-50

Graph 32. Relative difference between coefficients of variance



The system which has more variability in the trucks number needed is the Kanban system with the shortest set-up dispatching rule but its variation is less than 2%. Hence, we cannot considerate effective variations with respect to the different coefficients of variance for any model, neither EOQ neither Kanban.

To go further in detail, we will compare the behavior of full trucks and non-full trucks regarding to the variability in demand.

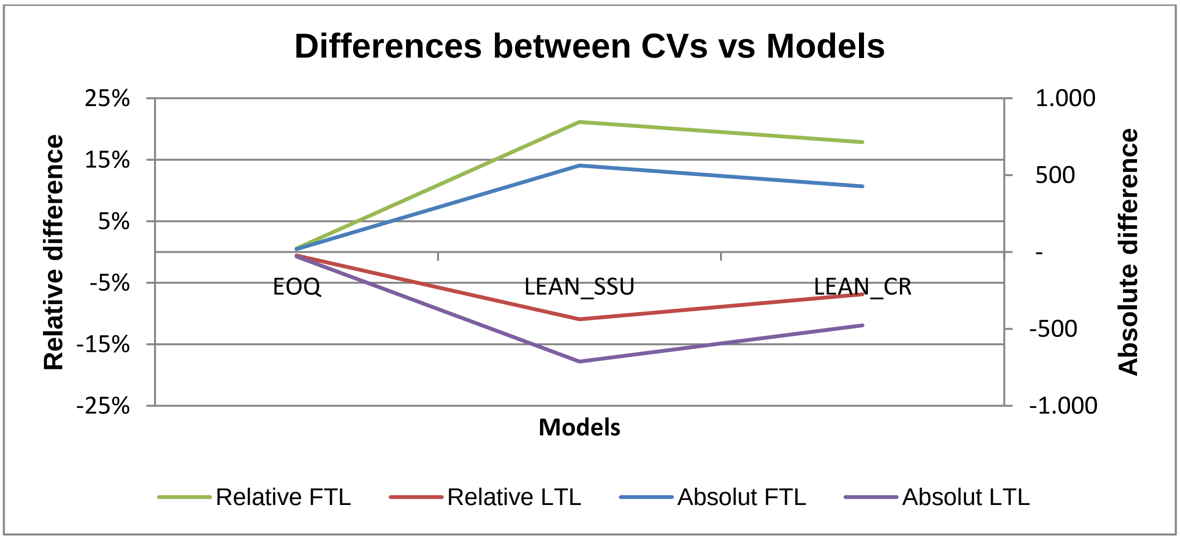
Table 32. Total trucks depending on the coefficient of variance and the full or non-full condition

	LTL		FTL	
Models	**CV=0,8**	**CV=0,4**	**CV=0,8**	**CV=0,4**
EOQ	5.016	5.046	3.202	3.183
LEAN_SSU	6.510	7.222	2.664	2.101
LEAN_CR	6.939	7.416	2.391	1.963

Table 33. Relative and absolute difference between coefficients of variance for total FTL and total LTL

	LTL		FTL	
Models	**Relative LTL**	**Absolut LTL**	**Relative FTL**	**Absolut FTL**
EOQ	-0,59%	-30	0,57%	18
LEAN_SSU	-10,94%	-712	21,14%	563
LEAN_CR	-6,88%	-477	17,88%	427

Graph 33. Relative and absolute difference between coefficients of variance for total FTL and total LTL for each model



As we can observe in graph 33 and table 33, the EOQ system does not present any difference in the number of FTL changing the demand stability (or changing the coefficient of variance) and consequently, nor differences in the number of LTL. But, both Kanban systems do with the same behavior.

The total trucks needed for both Kanban system does not vary for different CVs but the condition of these trucks do. For high variabilities in demand (CV=0,8) more trucks are shipped under the condition of FTL and otherwise, for low variabilities in demand (CV=0,4) more trucks are send under the condition of LTL.

8. Conclusions

After analyze the results obtained with the 120 simulations done with the Arena software, 40 with each model (EOQ, Kanban with shortest set-up dispatching rule and Kanban with criticality dispatching rule) and some different conditions in terms of demands, demands variability, saturations, batch sizes and levels of service, we got some conclusions.

The service level depends on the availability of the products to deliver to the next stage and at the end, to the customers. Few stocks imply more risk of being out of stock and consequently, the probability of do not provide products to the next step increase.

"The higher the inventory level the higher the level of service provided"

The first aim of this project is to show that Kanban systems are more competitive than EOQ systems.

"EOQ system is the one which more inventory needs to satisfy the customers' demands for any service level"

The Kanban system using the criticality dispatching rule requires between 40% and 50% less stock than the EOQ model, the highest differences are for low levels of service. Otherwise, the highest differences favorable to the Kanban system with the shortest set-up dispatching rule are for high levels of service. Using the shortest set-up dispatching rule, the reduction in the inventory level is between 5% and 20%.

"The shortest set-up model has more improvements in the amount of inventory needed as lower the batch size compared to the others systems"

The objective applying this rule is minimize the set-up time, hence, the greater the number of set-ups the greater the benefits compared to the others systems. In the case of the criticality dispatching rule and Kanban system, its best in terms of inventory compared to the EOQ system is for a batch reduction of 60%.

"The lower the batch size the lower the inventory"

This statement is quite obvious, after each batch production, the greater the batch size the greater the stock for any model. It has to be stressed that as lower is the batch size, more difficult is the improvement in the inventory reduction.

The model which varies less in function of the saturations is the EOQ. This statement is probably because the system is not totally saturated. We proved that…

"…the Kanban system with shortest set-up dispatching rule is less saturated with the same input data on the supply chain"

It would be interesting for future research, to analyze systems totally saturated and show the differences in saturations with the same input data.

"The greater the demand variation the higher the inventory level necessary to ensure the quality service required for any model"

If the demand is less stable there are more backlogs and more products with no demand. The behavior is more extreme in both sides of the demand. Comparing the inventory in stock with demands with high variability and low variability the EOQ system is the one bears better the changes in demands.

In terms of necessary transports to ensure the service, …

"…more trucks are needed using the Kanban systems,…"

…especially the one which uses the criticality dispatching rule. It is because the frequency of the orders in Kanban systems are higher than for the EOQ system.

Using the Kanban system, the shortest set-up dispatching rule needs less trucks than the criticality model for services levels lowers than 98% and in the other way for higher levels of service. The criticality dispatching rule has more risk of being out of stock as higher is the service level. Hence, the higher the service level the better the behavior of the criticality rule compared to the shortest set-up.

"The higher the service level required the higher the percentage of FLT in front of LTL"

The higher the service level, the higher the amount of products delivered to the next stage and consequently, more volume has to carry the trucks and more trucks are full.

"The sum of FTL and LTL from the PM to the retailers is 2.000 for any case, one per day"

One transport per day is obligated either in condition of FTL or LTL and no more can be release because the demand and production capacity is not enough to full two trucks in one day. The amount of trucks shipped from the PM to the SM is not one per day (2.000 trucks) from each primary manufacturer because no orders are send every day to every PM.

"The higher the service level and the lower the batch size, the worse the Kanban models compared to the EOQ"

It is known that the lower the batch size and the higher the service level, the higher the production orders and consequently the higher the amount of trucks shipped from the PM to the SM. Remember that the batch size for the EOQ systems always remains equal.

The main difference between both Kanban models is that the shortest set-up model has much greater variations depending on the batch reduction and the criticality model present much greater variation in function of the service level. The shortest set-up lost efficiency for small batches because the frequency of orders increment much more than for the criticality dispatching rule.

"The higher the batch size the higher the percentage of FLT in front of LTL"

As more products are produced in each order, ore probabilities to fill the trucks. Aligned to this, the lower the batch size, the lower the percentage of FTL and hence, the higher the trucks needed.

The differences in the trucks needed to transport the total number of products from one stage to the other are related to the backlog and the frequency in production orders.

"The higher the backlog the higher the amount of pieces to send later with another transport"

"The higher the production orders the higher the number of days with production on the PMs and hence, the higher the transports to do"

All three systems are very similar for different saturations; it means that all of them are very stable for different demands rates.

The coefficient of variance neither has an important effect on the transports needed. The variation due to the demand variability is in all cases lower than 2%.

The EOQ system needs the same amount of trucks to transport the products to the next stage and even more, in both cases, the FTL represents the 40% of the total transports. But, both Kanban systems present differences not on the total amount of trucks but on the condition of these.

"The percentage of FTL for high demand variability is higher than for low demand variability"

To send a LTL it does not mind the quantity of products to carry. Then, the variability does not influence to do not ship a truck. Otherwise, the variability can influence to fill at maximum capacity any truck.

9. Future Research

Possible future research aligned to this project:

- Evaluate the costs of the supply chain, not only in terms of quality as it was done in this project (inventory and transport) but also in terms of quantity.
- Set physical situations of the manufacturer to be able to calculate the real cost of transport.
- Change the model of transportation in order to do routes between the different PMs. If some PMs have not produced enough products to ship a FTL, the trucks can go to other manufacturers to carry those products and continue the route to the SM.
- Evaluate both Kanban systems with full process capacity for EOQ system or criticality model to ensure that the shortest set-up model will need less set-up time and it will affects the saturation production and its productivity. With shortest set-up time, more products will be able to be produced.
- It will be interesting that the SM acts like an assembly organization which requires some specific products to get others. For example:
    - Product 1, 3, 7 and 16 to produce the product A
    - Product 4,7, 15, 10 and 21 to produce the product B
    - Etc.

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11.Acknowledgment

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Furthermore, I would also like to acknowledge all of those people who made my stage in Milano easier, having great experiences and feeling at home in every moment.

Annex 1. Tables about reviewed characteristics

Table 34. Articles published categorized by country and continent

Country	No. of articles	%
United States	24	36,9%
United Kingdom	14	23,1%
Taiwan	4	6,2%
France	3	4,6%
Netherlands	2	3,1%
Sweden	2	3,1%
Germany	2	3,1%
India	2	3,1%
Japan	2	3,1%
Canada	1	1,5%
Spain	1	1,5%
Greace	1	1,5%
Belgium	1	1,5%
Colombia	1	1,5%
Brazil	1	1,5%
Switzeland	1	1,5%
Poland	1	1,5%
Italy	1	1,5%
Total	64	100%

Continent	No. of articles	%
North America	25	38,5%
Europe	29	46,2%
Asia	8	12,3%
South America	2	3,1%
Total	64	100%

Table 35. Articles published categorized by journal

Journal	No. of articles
International Journal of Production Economics	9
Journal of Operations Management	9
European Journal of Operational Research	7
International Journal of Operations and Production Management	4
International Journal of Physical Distribution and Logistics Management	4
International Journal of Production Research	4
Industrial Management and Data Systems	2
Journal of the Operational Research Society	2
Management Science	2
Supply Chain Management	2
Annals of Operations Research	1
Applied Mathematical Modelling	1
Business Process Management Journal	1
Canadian Journal of Emergency Medicine	1
Computer Integrated Manufacturing Systems	1
Computers in Industry	1
Construction Management and Economics	1
Electronic Scientific Journal of Logistics	1
Engineering, Construction and Architectural Management	1
European Management Journal	1
Factory, the Magazine of Management	1
Fuzzy Sets and Systems	1
IIE Transactions (Institute of Industrial Engineers)	1
Industrial Marketing Management	1
International Journal of Advanced Manufacturing Technology	1
International Journal of Innovative Computing, Information and Control	1
Journal of Cleaner Production	1
Journal of Theorical and Applied Electronic Commerce Research	1
Operations Management Models and Principles	1
Production and Operations Management	1
Total	64

Annex 2. Arena model

Figure 21. Initial Inventory OB_PM4, OB_SM and D for family 3

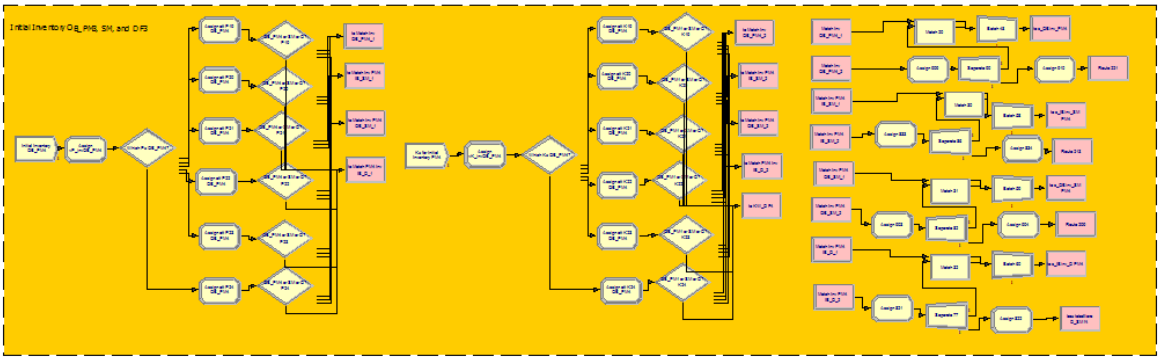

Figure 22. Initial Inventory IB_PM4

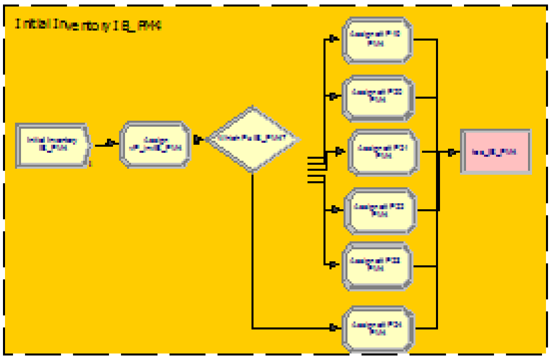

Figure 23. Virtual Board PM

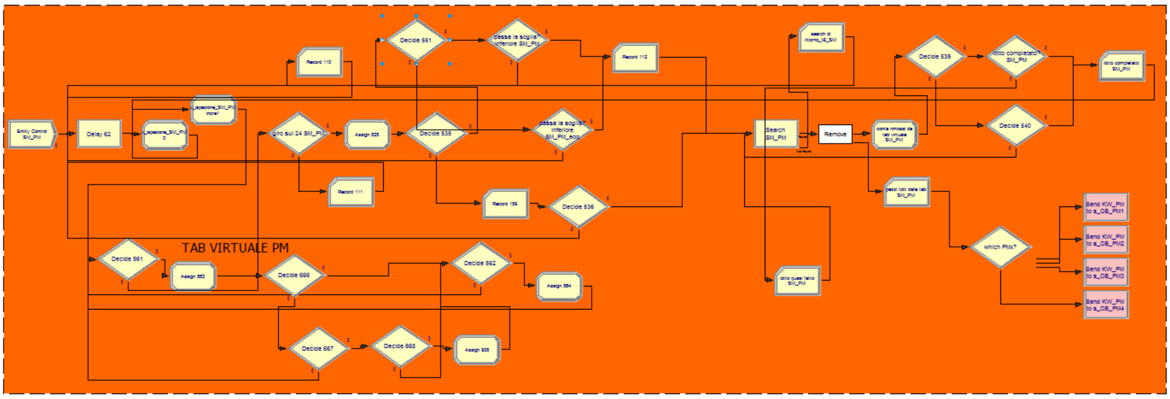

Figure 24. Entity Control for PM production, shortest set-up time dispatching rule

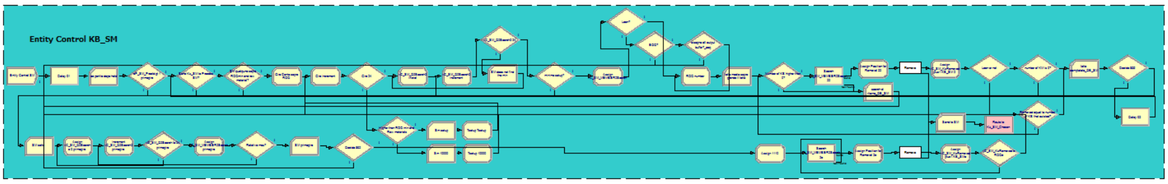

Figure 25. Entity Control for PM production, criticality dispatching rule

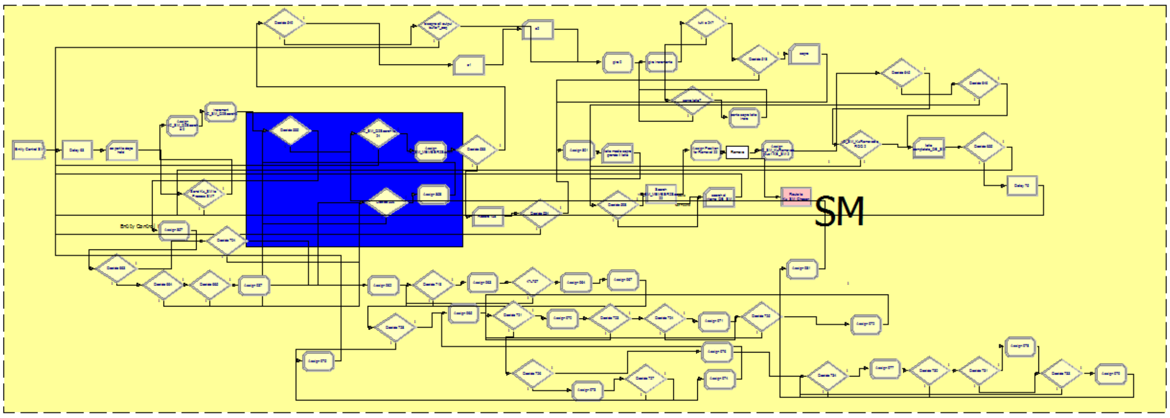

Figure 26. Primary Manufacturer

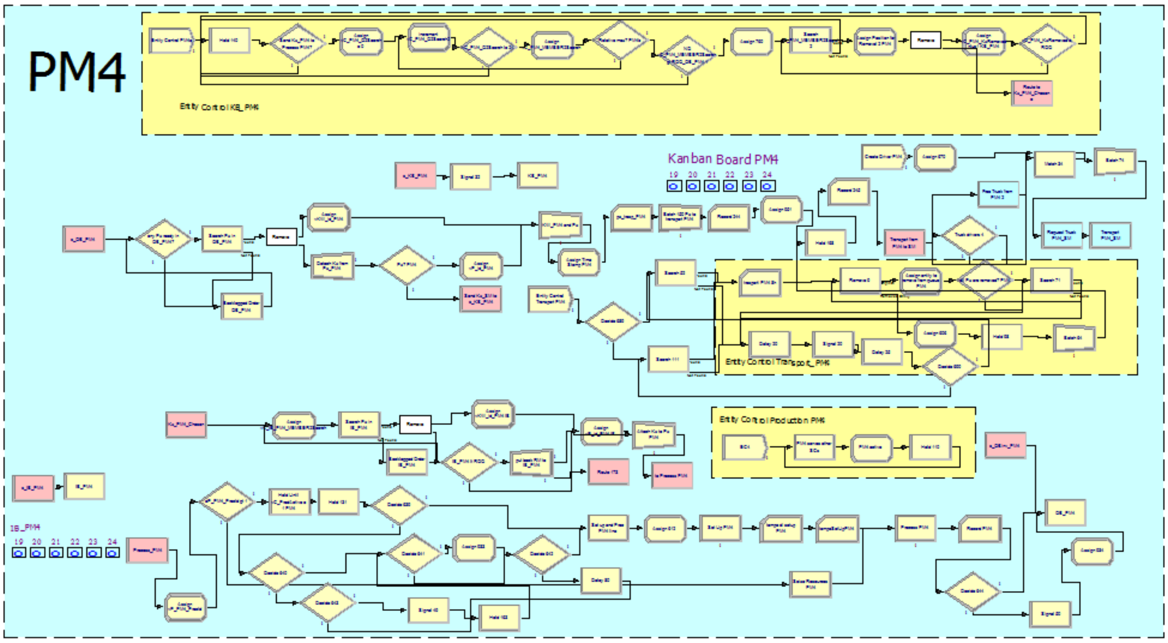

Figure 27. Virtual Board SM

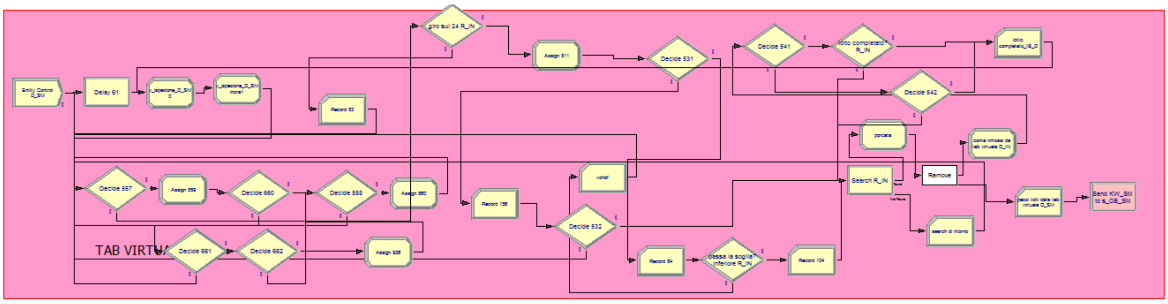

Figure 28. Entity Control for SM production, shortest set-up time dispatching rule

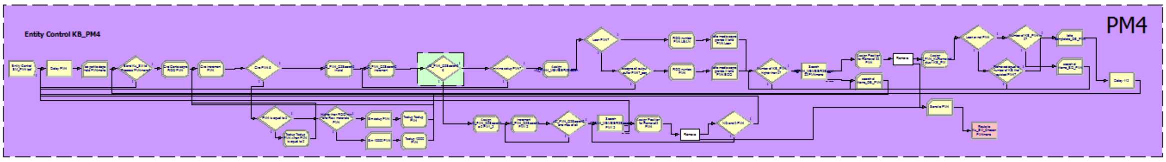

Figure 29. Entity Control for SM production, criticality dispatching rule

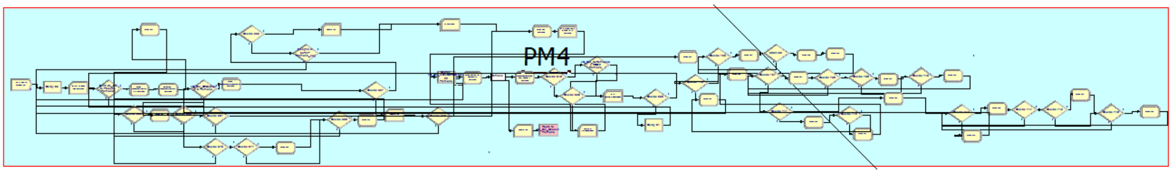

Figure 30. Secondary Manufacturer

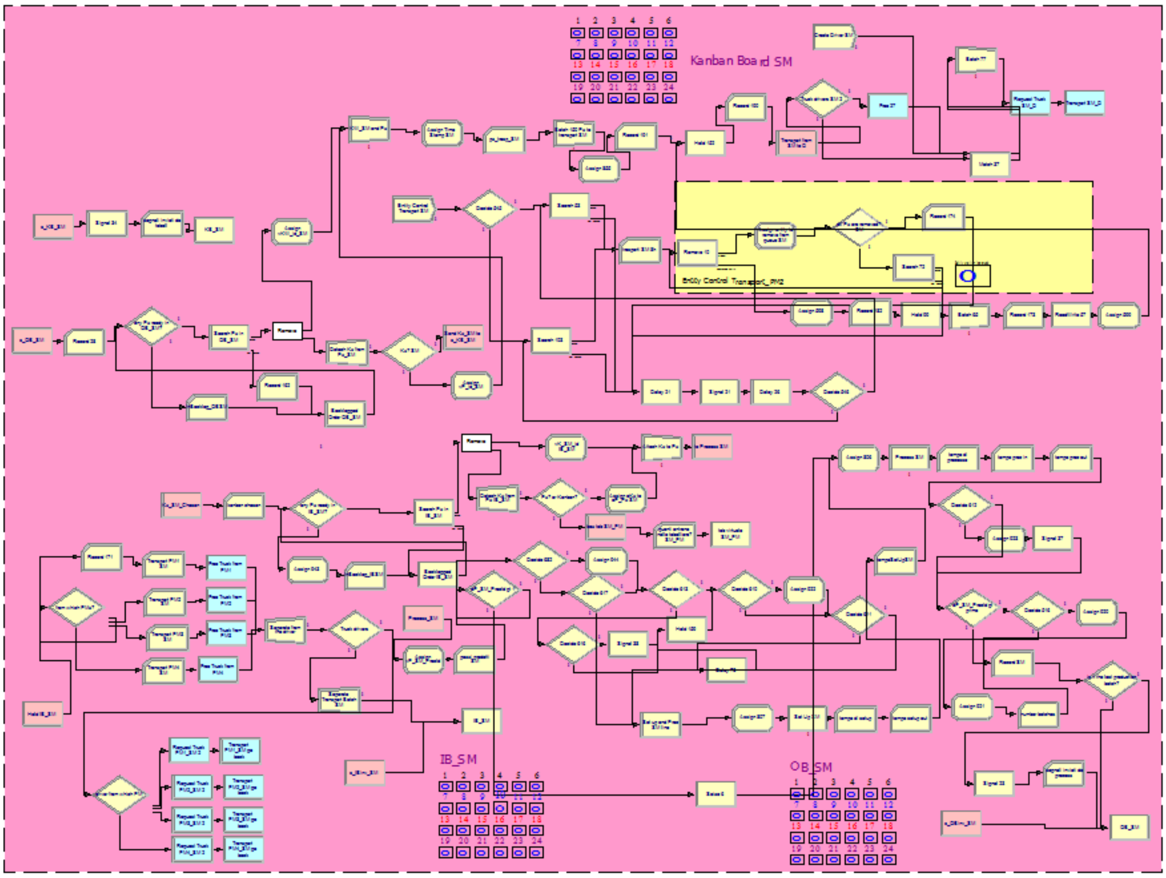

Figure 31. Retailers demand

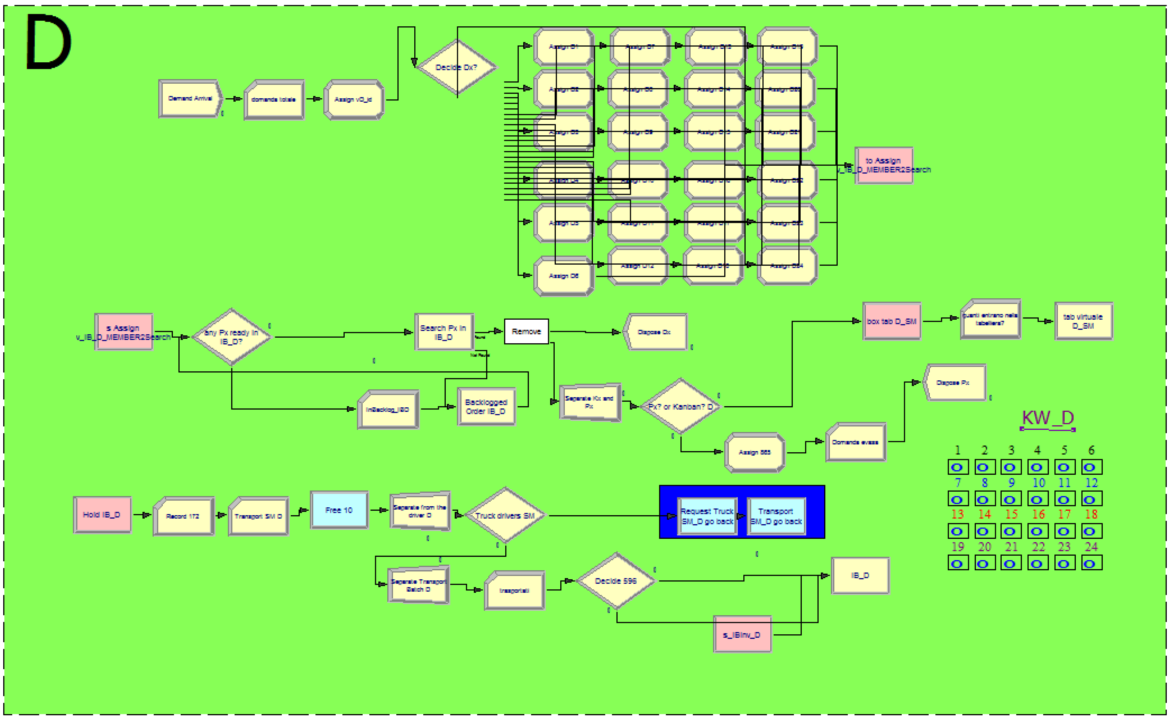

Figure 32. Stockout Checking

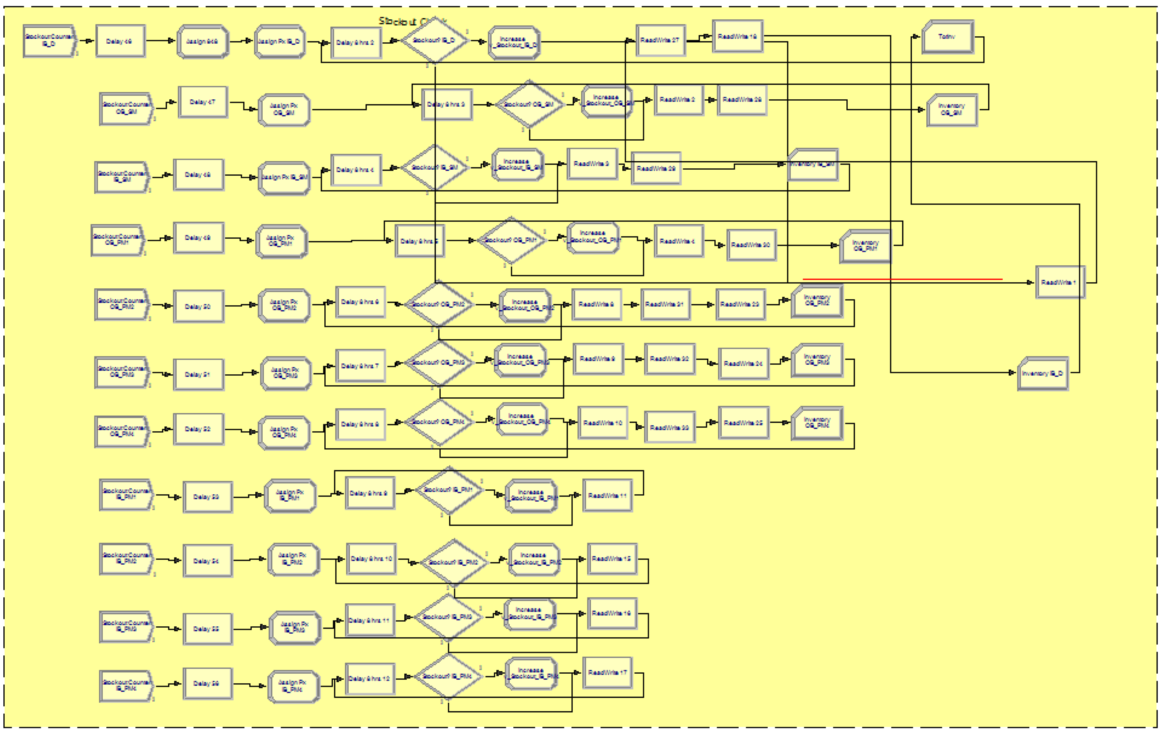

Figure 33. Output Folder Generator