Lean Supply Chain in Pharmaceutical Industry:
Modeling and Simulation Of A SAP Environment

by

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Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

September 2011

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Abstract

The global pharmaceutical business environment has been rapidly changing and has more competitive. Competition in pharmaceutical industry extended far beyond the traditional battle field, research and development. Bayer AG, a leading pharmaceutical company, decided to evaluate lean management as a tool to improve their competitiveness in the market.

This thesis attempts to understand the system impact of the lean management implementation to the Bayer supply chain using modeling and simulation tools. The results of the model will be used to determine the system characteristics of current practice and lean practice. The objective of this thesis is to use the system characteristics generated from the simulation models and provide implementation recommendation to Bayer AG.

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Acknowledgements

I would like to begin by thanking Bayer AG for sponsoring this thesis research. In particular, I would like to thank my project sponsor Dr. Franz-Josef Toelle, project champion Dr. Marc Albers, and everyone from Bayer AG for their support during this research project. This project is not possible without their help.

I would also like thank my thesis advisor Professor David Simchi-Levi for his guidance and assistance throughout this thesis research.

I would also like to thank my fiancée Nikki Liang for her unwavering support throughout my study at MIT. She has sacrificed a great deal for me to fulfill my dream at MIT.

Lastly but certainly not least, I would like to thank God for making this life changing experience possible.

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Chapter 1: Introduction

1.1 The Pharmaceutical Industry

The pharmaceutical industry is one of the largest industries in the world. Traditionally, pharmaceutical companies rely heavily on their patents to generate revenue which led to high concentration of resources in research and development. In 2010, top 15 pharmaceutical companies generated over $476 billion revenue. On average, each company spends 17.78% of its revenue, approximately $4.3 billion dollars, on research and development (Table 1).

With so much concentration in R&D, many pharmaceutical companies put less effort in lean management. In the past two decades, lean management became the hottest topic in many industries, such as electronic, retail, and automobile. Pharmaceutical industry also showed interest in lean management, and companies such as Pfizer, Novartis, and Amgen stated their operational excellence programs earlier this decade.

While there are many publications on successful lean projects by professionals and researchers, pharmaceutical industry was unable to produce the similar result comparing to electronics, retail, and automobile industry. The most commonly used measurement of leanness is the inventory turnover. In the past five years, Wal-mart's inventory turnover was improved by 15.5%, from 7.7 turns per year in 2005 to 8.9 turns per year in 2010. In the same period of time, top 15 pharmaceutical companies' inventory turnover showed an average decrease of 16% (Table 2). The lack of success on lean implementation was caused by resistant to change, lack of system thinking, and poor execution.

Pharmaceutical companies have a strong silo effect which communication is not effective between different functions. Changes are very difficult to implement in this environment. Without effective communication, system-wide improvement cannot be achieved. An interview was conducted to employees of two leading pharmaceutical and biotech companies, and over half of the interviewees did not know the responsibility of

their upstream or downstream functions. This result will lead to poor project selection and execution. While pharmaceutical industry falls behind on lean management, the business environment becomes more competitive.

Company	Revenue of pharmaceutical segment, in millions of USD	Pharmaceutical Research and Development Budget, in millions of USD	Total sales, in millions of USD	Share of pharmaceutical segment, %	% of Pharmaceutical Revenue for R&D Budget
Pfizer	$ 45,448	$7,845	$ 50,009	90.88%	17.26%
Sanofi-Aventis	$ 40,871	$6,392	$ 40,871	100.00%	15.64%
Novartis	$ 38,455	$7,469	$ 44,267	86.87%	19.42%
GlaxoSmithKline	$ 36,746	$6,181	$ 44,422	82.72%	16.82%
AstraZeneca	$ 31,905	$4,409	$ 32,804	97.26%	13.82%
Merck	$ 26,929	$5,845	$ 29,121	92.47%	21.71%
Johnson & Johnson	$ 22,520	$4,591	$ 61,897	36.38%	20.39%
Eli Lilly	$ 20,629	$4,327	$ 21,836	94.47%	20.98%
Bristol-Myers Squibb	$ 18,808	$3,647	$ 18,808	100.00%	19.39%
Abbott	$ 16,486	$2,743	$ 30,765	53.59%	16.64%
Takeda	$ 14,204.00	$3,195	$ 15,803	89.88%	22.49%
Boehringer-Ingelheim	$ 14,027.00	$3,089	$ 17,741	79.07%	22.02%
Teva Pharma	$ 13,814	$802	$ 13,899	99.39%	5.81%
Bayer	$ 13,344	$2,192	$ 43,468	30.70%	16.43%

Table 1 Top 15 Pharmaceutical Firm Financials (Yahoo Finance)

In pharmaceutical industry, when patents expired, generic drugs producers can easily reverse engineer the formula, and then sell it at a much lower price. Teva Pharmaceutical, a generic drug company, published a study that estimate global generics market will reach $120 billion dollars in 2012, which will double 2007's market

share [Teva Pharmaceuticals, 2008]. Teva's study also reviled that over $50 billion worth of branded drug will reach their patent expiration date by 2013. According to FDA's Orange Book, 79% of the branded drugs have at least one generic counterpart. Branded manufacturers have to focus on cost reduction on those drugs with expiring patents in order to compete with generic drugs.

Company	Inventory Turns 2005	Inventory Turns 2010	Inventory Turns Difference between 2005 and 2010	% of Change
Pfizer	1.3	1.1	-0.20	-15.4%
Sanofi-Aventis	2.2	2	-0.20	-9.1%
Novartis	2.4	2.1	-0.30	-12.5%
GlaxoSmithKline	2.2	1.8	-0.40	-18.2%
AstraZeneca	2.1	3.4	1.30	61.9%
Merck	2.9	2.3	-0.60	-20.7%
Johnson & Johnson	3.6	3.6	0.00	0.0%
Eli Lilly	1.7	1.6	-0.10	-5.9%
Bristol-Myers Squibb	2.4	3.5	1.10	45.8%
Abbott	4.1	4.4	0.30	7.3%
Boehringer-Ingelheim	2.5	1.7	-0.80	-32.0%
Teva Pharma	2.3	1.94	-0.36	-15.7%
Bayer	2.6	2.3	-0.30	-11.5%

Table 2 Inventory Turnover Trends of Top Pharmaceutical Firms (Yahoo Finance)

Another way for branded drugs manufactures to compete with generic drugs manufactures is to invent more new drugs. However, new drug production becomes more difficult in recent years. In Phrma Profile 2011 report, the median number of procedures per clinical trial is increased by 49% and the total work burden per protocol is grew by 54% between year 2000 and 2007 [PhRMA, 2011]. The increase of regulations resulted in higher R&D cost and longer commercialization process, but pharmaceutical industry is not the only one slowing down. According to the Ernst & Young's report [3], there was a clear trend that showed the number of FDA product approval rate was slowed down dramatically since 1996 (Figure 1). This has become a

problem for all non-generic drug producers since they cannot cash-in on their product until the product label is approved by FDA. To deal with this problem, one of the leading biotech companies recently implemented lean laboratory to drive down the R&D cost and the R&D cycle time.

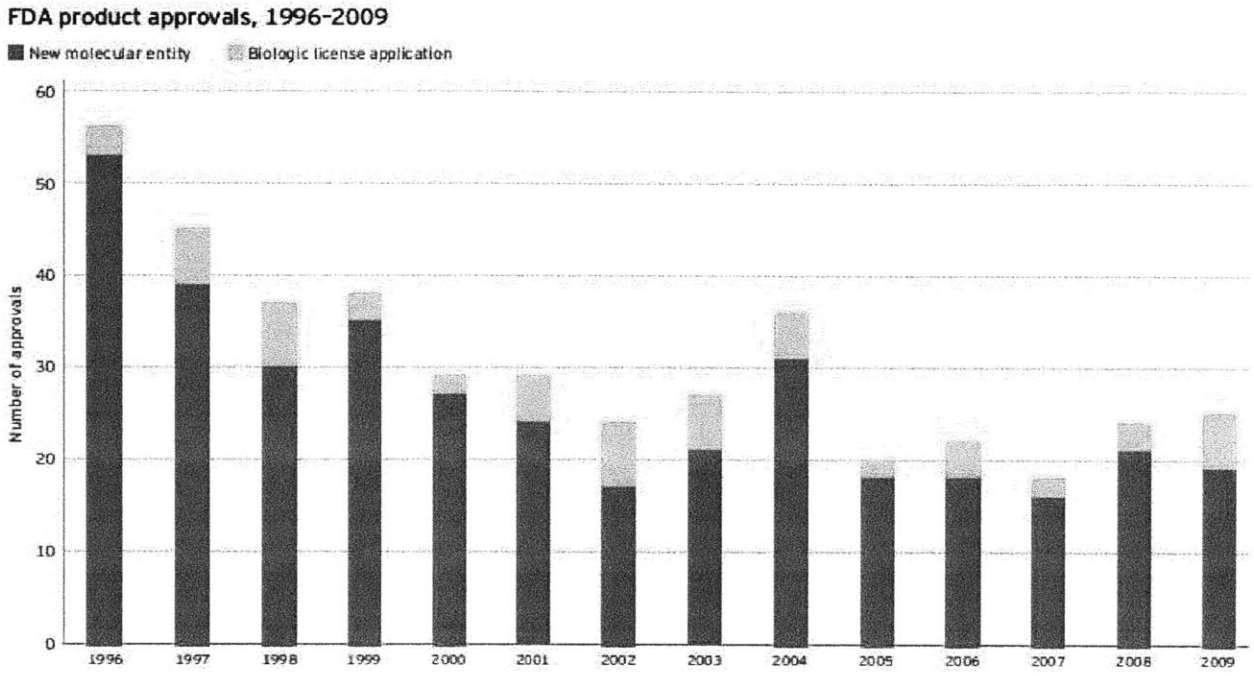

Figure 1 FDA Product Approval Rate (Ernst & Young, 2010)

Another challenge pharmaceutical industry has to face is that the demand for drug is projected to increase at a much faster pace than capacity. United States, the largest market for pharmaceutical products, recently changed their healthcare policy. This change will generate heavy demand. President Obama signed The Health Care Reform bill, one of the most expensive social legislation, early last year. This legislation carries many positive and negative implications on the future of pharmaceutical industry. According to President Obama, this bill will provide health insurance to 32 million additional Americans and legal residents. As the insurance coverage increases from 83% to the estimated coverage of 95%, the demand for drugs should increase as well. Country such as China and India will also have high demands as baby-boomers reach their retirement age. To satisfy the increasing demand while driving down cost, pharmaceutical industry has to increase their efficiency through lean management.

1.2 Bayer AG

Bayer AG is a global chemical and pharmaceutical holding company headquartered in Leverkusen, Germany with core competencies in the fields of health care, nutrition, and high-tech materials. With annual revenue over $43 billion, Bayer is one of the largest companies in the world. In 2010, Bayer employed 108,400 full-time employees throughout its 302 subsidiaries around the world.

True to its own mission statement, "Science for A Better Life", Bayer invests approximately $2.2 billion dollar annually in research and development to improve the quality of life. Because of this strategy, Bayer has become the pioneer for many important discoveries for the past two hundred years. The most famous discovery of all is Aspirin. As one of the most widely used drug since its discovery in 1897, its worldwide consumption was estimated to be 40,000 tons per year [Warner, 2002].

Bayer AG was reorganized in 2003 into three business area companies, Bayer HealthCare, Bayer CropScience, and Bayer MaterialScience, and three service area companies, Bayer Business Services, Bayer Technology Services, and Currenta. The business area companies and service area companies are legally independent corporations. These six companies are managed by Bayer AG, the parent management holding company. This reorganization effort separates operational management from strategic management. Bayer AG took the responsibility of strategic management while each of the six companies took the responsibility of their respective operational management areas.

Unlike other major pharmaceutical companies, Bayer's pharmaceutical revenue only accounts for 62% of its total revenue. With only three blockbuster drugs, Bayer was able to reach #14. 2010 is a forgettable year for Bayer, most of the product line did not show much growth except Nexavar, an oncology drug. In next few years, Bayer will face stiff competition in two out of three blockbuster drugs.

U.S court invalidated Bayer's largest blockbuster drugs, Yasmin, in 2008 which allows Barr Laboratories to produce YAZ, a generic version of the drug, at a much lower cost.

Betaferon, a multiple sclerosis drug and the second largest blockbuster drug of Bayer, is projected to loss its market share in the upcoming years. In the next five years, there will be 17 more possible entry to the multiple sclerosis market with 6 generic products (Table 3). Bayer will need to make up the possible revenue loss through new product introduction and efficiency increase.

Drug Name	Manufacture	Projected Year of Introduction
Fampridine	Acorda	2010
Cladribine	Merck Serono	2010
FTY720	Novartis	2010
Generic Copaxone	Generic Manufature	2011
Laquinimod	Teva	2012
BG-12	Generic Manufacture	2012
Campath	Genzyme	2012
Teriflunomide	Sanofi Aventis	2013
PEG IFN B-1 a	Generic Manufacture	2013
IFN Biosimilars	Generic Manufacture	2013
BAF312	Novartis	2015
MN-166	MediciNova	2015
TV-1102	Teva	2015
Atacicept	Merck Serono	2015
Daclizumab	Generic Manufacture	2015
Ocrelizumab (2H7)	Generic Manufacture	2015
Firategrast	GSK	2015

Table 3 Projected MS Drug Competitors

1.3 Supply Chain of Bayer

Bayer's supply chain can be broken down into four modules; Product Distribution, Active Pharmaceutical Ingredient (API) Sourcing, Production Planning, and Production Process (Figure 2).

1.3.1 Product Distribution

Bayer has distribution center in six continents. There are three levels of distribution: production facility to regional distribution facility, regional distribution facility to local distribution center, and local distribution center to customers. When customer demand arrives, products will be check out of the inventory at local distribution center and the customer demand data will be recorded into sales database. This information will then be used for demand forecast and production planning process. Regional distribution facility will replenish the local facility while receiving replenishment from production facility.

1.3.2 Production Planning

There are two inputs for production planning; sales forecast and sales database. Each region's sales manager will estimate and compile next 36 months' sales forecast. This information will be sent to demand forecast team for further analysis. Demand forecast team will utilize actual sales database to generate statistical forecast and compare with sales forecast from regional sales manager to determine the demand forecast for next 36 months.

This information is entered into SAP, an enterprise resource planning (ERP) system. Advance Planner and Optimizer (APO), a key component of SAP, will conduct mix-integer optimization using capacity and other resources constraints to determine the production schedule. This schedule will tell production department which products need to be produced in specific quantity at specific production cycle. Bayer practices single production site strategy where any given product will only be produced at a specific site. Therefore SAP does not need to determine where the product needs to be produced. Once production schedule is generated, a bill of material (BOM) is developed for vendors to provide material for production.

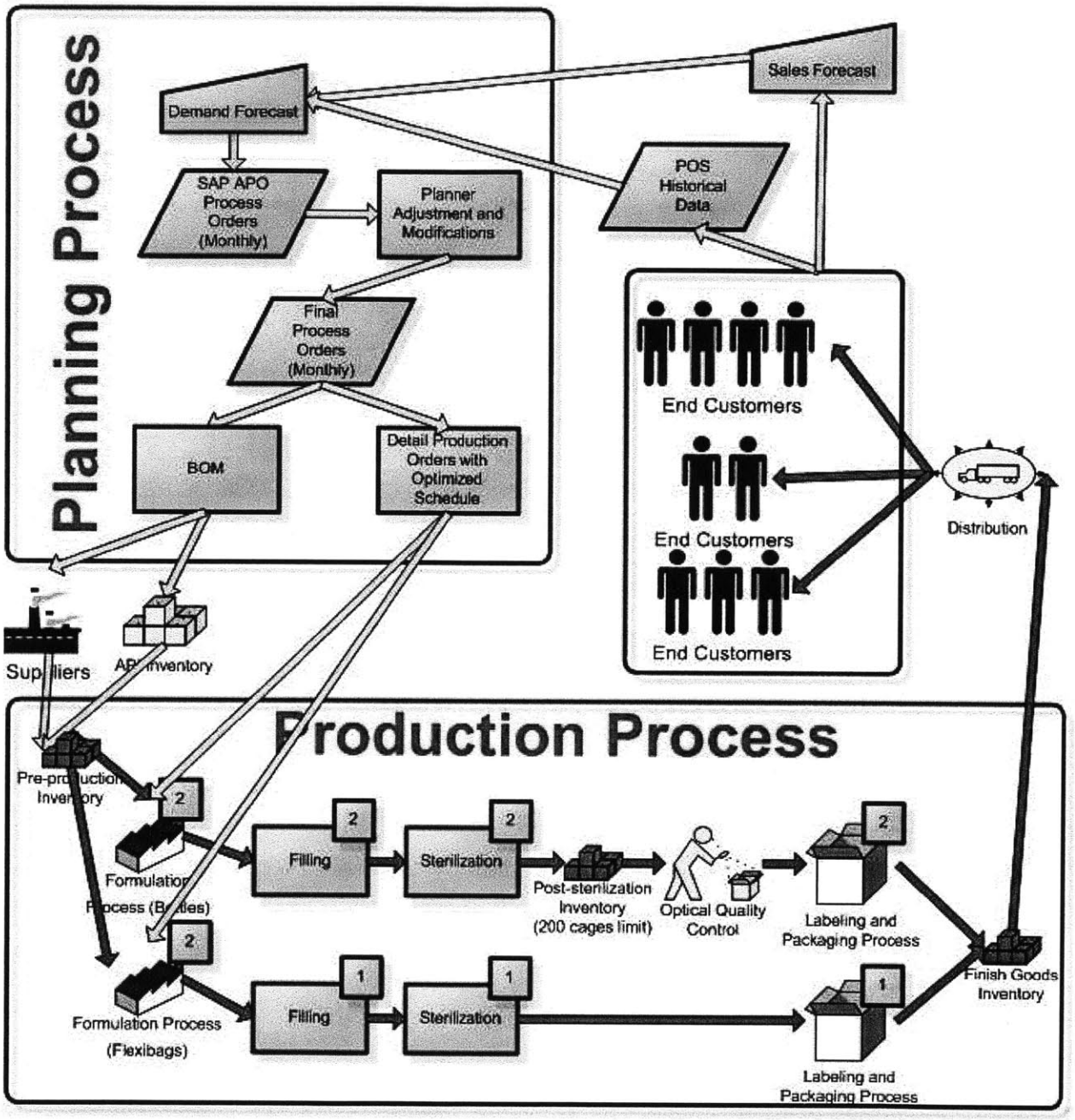

Figure 2 Bayer Supply Chain Overview

1.3.3 API Sourcing

A drug is composed of two parts: API, the drug itself, and excipient, extra ingredient that decides the form of the drug. API sourcing is critical to drug production. In Bayer, some APIs are sourced from manufactures all over the world, and some are produced internally in API facilities. API will be supplied to each production site based on BOM generated through SAP.

1.3.4 Production Process

Finalized production schedule generated from SAP provides production department the products need to be produced for the production cycle. The schedule does not contain the production sequence. Production planner will use a heuristic tool to minimize changeover cost and produce a detail schedule with production sequence. The production department will produce based on the detail schedule. Once production process is finished, product will either be stored or ship out for replenishments.

1.4 Motivation

Bayer understands the importance of lean in pharmaceutical industry. A system like SAP, put in years ago, was used to eliminate waste and increase efficiency. APO will provide production planner information such as what to produce, when to produce, and how much to produce. Planner will have to decide on the production sequence using a heuristic tool to minimize the changeover cost. This process is called a cost driven planning process.

In theory, a cost driven planning process will produce product at the lowest cost while satisfying customer demand. But in reality, the optimal schedule was rarely achieved for variety of reasons. The schedules are frequently suboptimal due to constraints simplification, fixed random variables, and adjustment to the schedule. Any of the reason mention above can cause results to deviate from optimal solution.

Another problem with cost driven planning process is that the products varies from month to month. Consistency is the foundation of lean management. Without consistency, continuous improvement techniques, such as Single Minute Exchange of Die (SMED), cannot be applied. Without continuous improvement, the best schedule SAP APO can only produce an optimal schedule in a suboptimal process. Inconsistency also causes unnecessary pressure on production operators, planners, and other supporting teams. A mistake due to pressure in production or planning can be costly. A

simplified planning and production process is needed in order to create a consistent production environment.

Production wheel, a lean tool, can be used here to simplify the planning and production process. Instead using SAP APO to find an optimized production schedule, a fixed sequence of production is created to minimize changeover time. Using a production wheel, production managers will know exactly what is produced in the next production cycle. Through frequent changeover with smaller lot size, production department will be encouraged to improve the changeover process which promotes lean concepts and build a foundation for continuous improvement.

In theory, production wheel is an excellent tool to improve consistency. In reality, there are still many questions need to be answered before implementation. Bayer decided to evaluate current system, a cost driven planning system, and future system, a production wheel system, to answer one question: Can production wheel provide the same service level at lower cost compares to the current system?

1.5 Methodology

The approach to this project is to provide understanding of the behavior of the systems using computer simulation. Each system will be designed and simulated using computer simulation software called Arena. Key Performance Indicator (KPI), such as fill rate, cycle time, inventory level, etc. will be tracked and analyzed. The result from the simulation will be analyzed and used to answer Bayer's questions.

This process will follow a 4 steps process:

1) Evaluate Business Characteristics - Chapter 1
2) Design, simulate, and validate current state and future state - Chapter 3 and 4
3) Analyze characteristic of state, future state - Chapter 5
4) Offer observations and recommendation - Chapter 6

1.6 Research Scope

The scope of this project will be limited to a single unidentified facility in Germany. This production facility produces 138 SKU in 2010 using six different APIs. Due to data inconsistency, only 99 products will be modeled and simulated. This model will exclude API manufacturing and sourcing process but include the production process where API is transformed into finish goods.

This facility supplies distribution center worldwide. Therefore finish good inventory is scattered around the world which includes production facility, regional distribution centers, and local distribution centers. To simplify the process, this thesis will exclude complicated pharmaceutical regulations in international trades and transportation process between production facility and distribution centers. Therefore there will be only one finish good inventory to supply directly to the customers (Figure 3).

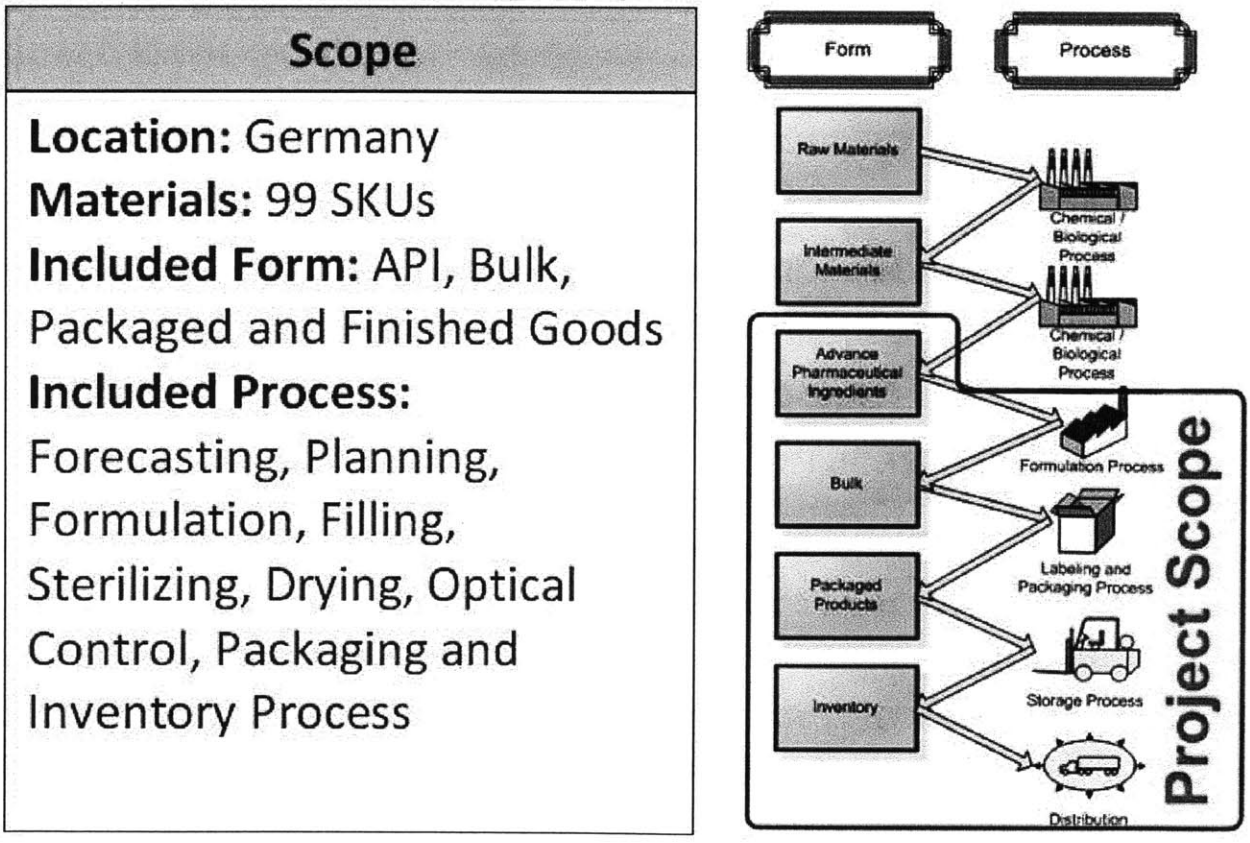

Figure 3 Project Scope

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Chapter 2: Literature Review

The theme of this thesis is to evaluate overall supply chain impact of lean methodologies, specifically production wheel, in a SAP environment. While there are many literatures on lean in pharmaceutical industry, the integration of lean in a SAP environment cannot be found. An extensive literature review was completed with the purpose of understanding supply chain management, lean management, SAP system, and modeling and simulation.

2.1 Supply Chain Literatures

Council of Supply Chain Management Professionals' (CSMP) current definition for supply chain management is that supply chain management integrates supply and demand management within and across companies [CSCMP, 2011]. With such broad definition, supply chain management includes all activities from marketing department who gather demand data to retailers who provide distribution to final consumers. A popular model, Supply Chain Operations Reference-Model (SCOR), is more appropriate considering the scope of this thesis.

SCOR describes supply chain in three levels of hierarchies [Stadtler et. al., 2008]. At the first level of hierarchy, which includes plan, source, make, deliver, and return, scope of the supply chain is determined (Figure 4). At the second level, a supply chain strategy or configurations, such as Make-to-Stock, Make-to-Order, or a combination of the two strategies, is determined. At the third level, business activities are derived from the supply chain strategy determined at level two. This model can be used to describe Bayer's supply chain.

Once the model of the supply chain is completed, it is important to measure its performance. There are two level of performance management: system level and component level. At system level, tools such as Economic Value Added (EVA) [Brewer et. al., 1999] and Activity Based Costing (ABC) [Kaplan et. al., 1987] can be used to determine the economic profit and cost structure of the entire supply chain. EVA translates the supply chain KPIs, such as fill rate, inventory level, and cycle time, into

financial KPIs, such as gross margin, total expenses, and current and fixed assets (Figure 5). This is a popular tool to interpret supply chain impact for non-supply chain professionals. On the other hand, ABC analysis determines the cost-bottleneck of the system. This method can help lean professionals to identify focus-improvement projects.

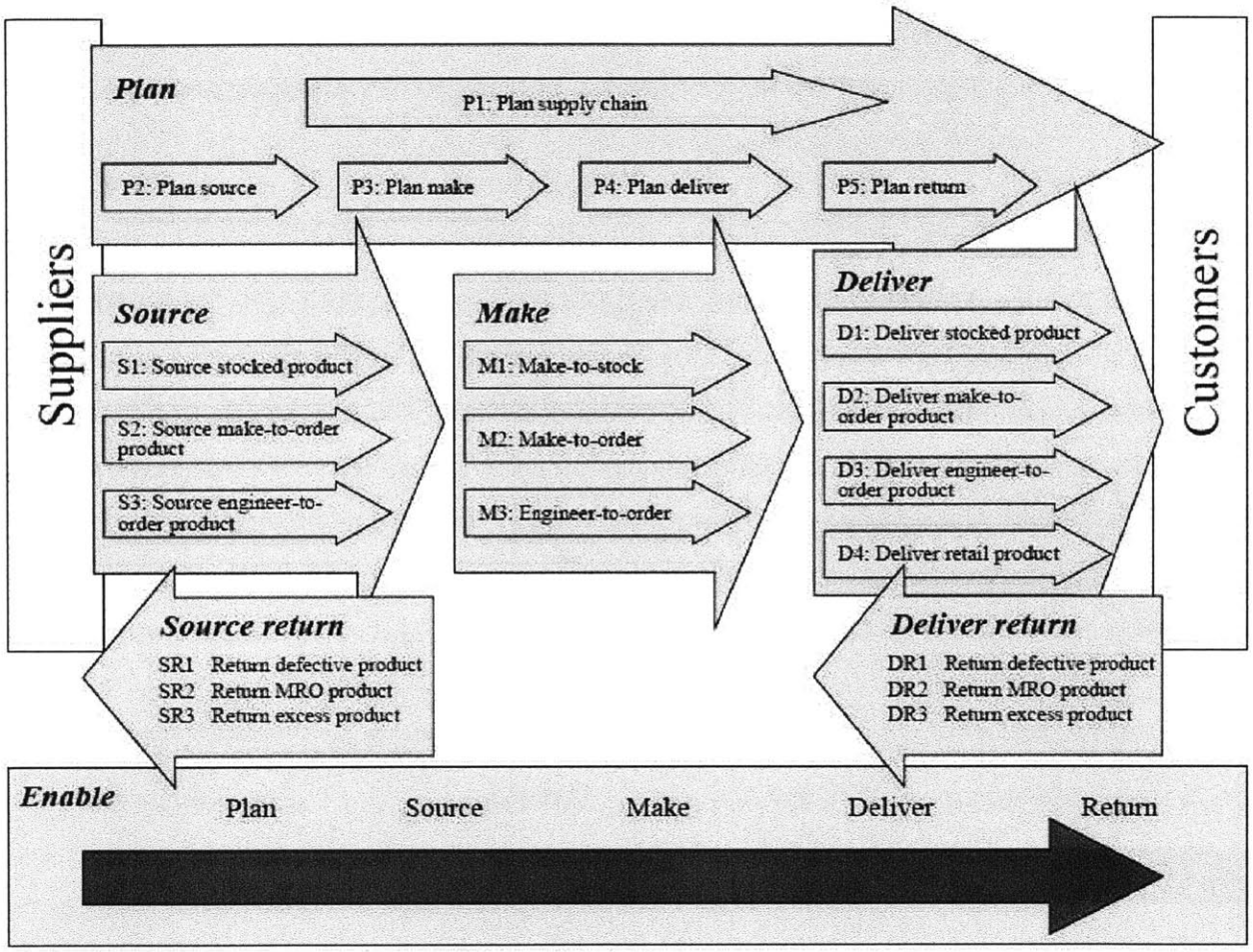

Figure 4 SCOR Level 1 and Level 2 (Stadtler et. al., 2008)

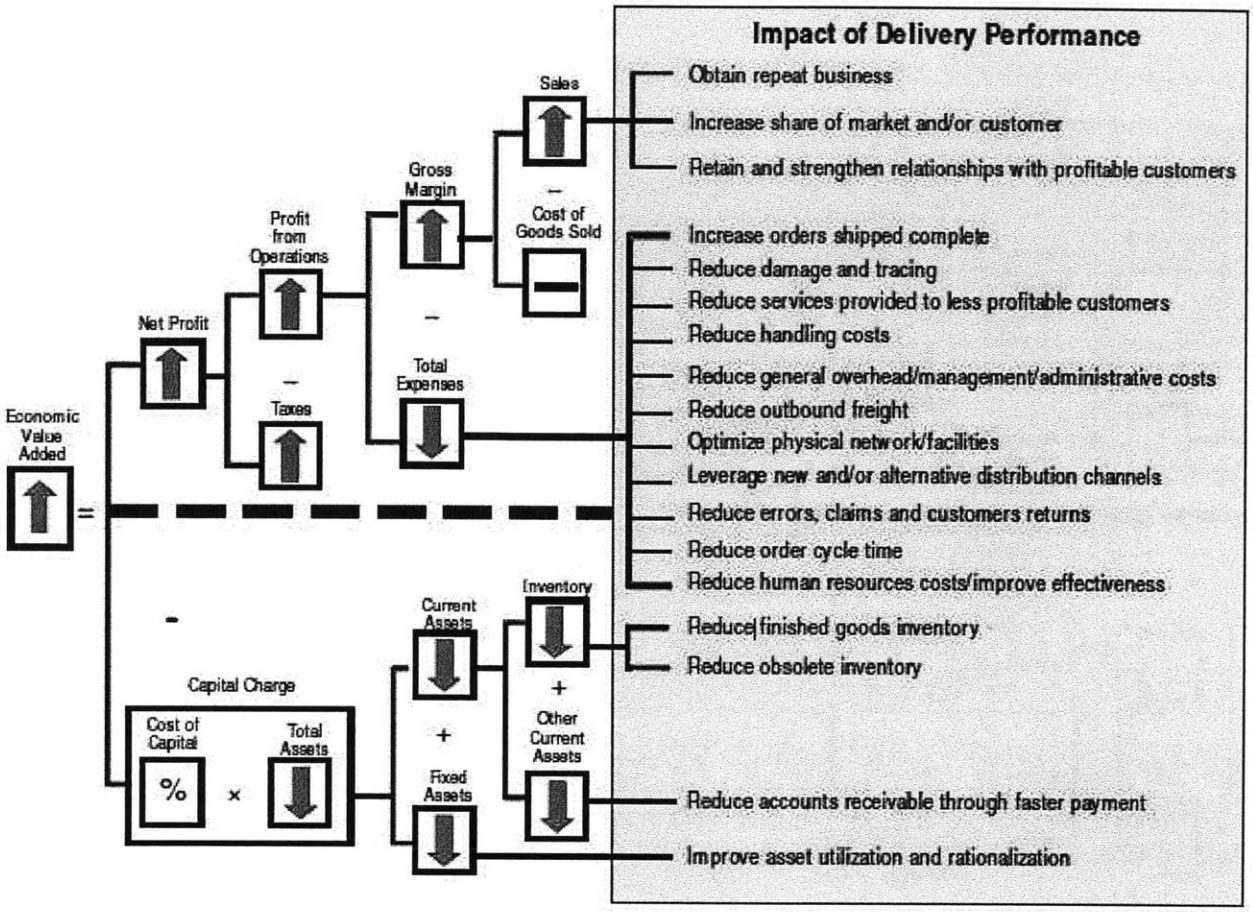

Figure 5 Impact of Delivery Perfomance using EVA (Lambert and Pohlen, 2001)

At component level, four categories of KPI, delivery performance, supply chain responsiveness, assets and inventories, and cost [Silrie, C., Wagner, M., Supply Chain Analysis (2008), Springer, P37-62] can be used as benchmark when comparing different systems. Most commonly used KPIs for delivery performance are fill rate (Equation 1), number of stock outs, cycle time (Equation 2), and forecast measurements. Mean absolute deviation (MAD), mean square deviation (MSD), and bias (BIAS) are the three commonly used quantitative measurements for forecast models [Hopp et al., 2008]. Fill rate and number of stock outs are the contributing factors for gross margin while cycle time and forecast measurements are contributing factors for total expenses. Improvement in either gross margin or total expenses will improve the profit-from-operations.

$$FillRate = 1 - \frac{BackOrderAtEndofPeriod}{TotalDemand}$$

Equation 1 Fill Rate

$$CycleTime = \frac{WIP}{Throughput}$$

Equation 2 Cycle Time

$$MAD = \frac{\sum absolute(F(t) - A(t))}{N}$$

Equation 3 Mean Absolute Deviation

$$MSD = \frac{\sum (F(t) - A(t))^2}{N}$$

Equation 4 Mean Square Deviation

$$BIAS = \frac{\sum (F(t) - A(t))}{N}$$

Equation 5 Forecast BIAS

- F(t) is the forecasted value for time t
- A(t) is the actual value for time t

Supply chain responsiveness describes the ability of the supply chain to deal with unexpected changes. Such changes can occur in raw material supply, production capacity, and market demand. There are no specific KPIs for supply chain responsiveness. This thesis will use the rate of change of delivery performance to determine supply chain responsiveness.

Assets and inventory of a supply chain is another important measurement. In accounting, common measurements for assets and inventory includes asset utilization, inventory turnover, average inventory value, and average inventory level. This thesis will only consider asset utilization, average inventory value, and average inventory level. Applying EVA model, average inventory value and average inventory level are

considered as the KPI for current asset while asset utilization is considered as the KPI for fixed assets. Improvement in these two areas will result in capital gain.

Lastly, the supply chain cost has to be measured. Peter Bolstorff's article, "Supply Chain Performance" [Bolstorff, 2003] suggest the total supply chain cost is the sum of order cost, management cost, material acquisition cost, planning cost, inventory cost, IT cost, return management cost, cost of goods sold (COGS), and SG&A cost. Due to the scope of this project, management cost, material acquisition cost, planning cost, IT cost, return management cost, COGS, and SG&A cost are ignored. This thesis will only consider changeover cost and inventory holding cost. Using average inventory value, we can determine inventory holding cost for the supply chain (Equation 6). These two costs are part of total cost in EVA. Improvement in these two costs will improve profit-from-operation.

$$InventoryHoldingCost = HoldingCostRatio * Average InventoryValue$$

Equation 6 Inventory Holding Cost

2.2 Lean Literatures

Lean was first mentioned in James Womack's book "The Machine that changed the world" [Womack et. al. 1990]. The concept of lean was inspired by Eiji Toyoda, owner of Toyota, and developed by Taiichi Ohno, widely considered as the father of lean manufacturing. After Mr. Toyoda's visit from Ford's production facility, he felt that there were possibilities to improve even the greatest production system of 1950s, Ford's Production System. This became the concept of continuous improvement. Instead of coping Ford's mass production system, Taiich and Eiji developed a new system called Toyota Production System (TPS).

TPS, also known as the Lean Manufacturing or Lean Management, emphasizes doing more with less. Key elements of lean management include waste reduction, stability improvement, Just-In-Time (JIT), Jidoka, Kaizen, and Hoshin Planning [Dennis P. et. al. 2007].

Traditionally, there are seven wastes in the lean: motion, waiting, transportation, defect, over-processing, inventory, and over-production. Recently, a new waste, knowledge disconnection, was added to the list. Each waste represents inefficiency of the system and opportunity for improvement. The worst waste out of the eight wastes above is the waste of over-production. When over-production occurred, all seven other wastes occurred. The eight wastes are the knowledge foundation for any lean practitioner.

Lean Management implementation requires a stable work environment. It emphasizes on waste elimination at its root cause. In an unstable system, root cause cannot be identified. Therefore a stable environment is a prerequisite for any lean organization. Stability need to be achieved at four levels, commonly known as the 4 Ms: Manpower, Machine, Material, and Method. At each level, tools such as production wheel, 5S, TPM, visual control, and work standardization can be used to improve stability.

Once stable environment is achieved, lean practitioners can implement more advance tools such as JIT, Jidoka, and Hoshin Planning. JIT is a pull supply chain that only produces the right product, right quantity, and right time. The upstream process is triggered by the downstream process, and ultimately is triggered by customers. This system was designed to minimize waste and maximizing flexibility. The prerequisite of this system is to achieve world class quality control.

Jidoka is the Japanese word for automation. It is one of the tools that lean practitioner can use to improve quality control. This technique will stop the production process immediately when defects occurred. Production will not resume until the problem has resolved. This eliminates the possibility of overproduction of defect products. Another tool called Poka-yoke, error prevention technique, is also commonly used to provide a fool proof process to minimize defects in production process.

The key success factor of lean management is the culture of continuous improvement. Kaizen, the Japanese word for continuous improvement, is a concept which focuse on small improvement projects that can be finished in short period of time. In Kaizen

environment, employees are encouraged to generate and execute improvement ideas, also known as grassroots projects. Other tools such as Gemba Walk can also be used to improve Kaizen environment. A company can only call themselves a lean company once they achieved the culture of continues improvement.

2.3 SAP Literatures

SAP stands for Systems Applications and Products in Data Procession. It is an ERP system used by 70% of Fortune 100 companies and 50% of Fortune 500 companies [Gartner research 2008]. Traditional modules in SAP, a.k.a SAP R/3, was modulated in different business functions, such as Finance & Controlling, Sales & Distribution, Material Management, Production Planning, Quality Management, Warehouse Management, Logistics Execution, Human Resource, Project Systems, Environment Health and Safety, and Product Life Cycle Management. In 2003, SAP AG released the newest EPR software called mySAP Business Suite, which included all functions from SAP R/3. The new dimension products in mySAP include Customer Relationship Management, Supplier Relationship Management, and Supply Chain Management.

SAP Supply Chain Management (SAP SCM) includes 5 subsystems; Advanced Planning and Optimization (APO), Forecasting and Replenishment (SAP F&R), Supply Network Collaboration, Event Management, and Extended Warehouse Management. SAP APO focuses on SCM which includes external partners [Knolmayer, et. al., 2009]. This subsystem contains 6 different modules: demand planning (DP), Supply Network Planning (SNP), Supply Chain Collaboration (COL), Production Planning and Detailed Scheduling (PP/DS), Global Available-to-Promise (ATP), Transportation Planning and Vehicle Scheduling (TP/VS), and Maintenance and Service Planning (MSP).

The APO DP module will provide an aggregated level of forecast on future demands from sales history and sales forecast. SNP module will use the forecasted future demand generated from DP, available resources, and production constrains to network planning between sourcing, production, and distribution. The initial network planning through SNP will allow partners, such as suppliers and distributors, to interact with the

detail planning process using COL. Partners will collaborate with planners to make adjustment in resource and constraints for future production process. This information will then be utilized by PP/DS to determine a detail production schedule through mix-integer optimization process. Once detail production schedule is complied, ATP will generate due dates for sales managers to use as an estimated due date for future orders. TP/VS will handle transportation logistics, and MSP will handle production support and maintenance logistics.

2.3 Modeling and Simulation

Modeling and simulation (M&S) is an essential tool for systems engineering. M&S is commonly used to model complex system, such as manufacture, service, military, transportation, and supply chain process. Instead of describing the best situation to use M&S, Banks et. al. described 10 rules when M&S is not appropriate. Applying these 10 rules, we are able to determine M&S is an appropriate tool to use (Table 4).
M&S is a complex process. Banks et. al. provided a 12 steps systematic process to execute this project: 1) problem formulation, 2) setting project objective, 3) data collection, 4) model conceptualization, 5) model translation, 6) model verification, 7) model validation, 8) experimental design, 9) model simulation and analysis, 10) additional simulation runs, 11) documentation and reporting, and 12) implementation [Banks et. al. 2005]. This thesis will follow this approach but will not include implementation since that is considered out of scope.

There are many simulation languages available in the market, such as GPSS, SIMAN, Simscript, and SLAM. They are highly flexible and powerful to execute complicated system simulation. However, these simulation languages are difficult to present due to lack of graphical interface. Arena provides graphical interface with the flexibility of simulation language [Kelton et. al. 2003].

	10 Rules when simulation is not appropriate	Bayer Project
1	The problem can be solved using common sense analysis	The problem is too complex for common sense analysis
2	The problem can be solved analytically using a closed form	The problem is too complex for closed form
3	It's easier to change or perform direct experiments on the real	Direct experiments is too costly and difficult to perform
4	The cost of the simulation exceeds possible savings	Simulation cost was justified by Bayer
5	There aren't proper resources available for the M&S project	Both MIT and Bayer will provide proper resources
6	There isn't enough time for the model results to be useful	There is enough time, 8 months, for M&S project
7	There is no data or not enough data for simulation	Data is not complete but enough for M&S
8	The model can't be verified or validated	Model can be V&V with past data
9	Project expectations can't be met	Project expectation is clear and can be met
10	If system behavior is too complex, or can't be defined	System behavior is complex but can be defined

Table 4 Ten Rules Analysis for Bayer Project (Banks et. al., 1997)

In Arena, the most commonly used model is the event-driven simulation model. The model can be divided into four parts: 1) entity arrival, 2) system process, 3) entity departure, and 4) simulation termination. When entity arrived to the system, characteristic of the entity will be assigned then the entity will be transferred for process. After process, the entity will exit the system where KPIs will be recorded. Simulation will not stop until termination condition is met. In Arena, the KPIs will be compiled by Crystal Report, a reporting-software developed by SAP, which can be used for analysis.

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Chapter 3: Current State

3.1 Overview

As discussed in chapter 1, there are four modules in Bayer's supply chain: product distribution, API sourcing, production planning, and production process. Product distribution module will not be modeled in its entirety since the project scope excluded transportation and multiple finish goods inventory. This thesis will only consider one finish goods inventory, and distribution process is instantaneously and directly serves end consumer. This simplification is reasonable since bullwhip effect is minimal in Bayer's supply chain due to practice of Vendor Management Inventory. API sourcing will also be considered as out of scope. In this model, we will assume infinite supply of raw material. This assumption should not affect the outcome of the simulation since API shortage rarely happens. This model will focus on production planning and production process.

There are four modules in Arena models: demand and production logic, production sequence, production process, and KPI collectors (Figure 6). Product distribution and part of the production planning are modeled in demand and production logic module. In this module, demand is generated, and product will be check out from finish good inventory (Figure 7).

The production sequence, part of production planning process, is modeled in a separate module, called production sequence module. This module will look at the products in the production queue and provide an optimal schedule to minimize the changeover cost. Once the optimal sequence is determined, the product will be sent to production process where product is formulated, filled, sterilized, dried, inspected, and packed. After the product is packed, they will be check into finish goods inventory. At this time, important KPIs will be collected for future analysis.

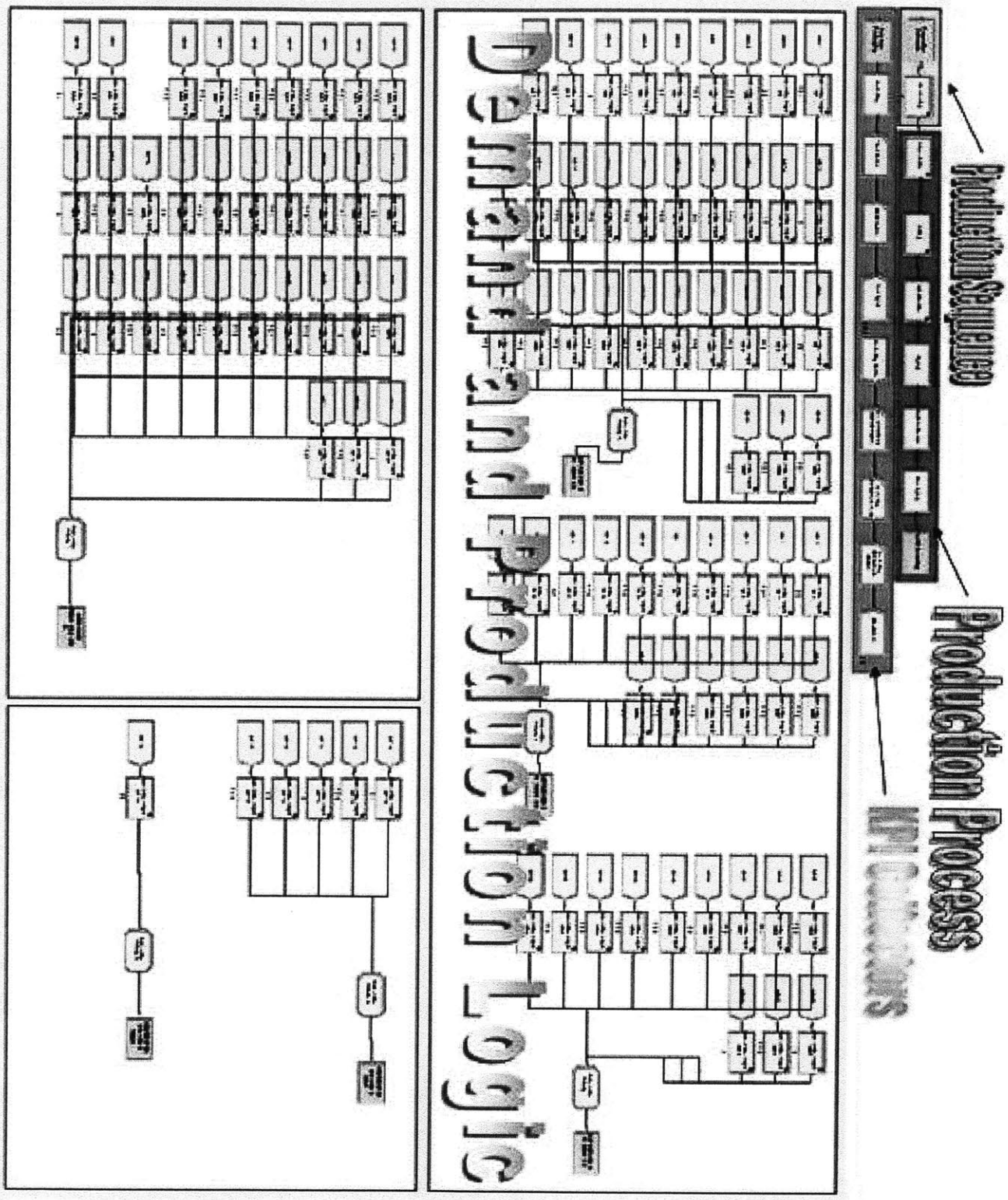


Figure 6 Current State Arena Model

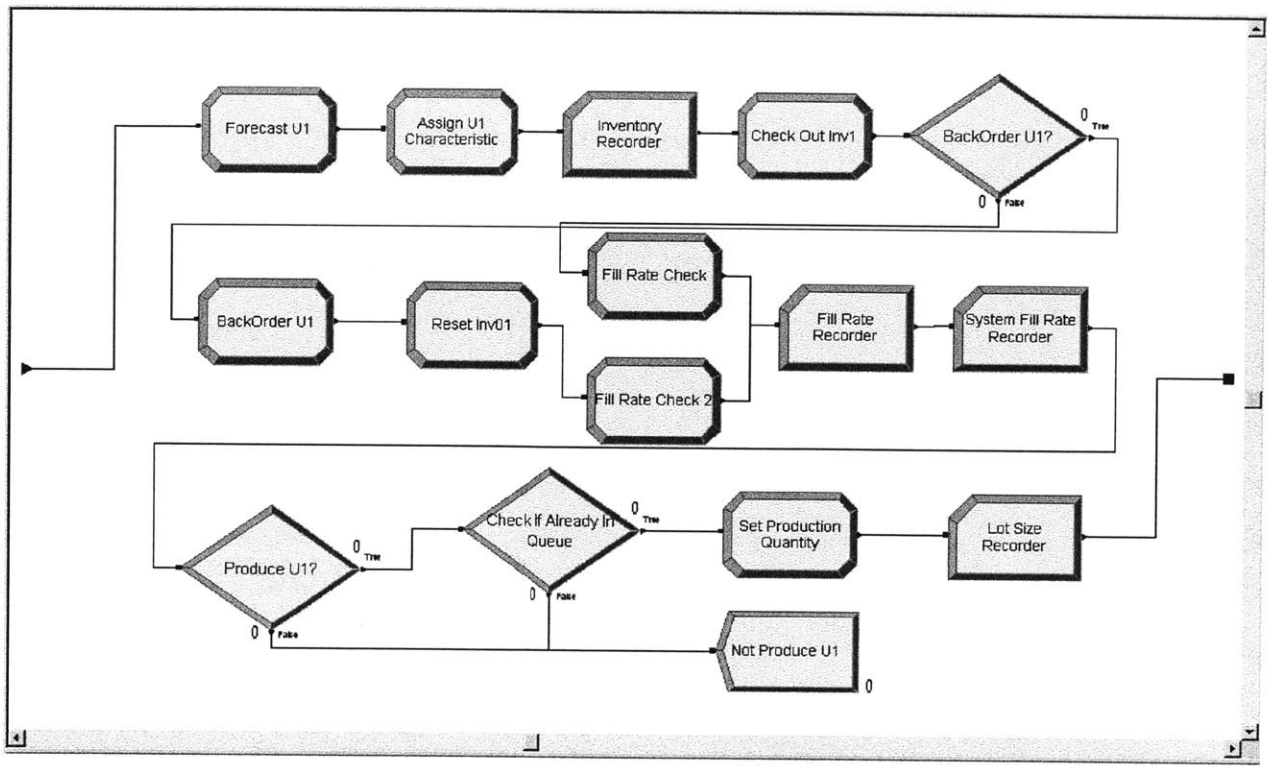


Figure 7 Demand and Production Logic for Product U1

3.2 Current State Supply Chain Structure

3.2.1 Demand and Production Logic

After clearly understand the supply chain structure and project scope, the current state model can be developed in Arena. Bayer relies on SAP to determine an optimal schedule using mix-integer optimization, and Arena is not designed to run real time optimization. Therefore a new schedule system has to be developed to replicate SAP's planning process.

The schedule provided by SAP minimized overall supply chain cost using demand forecast and other resource constraints. Demand forecast is updated in a monthly interval. A new schedule is generated by SAP every time when demand forecast is updated. Therefore we will assume SAP schedule is determined at the beginning of every month.

This type of review system with constant time interval is defined as periodic review system. At each review, SAP triggers production if coverage time falls below the threshold of 45 days. The coverage time is described as how long current inventory, excluding safety stock inventory (Equation 7), will last based on the forecast. We will use a coverage time ratio (Equation 8) to determine if production is needed. If the coverage time ration falls below 1, production is triggered.

$$SafetyStockInvenotry = SDev * ServiceFactor * LeadTimeFactor$$

Equation 7 Safety Stock Inventory

$$CoverageTimeRatio = \frac{CurrentInventory - SafetyStockInventory}{Next45DaysOfDemand}$$

Equation 8 Coverage Time Ratio

Demand forecast data is needed to calculate coverage time. Using 2010's sales data, each product was fit into probability distribution. The example in Figure 5 shows that particular product follows a normal distribution with mean of 18,058 bottles and standard deviation of 2,284.1 bottles. At 95% of confidence interval, that product will have a monthly demand between 13,490 bottles and 20,626 bottles. In this example, the product's demand profile fits nicely in the normal distribution. For some products, the demand profile cannot fit into one probabilistic distribution. In that case, multiple probability distributions were used to describe the demand profile.

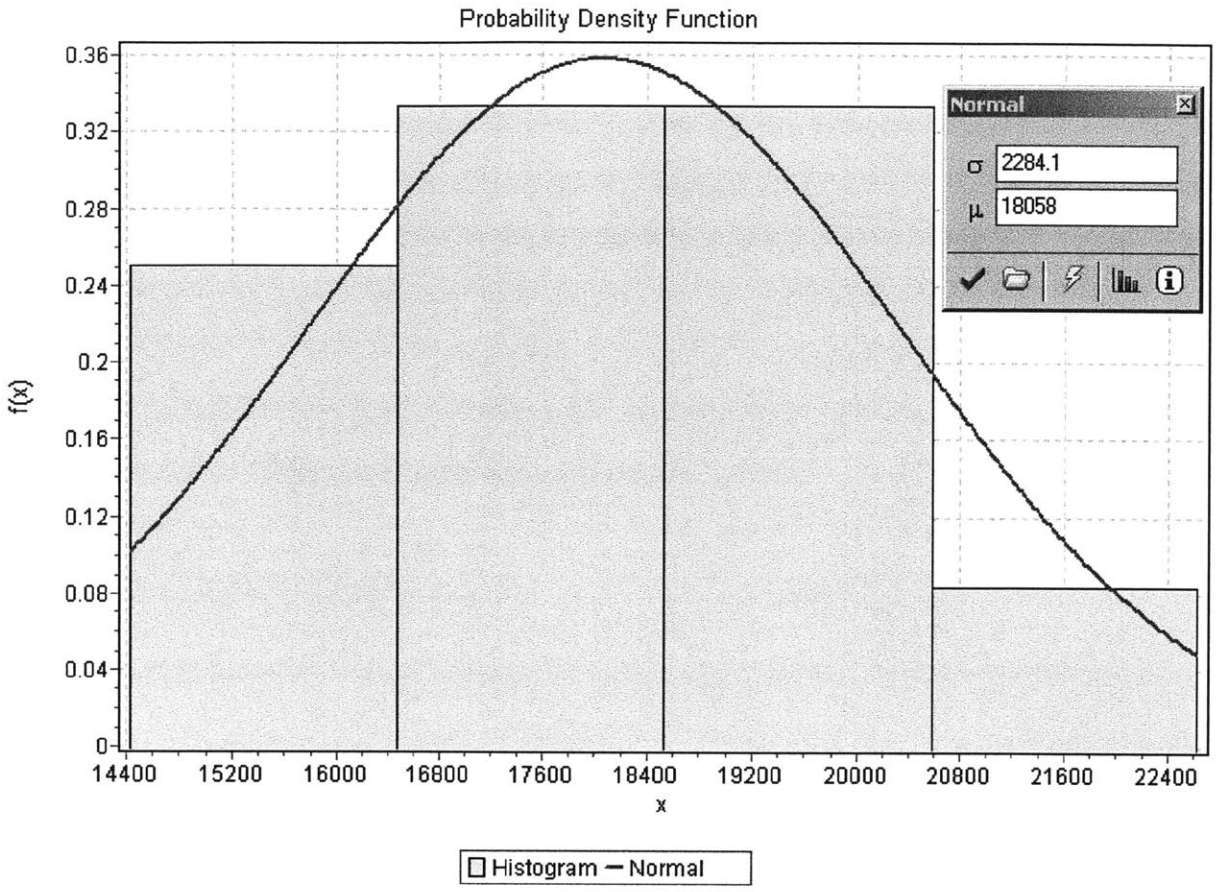


Figure 8 Example of Fitted Distribution

Two or more distributions were used to describe the products with high demand variation. For example, product U10 cannot be described with one probability distribution. The past data fits nicely into triangular distribution 25% of time and gamma distribution 75% of time. In that case, we will use decision module to set demand to triangular distribution 25% of time and gamma distribution 75% of time (Figure 9).

Actual future demand is generated at the beginning of each review period using these distributions. Forecast demand is generated by multiplying actual future demand by the forecast error. Historical data of forecast demand and actual sales showed that the forecast team at Bayer has a strong bias of over forecast. The margin of over forecast increases as the forecast gets further into future. For example, if x is the forecast error for period 1, and y is the forecast error for period 2, then y >= x. These values were calculated and set as the over-forecast-multiplier.

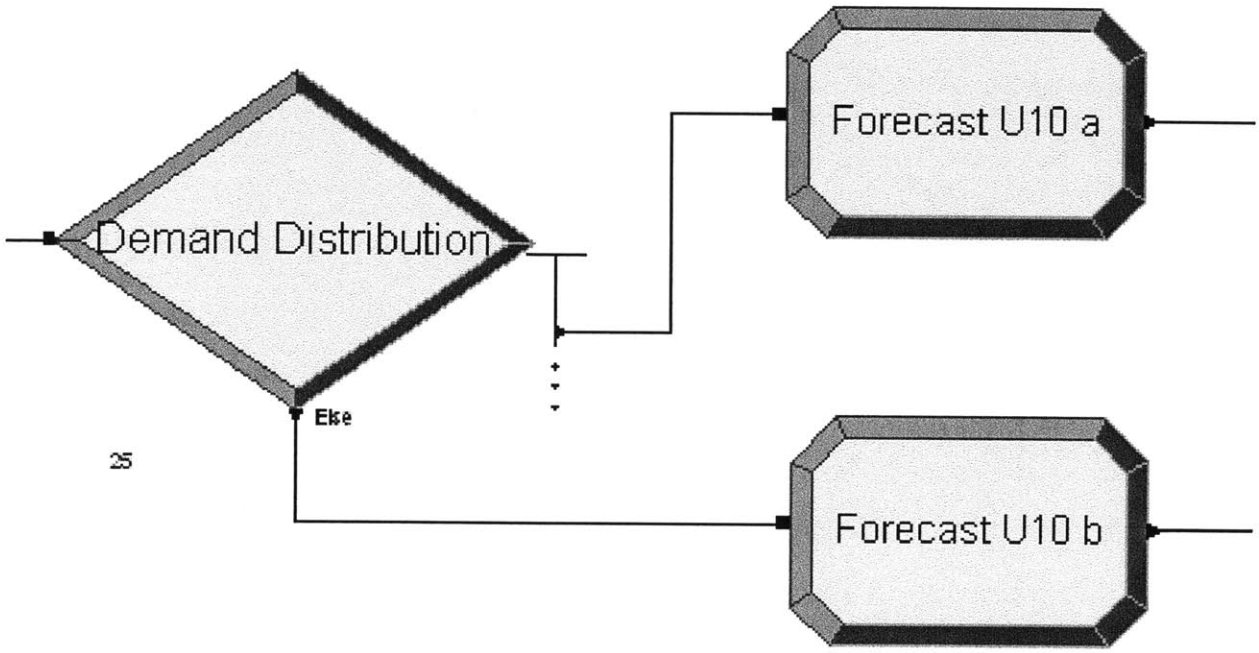


Figure 9 Demand Generators for Product U10

At the beginning of each period, demand will be checkout from current inventory. If inventory, including safety stock, is less than demand, backorder is generated and will be added on top of this month's production quota. The back order products will be shipped directly to customer without entering finish good inventory.

Production is triggered when coverage ratio is less than one. To determine the production quantity, past production data was analyzed. The average order up to point is 90 days of coverage time. However, there are some products with coverage time much higher than 90 days. This was caused by SAP's complicated cost optimization method. To duplicate SAP's cost optimization characteristic, economic order quantity (EOQ) model was used.

EOQ model is commonly used to find the perfect balance between inventory holding cost and ordering cost (Equation 10 and 11). Holding cost was provided by Bayer while

ordering cost is calculated using average changeover cost. This model will not include administrative cost. Actual demand used is the actual annual demand of 2010. Actual sales price was used as the cost per unit. EOQ was determined for all 99 SKUs.

$$EOQ = \sqrt{\frac{2 * ActualDemand * OrderingCost}{HoldingCost}}$$

Equation 9 Economic Order Quantity

$$HoldingCost = CarryingCost * CostPerUnit$$

Equation 10 Holding Cost

To simulate cost optimization, the production lot size has to be greater or equals to EOQ. However, most of the product has an average order-up-to lot size of 90 days. Combining average order-up-to lot size with EOQ, we are able to generate a similar production lot size compares to SAP using Equation 11.

$$QtyTo\,\mathrm{Pr}\,oduce = Max(EOQ, 90daysForecastDemand)$$

Equation 11 Quantity to Produce

3.2.2 Production Schedule

Once SAP produced the schedule, planner will use heuristic to determine production sequence by optimizing changeover time. Changeover time depends on the current product's product type and previous product's product type. There are a total of six product types between 99 SKUs. To simulate this process, optimal production sequence was determined through nearest neighbor algorithm. In production schedule module, products will be rearranged in the order which will minimize the changeover cost.

3.2.3 Production Process

There are five main production processes: formulation, filling, sterilization, drying, optical control, and packaging (see Figure 10). Each process is constrained by number of machines/lines, availability, and number of shifts (see Table 5). Space limitation is ignored on drying station.

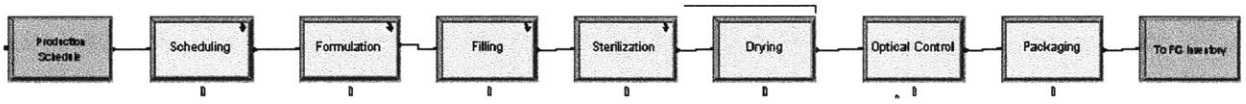


Figure 10 Production Process

Processes	# of Lines	Availability	# of Shifts
Formulation	2	x-breakdown	3
Filling	2	x-breakdown	3
Sterilization	3	100%	3
Drying	infinite	100%	3
Optical Control	2	x-breakdown	2
Packaging	2	x-breakdown	3

Table 5 Production Process

3.2.3 KPI Collectors

Arena will keep track of general statistical summary for each product, such as the number of entity generated (number of review). KPI collectors were designed to collect data which Arena does not track by default. The KPIs collected include individual product fill rate, overall system fill rate, cycle time, inventory level (bottles), and inventory value (Euros).

3.3 Model Simulation

The model was simulated with warm up period of two years before data collection begins. This warm up period will eliminate outliers before system reaches a stable state. To ensure the data collected is normally distributed, data is gathered and compiled in 50 replications with length of 100 years for each replication. Central limit theorem ensures

that sufficiently large number of independent random variables will follow normal distribution.

3.4 Validation

The result of the Arena model produced two categories of KPIs which can be used to validate current state model: delivery performance and assets & inventories. The Arena model's output showed less than 10% of error across all four KPIs; the fill rate and the cycle time describe the delivery performance, the inventory level and the inventory value describe the assets & inventories (Table 6).

KPI	Current State	Actual Data	% of Deviation
Fill Rate	97.33%	99.00%	1.72%
Cycle Time (Hours)	68.25	68.00	0.36%
Inventory (Bottles)	1,478,708	1,577,149	6.66%
Inventory (Euros)	3,809,182	3,600,654	5.47%

Table 6 KPI Comparison between Current State and Actual Data

The simulation model's fill rate is slightly lower than the target fill rate of 99%. In reality, the fill rate is higher because there are many tricks to manipulate a system to improve the fill rate which is not reflected in this simulation model. For example, if a customer ordered 500 units of product A for period 1 and there are only 200 units available in inventory, the most common practice is to negotiate with the customer to split one order into two orders; 200 units in period 1 and 300 units in period two. If customer accepts the offer, then the extra 300 units of order is not consider as back order. The simulation model did not include such options to boost fill rate; therefore, a slightly lower fill rate of 97.33% is reasonable.

The cycle time of the product reflects the average time a lot of order will spend in the system. The data from 2010 showed us the average cycle time is 68 hours. Cycle time yield by current state simulation model is 68.25 hours. With deviation less than 1%, we can conclude that the simulation model produced accurate system cycle time.

Inventory level and inventory value are two of the most important KPIs to determine the effectiveness of the simulation model's effort to duplicate SAP's scheduling policy. Inventory level of the simulation model is only 6.66% higher than the actual data, and the inventory value is 5.47% higher than the actual data. With less than 7% of error on both inventory level and inventory value, simulation model successfully duplicated SAP's scheduling policy. Overall, we can conclude that the simulation model is an accurate representation of Bayer's production supply chain.

Chapter 4: Future State

4.1 Overview

The future state Arena model is based on the current state Arena model (Figure 11). The major difference between two states is the production sequence. Current state uses a cost optimization approach where production sequence is determined at the beginning of each review period to minimize changeover cost. In future state, production wheel will determined the production sequence.

4.2 Future State Supply Chain Structure

Production wheel is a predetermined production sequence where changeover costs were minimized. The wheel is determined in three steps provided by Bayer.

1. Use traveling salesman algorithm to determine the optimal changeover cost between product types
2. Use traveling salesman algorithm to determine the optimal changeover cost within each product type base on the bottle size
3. Sorted products within each bottle size by material ID

Bayer's intention is to create stability in production sequence and each product will have dedicated machine for filling and packaging. The traveling salesman algorithm showed that the minimal changeover cost can be achieved through two production wheels. Each wheel will contain three product types. First wheel contains 46 SKUs while second wheel contains 53 SKUs.

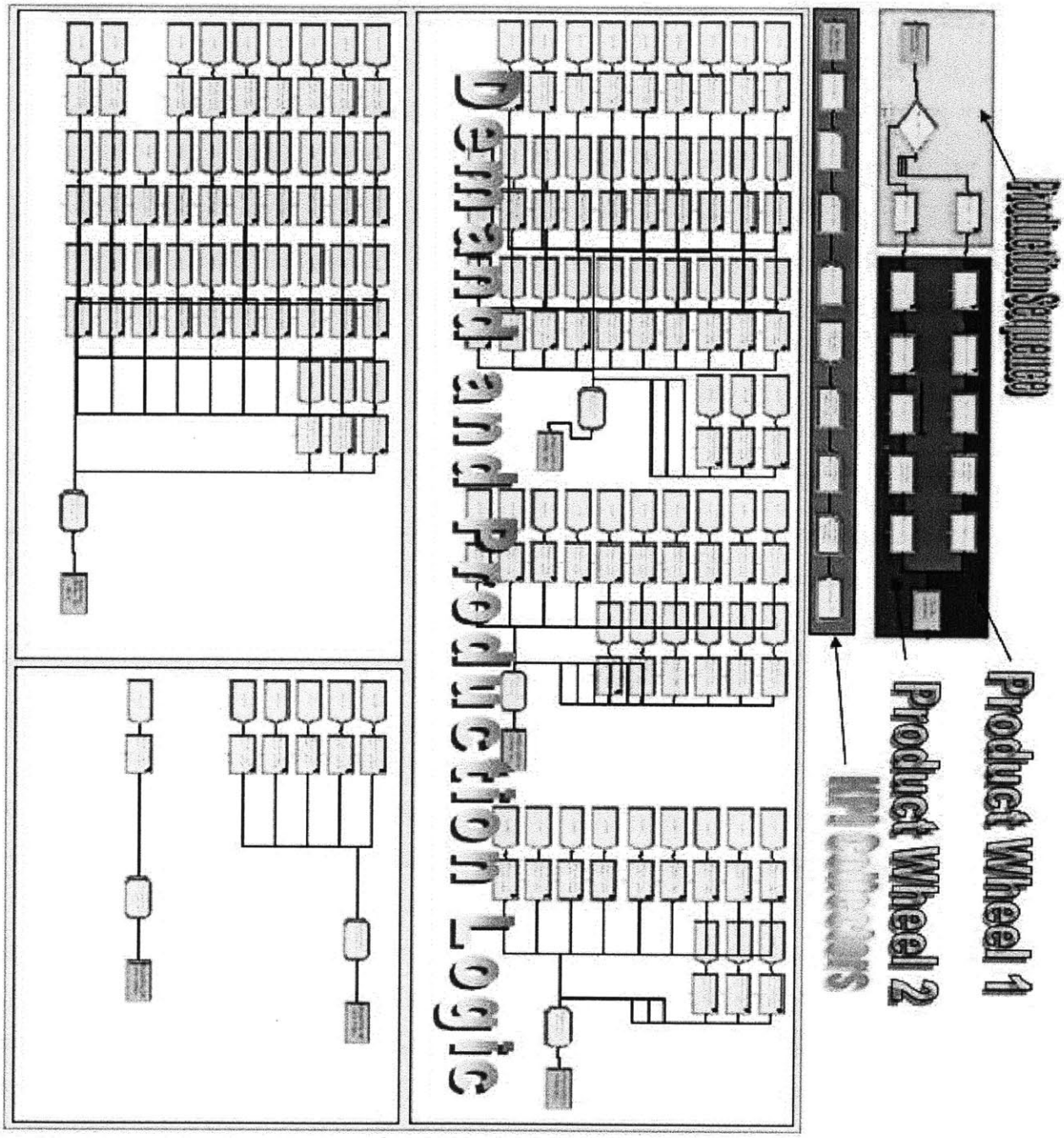


Figure 11 Future State Model

At the beginning of each review period, future state model will start at the first product of each wheel. If coverage time ratio for a product is under 45 days, production will be triggered. Otherwise, production will be skipped and wheel will be turned, and next product will go through coverage time ratio check. For example, the first wheel includes product type 5, 4, and 1. At the beginning of the period, production logic will start

inventory check with product type 5 and end with product type 1. The wheel will turn clockwise, and production will follow the exact sequence the wheel turns [see Figure 12].

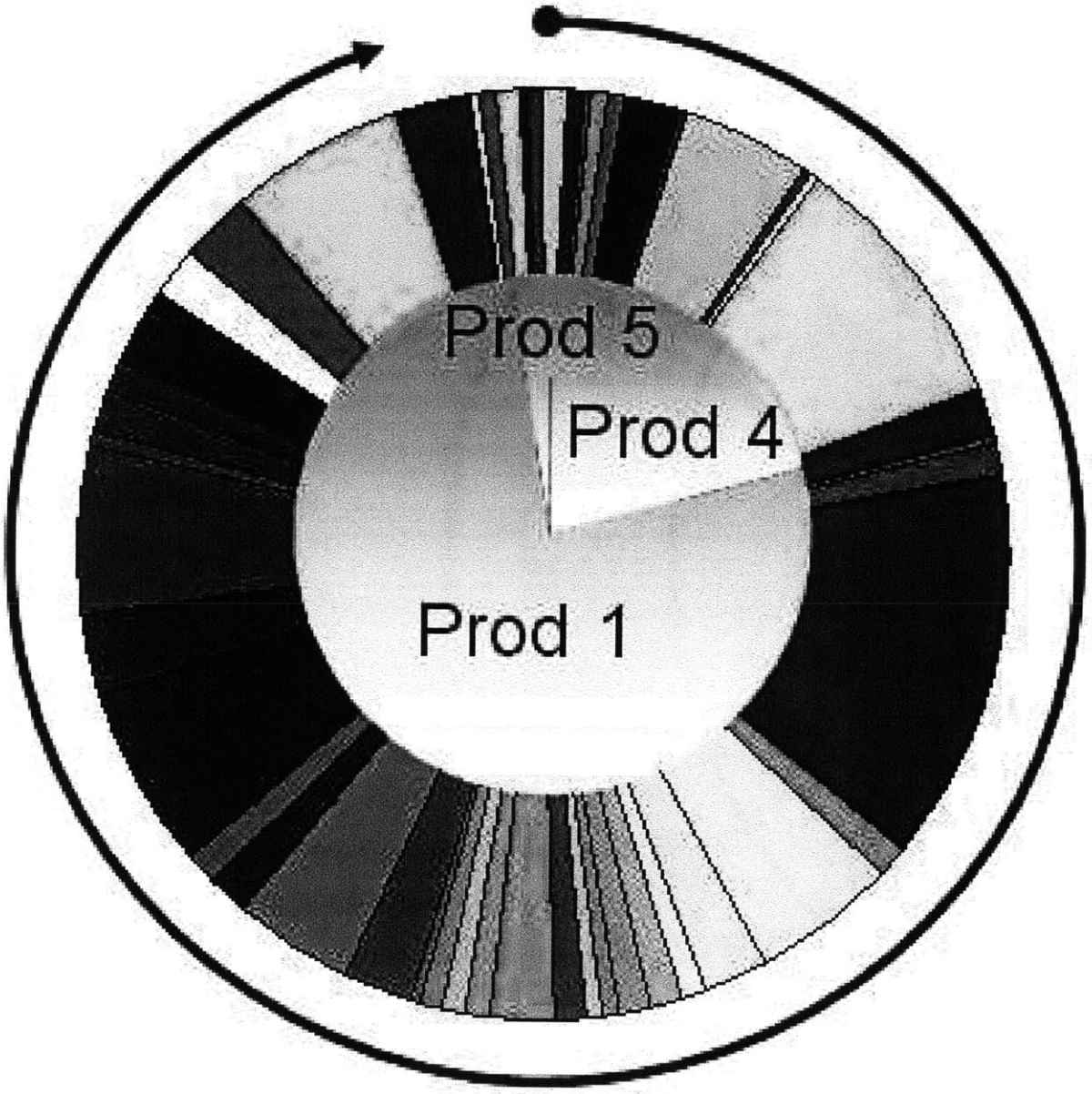


Figure 12 Product Wheel

In production wheel scenario, resources cannot be shared. For example, in current state, Filling Line 1 and Filling Line 2 can provide filling process for any product. Using production wheel, Filling Line 1 can only provide filling service for product type 1 and 6

while Filling Line 2 provides filling service for product type 2, 3, 4, and 5. Similar constraint exists in packaging process.

4.3 Model Simulation

The future state model is simulated with identical setup as the current state model. The simulation model will have 2 years of warm up time and the 10 replication with length of 100 years each. The result of this model will be compared in next chapter.

Chapter 5: Model Evaluation

5.1 Overview

In previous two chapters, we discussed the logic of current state model and future state model. The focus of this chapter is to determine and understand the differences between current state model and future state model. KPI comparison will be used to compare two systems at stable state. Then we will conduct sensitivity analysis to revile detail characteristics of both systems. This chapter will interpret and explain the KPI differences under stable state and characteristics from sensitivity analysis.

5.2 Key Performance Indicators

The KPI comparison between current and future states has provided some interesting insights (Table 9). Current state model outperformed future state model in terms of fill rate, cycle time, and changeover time. However, reminding KPI such as inventory level and inventory value is almost identical.

KPI	Current State	Future State	% of Deviation
Fill Rate	97.33%	88.45%	9.12%
Cycle Time (Hours)	68.25	78.39	14.86%
Inventory (Bottles)	1,478,708	1,427,004	3.50%
Inventory (Euros)	3,809,182	3,865,614	1.48%
Changeover (Hours)	1,169	1,487	27.23%

Table 7 KPI Comparison of Current State and Future State

5.2.1 Cost Comparison of the Two Systems

There are three costs this thesis will consider, inventory holding cost, changeover cost, and loss of sale. The inventory holding cost, is calculated using inventory value, for future state model is only 3.5% lower compares to the current state model. Therefore, we can conclude that there are no significant differences in terms of inventory holding cost between the two systems.

When comparing changeover cost, future state is 27.23% higher compares to current state. This suggests future state's changeover cost is approximately 27% higher as well. However, majority of the changeover cost, labor cost for example, are sunk cost and changeover cost is relatively small compares to inventory holding cost. We can conclude that the difference of changeover cost between two systems is insignificant.

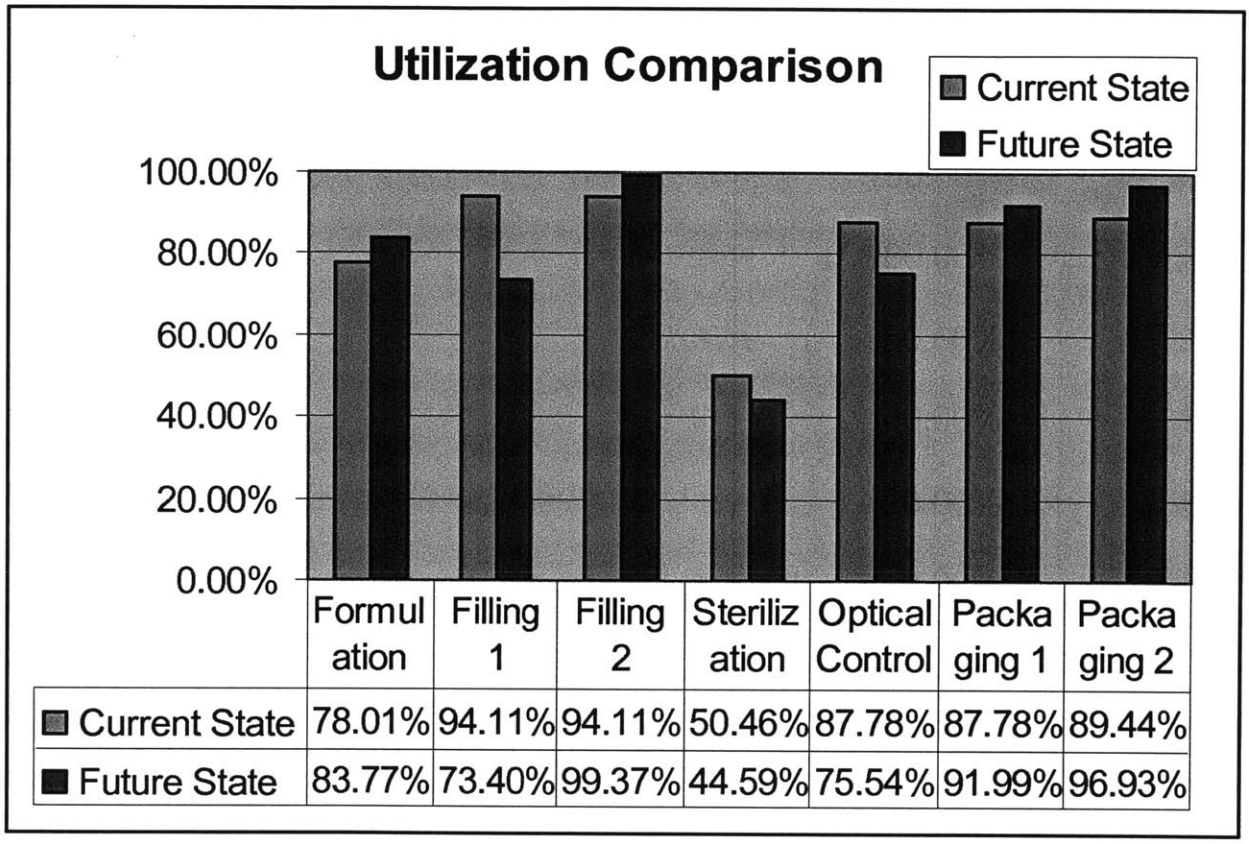
Lastly, future state has a fill rate that is 9.12% lower compares to current state. This suggests that the cost for lost sales due to low fill rate is significantly higher for future state model. Considered all three costs; we can conclude that future state model will cost more than current state model.

5.2.2 System Utilization

Table 7 suggests current state outperformed future state in fill rate, cycle time, and changeover time. This was caused by lack of flexibility in future state model. In production wheel, product has dedicated production path. For example, product U30 can only be filled at Filling Line 2 in future state. In a scenario where Filling Line 1 is available, and product U30 is queuing behind another product on Filling Line 2, current state model will provide the flexibility by allowing U30 to be produced in Filling Line 1 instead of waiting in the queue. However, in future state model, U30 will have to wait for Filling Line 2 even though Filling Line 1 is available. This lack of flexibility will lead to higher cycle time for product U30. As Filling Line 2 becomes more congested, the fill rate for products in that line will decrease. This phenomenon, unbalance workload between resources, can be shown through resource utilization comparison of the two systems. In Figure 13, future state shows large deviation in terms of resource utilization between filling lines and packaging lines (Figure 13).

Similar to fill rate and cycle time, changeover in future state was outperformed by current state due to lack of flexibility in production sequence process. In current state, production schedule was determined at the beginning of each production cycle based on the products in each production cycle. In future state the production sequence is predetermined as every product will be produced. The sequence is optimal if all products

are produce in the production cycle. In reality, not every product will be produced in every production cycle. When a product in the production wheel is not produced in this cycle, this created a skips in production wheel. When the wheel skipped, the production sequence is no longer optimal and will result in higher changeover cost.



	Formulation	Filling 1	Filling 2	Sterilization	Optical Control	Packaging 1	Packaging 2
Current State	78.01%	94.11%	94.11%	50.46%	87.78%	87.78%	89.44%
Future State	83.77%	73.40%	99.37%	44.59%	75.54%	91.99%	96.93%

Figure 13 Resource Utilization Comparison

In summary, at the stable state, current state will outperformed future state in terms of fill rate, cycle time, and changeover hours due to extra flexibility in resource utilization and production sequence process. Current state also outperformed future state in terms of changeover cost and loss of sale. Based on the stable state analysis alone, we can conclude current state is significantly better compares to future state.

5.3 Sensitivity Analysis

Last section indicates both states perform at similar level in the category of assets and inventories while current state outperformed future state in every other KPI due to extra flexibility in resource utilization and production sequence process. However, last section

did not revile any system behaviors when changes occurred. In this section, we will conduct some sensitivity analysis to revile important characteristics of current state model and future state model.

5.3.1 Responsiveness

The responsiveness of a system is defined, in this thesis, as how well the system can perform under dramatic changes. For example, if a drug is promoted by Oprah Winfrey, then the demand for that drug will increase sharply, if history prevails. A long term strategy will allow Bayer to expand their production capacity by increase their capital investment and labor force to meet extra demand. This analysis will only focus on short term impact, where Bayer cannot add extra capacity to deal with demand increase. We will test the responsiveness of supply chain under extreme condition.

Overall System Demand Increase

In first scenario, we will analyze how both systems behave when overall system demand increased. To simulate demand increase, demand for each product is multiplied by a multiplier, ranging from 100% to 200%. The model was simulated with warm-up period of 1 year and simulation time of 10 years.

The results from simulation show both systems decrease at a similar rate. Using two samples student T test, with 95% of confident level, we cannot conclusively say that the change of fill rate in current state is different from future state. Therefore, with 95% of confident level, we cannot conclusively say one system is more responsive to change compares another system.

Demand Increase Multiplier	Current State Fill Rate	Changes	Future State Fill Rate	Changes
100%	97.33%	0.00%	88.45%	0.00%
110%	94.07%	-3.26%	85.17%	-3.28%
120%	90.25%	-3.82%	81.66%	-3.51%
130%	87.24%	-3.01%	77.79%	-3.87%
140%	83.99%	-3.25%	75.83%	-1.96%
150%	79.72%	-4.27%	72.29%	-3.54%
160%	75.81%	-3.91%	69.23%	-3.06%
170%	72.79%	-3.02%	65.89%	-3.34%
180%	70.39%	-2.40%	62.91%	-2.98%
190%	68.24%	-2.15%	60.24%	-2.67%
200%	64.81%	-3.43%	58.10%	-2.14%

Table 8 Total Demand Increase Impact On Fill Rate

Random Product Type Demand Increase

In first scenario, we cannot identify any significant difference between current state and future state's response to change in overall demand. In this scenario, we will test the responsiveness of each system when demand increase is applied to one randomly select product type. The model was simulated with warm-up period of 1 year and simulation time of 10 years.

Demand Increase Multiplier	Current State Fill Rate	Changes	Future State Fill Rate	Changes
100%	98.93%	0.00%	88.45%	0.00%
110%	95.25%	-3.68%	84.62%	-3.83%
120%	92.94%	-2.31%	83.85%	-0.77%
130%	91.84%	-1.10%	80.63%	-3.22%
140%	90.03%	-1.81%	78.47%	-2.16%
150%	88.09%	-1.94%	77.25%	-1.22%
160%	85.55%	-2.54%	75.89%	-1.36%
170%	83.82%	-1.73%	73.48%	-2.41%
180%	81.65%	-2.17%	71.42%	-2.06%
190%	80.48%	-1.17%	70.32%	-1.10%
200%	78.80%	-1.68%	69.71%	-0.61%

Table 9 Random Product Type Demand Increase Impact On Fill Rate

Similar to previous scenario, the data does not show clear sign of difference between two systems (Table 9). Applying two samples student T test, with 95% of confident level, we cannot conclusively say one system is more responsive to change compares another system.

In conclusion, both systems show no significant difference in responsiveness when overall demand increases or random product type demand increases. With 95% of confident level, we can conclude that there are no significant differences between responsiveness in current state and future state in both scenarios.

5.3.2 Changeover Improvement

The primary benefit of production wheel is to provide a stable environment for changeover improvement. To analyze the effect of changeover improvement, both systems was simulated using improved changeover time of 50% of the original changeover time and instantaneous changeover.

The result of the simulation suggests if changeover of the future state is improved by 50%, the cycle time will improve by 17.4% and outperformed current state model (Table 10). However, current state will still be superior in terms of fill rate even if instant changeover is achieved in future state. This phenomenon was caused by the lack of flexibility of future state in resource utilization.

	Current State	Future State		
		No Improvement	50% Improvement	Instant Changeover
Fill Rate	97.33%	88.45%	91.24%	93.85%
Cycle Time	68.25	78.39	64.74	51.61

Table 10 Sensitivity Analysis on Changeover Improvement

In conclusion, the future state model can achieve better cycle time compares to current state with only 50% changeover improvement. However, it cannot outperform current state in terms of fill rate through changeover improvement. This suggests the impact on fill rate from loss of flexibility outweighs the gain from possible changeover improvement.

5.3.3 Forecast Improvement

SAP schedule system, current state, is a make-to-forecast system. Since future state was derived from current state, future state is also a make-to-forecast system. Like the name suggested, make-to-forecast systems' performance heavily depends on the performance from forecast teams. Before we can conduct sensitivity analysis, we have to first analyze the historical data.

Comparing 18,550 data points, over 65% of the forecast data are higher than the actual sales data. Base on forecast data, over 65% of time, Bayer produced 26% more than needed (excluding safety stock replenishment), and the average BIAS per product is 2430 bottles. The average production lot size has coverage time of more than 3 months. Therefore if we estimate each production lot has an average BIAS of 9,315 bottles which leads to approximately 420,000 bottle of over production for each production cycle (Table 11).

	BIAS	Overproduction (Bottles)
Time 0	833.5553	0
Time 1	1190.793	58,944
Time 2	1701.133	84,206
Time 3	2430.19	120,294
Time 4	3159.248	156,383
Total	9314.92	419,828

Table 11 BIAS and Overproduction

After data analysis, we have to identify the impact of over forecast in both systems. To identify the benefit if this bias should be eliminated, both systems were simulated while setting over-forecast multiplier to 0. The model was simulated with warm-up period of 1 year and simulation time of 10 years.

The results from simulation suggest that both systems will perform better in all KPIs if forecast bias is eliminated (Table 12). Compare to current state, future state are much sensitive to forecast accuracy. In future state, Bayer can save approximately $29,000 in inventory holding cost and 30% cycle time.

	Saving in Inventory Holding Cost	Changes in Inventory Level (Bottles)	Changes in Fill Rate	Changes in Cycle Time
Current State	$ 5,828	1.02%	0.26%	14.42%
Future State	$ 28,628	4.99%	2.77%	30.30%

Table 12 Impacts on Forecast Improvement

In conclusion, forecast improvement is essential in both systems. Through elimination of forecast BIAS, Bayer can enjoy lower holding cost, more storage space, higher customer satisfaction, and faster production cycle. In future state the benefits will more than double in every category compares to current state. However, this also suggests future state is more vulnerable to forecast BIAS. An increase in forecast BIAS can be catastrophic.

Chapter 6: Recommendation and Project Closeout

6.1 Conclusion on Modeling Process

The previous chapters in this thesis have explained the detail modeling process. The process has successfully delivered current state model and future state model that outputs probabilistic system characteristics. The model utilized wide range of probabilistic distributions to describe the distribution process, scheduling process, and production process from historical data. In the following sections, we will discuss model limitation, and recommendation.

6.2 Model Limitation

The current state model was validated through comparison of important system characteristics with actual data systematic from 2010. In chapter 3, we have shown current state model is an accurate representation of Bayer's current supply chain. However, this model is not without compromise. Due to time constraints, assumptions were made and some factors are ignored and simplified. In this section, we will explain the three important factors we ignored in this model: inventory storage and work in progress space constraint, infinite and instantaneous raw material supply replenishment, and product life cycle.

In reality, space is an important constraint in any production and storage facility. One of the assumptions in this model is the unlimited space for drying process. Currently, bottleneck exists in filling process follow closely by packaging process and optical control process. The drying process is not the bottleneck of either system. Therefore this assumption is valid. However, if changeover is improved and production lot size is decreased, the bottleneck might shift to drying process. In that case, this model will no longer be valid until space constraint is added to the system.

Another important assumption in this model is the infinite and instantaneous raw material supply replenishment. SAP has the ability to provide BOM to raw material

supplier few months before the actual production. This allows suppliers to properly plan their supply chain to ensure availability of raw material at the time of production. Since raw material shortage is assumed to be a rare event, we can conclude this assumption is valid for the purpose of this project. In the event where raw material shortage becomes an issue, this model will no longer be valid until raw material supply chain is included to the system.

Lastly, this model did not consider product life cycle. The model assumes that the products maintain a stable demand. Both current state and future state exclude any product introduction and product phase out. In this thesis, we assume that the increase in demand from new products will be equalized by the decrease in demand of phasing-out products. At any given time, this assumption may or may not hold. It is up to the practitioner of this model to decide if this is a valid assumption.

These three assumptions are the most important assumptions of this model, and they are valid assumptions for the purpose of this project. Each of the three assumptions were discussed and approved by Bayer. However, it is still important to understand the limitation of this simulation model especially in an environment where these assumptions were violated. In such event, these models will no longer be valid.

6.3 Recommendation

This thesis is to evaluate the supply chain impact of the production wheel in a SAP environment. Bayer's long term objective is to create a competitive edge in their supply chain using Lean management. In Chapter 2, we discussed topics such as supply chain, SAP, M&S, and Lean management. There are three steps in the roadmap to Lean management: understand the concept of Lean, build a pro-Lean environment, and sustain Lean through continuous improvement. The production wheel is a Lean tool which can help lean practitioners to establish a pro-Lean/stable environment.

In Chapter 3 and 4, we explained the modeling process of current state and future state. Current state is considered as make-to-forecast system using SAP as a technology

enabler. Since future state is designed base on the current state model, we can conclude future state is also a make-to-forecast system. The only difference between two systems is the scheduling process. In current state, production sequence is different from one production cycle to another which creates unnecessary pressure on schedulers, operators, and other production support teams. In future state, a production cycle is predetermined and product will follow a predetermined production path to create stability in the system. However, this stability is not without compromise.

In Chapter 5, we compared KPIs of both systems and determined current state outperformed future state in every KPI. This is the result of loss of flexibility in future state. There are two flexibilities future state lost: production sequence flexibility and resource flexibility. In current state, production sequence is determined at the beginning of each production process. This practice ensure the optimal changeover time throughout the system. However, future state has a predetermined production sequence that is optimal if every product is produced in that production cycle. If a product is not produced in that production cycle, the changeover is no longer optimal which leads longer cycle time, lower fill rate, and more changeover time.

Compares to production sequence flexibility lost, resource flexibility lost have much higher negative impact on KPIs. In future state, each product will have its dedicated production path. This system does not allow product to be produced in any resource other than the dedicated resource even if other resource is capable and available. This will create an unbalance production workload which will lead to much longer cycle time and significantly lower fill rate. This result suggests initial implementation of production wheel will have significant negative impact on Bayer's supply chain. After comparing the initial state of both models, we decide to conduct sensitivity analysis to generate some system insights.

Through three different sensitivity analyses, we are able to identify three interesting system characteristics. The first characteristic we identified is that future state showed no significant difference compares to current state when demand increase globally, increase in every product, or a locally, increase in a random product type. This suggests

that demand increase is not affected by the flexibility lost in the future state. The second characteristic we identified is that the changeover improvement alone cannot outperform current state in terms of fill rate. This suggests that the loss of flexibility outweighs the benefit from changeover improvements. The last system characteristic we identified is that the Bayer forecast team has a strong tendency to over forecast. Through sensitivity analysis, we are able to identify the impact of over forecast on each KPI. The result showed future state is more sensitive to forecast BIAS compares to current state. This suggests controlling and reducing forecast BIAS is more important in future state than current state.

Through these system characteristics, we are able to estimate the impact of production wheel when implemented. At the initial implementation, it is likely to see a decrease in fill rate. It is wise to build up some inventory before production wheel implementation. The models suggest that the production wheel cannot outperform current state through changeover improvement alone. Therefore it is necessary for Lean teams to find other process improvement methods to bridge the performance gap between future state and current state. Lastly, forecast BIAS is an important issue and we are able to quantify the impact for both systems. The result is alarming. Production wheel is much more sensitive to forecast BIAS compares to current state. It is important for Bayer to control and minimize forecast BIAS as much as possible.

At the beginning of this thesis, Bayer is interested in if production wheel has the ability to provide the same service level at lower cost compares to the current system? The answer is clear with the simulation model. Production wheel cannot out preformed current state without improvements. With minor improvements in changeover and elimination of forecast BIAS, production wheel model can perform at similar level compares to current state model. Production wheel is only the first step towards lean management. There will be other improvements lean teams at Bayer can utilize in a stable environment. Therefore, based on the analyses of this thesis, we recommend the implementation of production wheel system with changeover and forecast BIAS improvements.

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