

**Analyzing Tradeoffs between Working Capital
and Production Capacity for Multi-Stage Manufacturing Processes**

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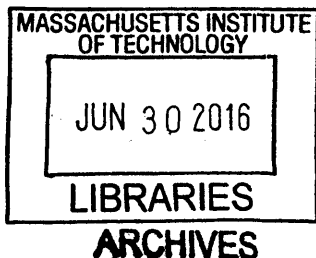
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Abstract

Large pharmaceutical companies struggle to find innovative ways to reduce work-in-process inventory in their production facilities. In our research, we focus on the tradeoff between inventory and production capacity through investing in new facilities and equipment. This tradeoff will depend on the company's objectives and what it is willing to give up in return for reducing inventory. We found that increasing capacity to reduce work-in-process inventory by investing in new facilities is not always the most favorable approach in terms of net present value. However, for flexibility or lead-time improvements, it may make sense to proceed with the investment. We developed multiple scenarios considering the company's future plans to reduce inventory or grow. These scenarios provide insights into the factors that improve the attractiveness of the investments and those that do not. Our financial analysis along with the guidelines and procedures that we have developed help the sponsor company most effectively reach its goal to reduce its work in process inventory.

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Biographical Notes

Karim Kamareddine grew up overseas in Lebanon. After high school, he attended college in Massachusetts. He has experience working in the Global Supply Chain of Pratt & Whitney, an aerospace manufacturer headquartered in Connecticut. He has experience in Supplier Quality, Procurement, Materials Required Planning and Strategic Sourcing. He holds a Bachelor of Science in Mechanical Engineering from the University of Massachusetts Amherst. Upon graduation from MIT, he will join Bayer Business Services as a Senior Consultant with a concentration in Management Consulting, Supply Chain Management and Technical Operations.

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¹ The word 'sponsor company' has been repeatedly used throughout the paper to maintain the company's anonymity.

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1. Introduction

Our thesis examines the tradeoff between net working capital and the capital investment of a major pharmaceutical company. First, we provide an overview of the challenges facing pharmaceutical companies, then break down the different cost elements needed to make specific supply chain investments and finally determine effective supply chain outcomes under different scenarios that consist of multiple stages and different changeover frequencies. This analysis provides us with tremendous insights into how different parameters can affect the outcomes of the different scenarios and ultimately the key performance indicators (KPI's) that the pharmaceutical company would like to focus on.

The production process for the pharmaceutical product in question is carried out in four stages where raw materials are converted into Active Pharmaceutical Ingredients (API's) sequentially. The output work in process inventory of each stage is the input of the next stage and there is considerable wasted time changing over from one stage to the next. We tend to study this production process in a very simplified approach by looking at the production schedule of one anonymized product at first and consequently analyzing how the work in process inventory of this product can be reduced while still maintaining an effective production process. This same analysis is also done for different multi-stage processes.

Our sponsor company's objective for this year is to reduce work in process inventory, so we have provided different investment scenarios that attempt to reduce this inventory while still maintaining a high return on investment. In an attempt to reduce net working capital, increase free cash flow and generate more profits, our sponsor company has asked us to provide guidelines and procedures to balance working capital and capital investment. Our thesis paper provides a quantitative analysis of specific investment scenarios to be used by key stakeholders at the sponsor company to evaluate options. The quantitative analysis is supplemented with reasoning that helps guide stakeholders to make informed decisions.

We used financial factors in our supply chain analysis to determine the tradeoff between capital investment and working capital with the primary objective of maximizing the net present value (NPV). We do this by first asking the sponsor company for the cost breakdown of a specific investment, calculating the free cash flows and the NPV of each investment, and then comparing different scenarios using Key Performance Indicators (KPI's).

In our paper, we consider a module to be the production facility that houses all the production equipment needed to create a finished product. We begin our analysis by examining a few simple scenarios and later expand the analysis by providing

supplementary scenarios that would provide the sponsor company with various real-life situations that they may encounter. We first examine a base scenario that includes a one module investment and a two-module investment. The one module investment is comprised of a 4-stage production process and requires 4 changeovers per year. The two-module investment is also comprised of 4 stages per module and requires a total of 12 changeovers per year. Refer to Appendix A for further details about the production schedule.

It is very important to evaluate exactly how these investments will impact our sponsor company's key performance indicators. Financial analysis will be key to understanding the effectiveness and feasibility of the investments. Finally, we provide the sponsor company with options to consider, depending on their main objective.

In our case, future demand is assumed to be constant and certain. The sponsor carries significant finished goods safety stock to provide good service in spite of variable demand and requested that the analysis focus on work in process inventory. We do point to opportunities to reduce finished goods safety stock as future work.

Some of the guidelines that we have provided to the sponsor company highlight the reasons to build one or many modules while mentioning some of the considerations that the company should not overlook. We also provide analysis highlighting key elements that may impact whether the company should pursue an investment such as: flexibility, risk, and adaptability.

We use financial analysis in conjunction with these other factors in considering tradeoffs among key performance indicators. We also develop several scenarios to evaluate tradeoffs between working capital and production capacity investments.

2. Literature Review

This section highlights focuses on supply chains in the pharmaceutical industry by referencing literature and discusses some the key elements that need to be outlined when making an investment decision.

2.1 The challenges

Pharmaceutical companies are facing rising challenges. Overall speaking, the pharmaceutical industry is becoming more liberalized on a global scale (Shah, 2004). The resulting competition along with more stringent regulatory control impel companies to increase profitability.

While traditionally companies place much emphasis on research and development (R&D) and charge a substantial premium for products to generate revenue, the

productivity of R&D is generally decreasing. To make things worse, the life cycles of new drugs are declining (Papageorgiou, Rotstein, & Shah, 2001). The new products, which normally take companies years to develop, not only face the uncertainty of clinical tests, but also the challenge of generic substitutes from competitors.

Faced with all these challenges, supply chain optimization is gaining prevalence as an excellent way to increase profitability. The diversity and complexity of new drugs, shortening life cycles, the globalization of the business which requires managing global manufacturing and supply networks all requires supreme supply chain management and optimization (Papageorgiou et al., 2001).

2.2 Pharmaceutical Supply Chain Characteristics

2.2.1 Overall Introduction of Supply Chain Layer

Sundaramoorthy and Karimi proposed that most pharmaceutical supply chains feature a layer structure as illustrated in *Figure 1* (Sundaramoorthy & Karimi, 2004).

Layer 1. In the first layer, companies interact with suppliers that provide raw materials and/or intermediates to the primary and/or secondary production sites and third-party contractors that supply intermediates.

Layer 2. This layer involves the primary production sites that produce active ingredient (API) using chemical or biochemical technology such as chemical synthesis, separations, fermentation, purification, etc. The input of this layer is raw materials and/or intermediates and the output are the API's.

Layer 3. This layer involves secondary manufacturing sites where the API's are transformed into a medicine that the patient can take, such as a tablet, capsule, syrup, injection, cream and ointment.

Layer 4. In this final layer, the warehouses, wholesalers, retailers, and end users.

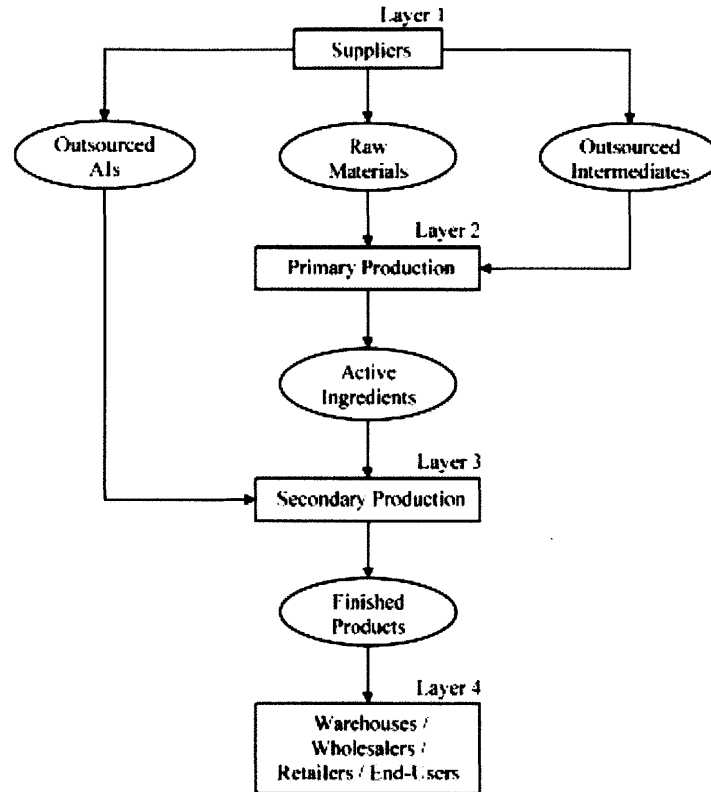


Figure 1: Typical pharmaceutical supply chain (Sundaramoorthy & Karimi, 2004)

2.2.2 Primary Manufacturing

Shah described the primary manufacturing process as one with long task processing times, multi stages and substantial inventories (Shah, 2004). This is due to the stringent requirements for validating cleaning and purity and the need for avoiding cross-contamination in the pharmaceutical industry (Sundaramoorthy & Karimi, 2004). In order to increase utilization of facilities, primary manufacturing often features long campaigns to minimize changeover. As a result, the traditional single-facility, long-campaign production yields considerable inventory at each stage and less responsiveness to market demand.

2.3 Optimization in Different Scenarios

In this section, we review literature that discusses supply chain optimization in different scenarios. The first two scenarios are most similar to our base model.

2.3.1 Multi-site and Multi-product

Kallrath developed a multi-site, multi-product, multi-period production network planning model for BASF with the objective of determining the production schedule given a certain demand (Kallrath, 2000). Grunow, Günther and Yang discussed the coordination

among multiple sites and the campaign schedules at different sites with a certain demand and tackled the problem using an innovative mixed-integer linear programming (MILP) model (Grunow, Günther, & Yang, 2003).

2.3.2 Incorporating Financial Considerations

Puigjaner and Laínez proposed a scenario-based multi-stage MILP model to maximize corporate value by combining financial factors with supply chain indicators (Puigjaner & Laínez, 2008).

2.3.3 Uncertain Demand

Verderame, Elia, Li and Floudas reviewed planning and scheduling under uncertainty (Verderame, Elia, Li, & Floudas, 2010). Two-stage stochastic programming, parametric programming, fuzzy programming, chance constraint programming, robust optimization techniques are common tools to approach optimization problems.

2.3.4 New Product

R&D in the pharmaceutical industry is exposed to greater risks compared with other industries. The uncertainty in clinical trial outcomes needs to be built into the optimization model of new products. Levis and Papageorgiou came out with a systematic mathematical programming approach for long-term, multi-site capacity planning with uncertainty in the pharmaceutical industry (Levis & Papageorgiou, 2004). They developed a two-stage, multi-scenario, MILP model and adopted a hierarchical algorithm to reduce the computational effort needed to solve the MILP model.

2.3.5 Different tax rates

Oh and Karimi illustrated the influence of regulations (corporate taxes, import duties and duty drawbacks) on the linear programming (LP) model to approach production-distribution planning problem (Oh & Karimi, 2004).

2.4 Investments Types

According to Götze, Northcott, and Schuster (2007), there are three main types of investments: Foundational, Current and Supplementary. Foundational investments are linked with a start-up and they can either be investments in a new company or in an existing company's branch at a new location. Current investments are replacement, major repair or general overhaul investments. Supplementary Investments refer to investments in equipment in existing locations and they can be classified as expansion, change or certainty investments. Our investment focuses mainly on the supplementary category.

2.5 The Investment Motive

Typically, the motive behind an investment can either be operational, strategic or financial and any company that decides to invest has a specific goal in mind that it would

like to attain. Quantitative methods and, in particular, mathematical programming models, have traditionally been used to make investment decisions at tactical or operational levels. However, mathematical models can and should also be used to address strategic decisions because these have a much greater impact on the results (Martínez-Costa, Mas-Machuca, Benedito, Corominas, 2014). Operationally, the company can be making the investments for the purposes of procurement, sales, administration, or research and development (Uwe Götze, Deryl Northcott, Peter Schuster, 2007). The investment will most likely have the biggest impact on the supply chain of the company but as Götze, Northcott, Schuster, (2007) stated, many investments that are instigated by one operational area affect other parts or decisions of the company.

Consider the decision to invest in a second module in a nearby location. The procurement of this long-term asset is primarily decided using assumptions about future production requirements. However, an expansion carried out to manufacture a new product type, for example, is an interdependent investment project, requiring considerable coordination of decisions from areas like sales, production, financing, human resources and research and development (Uwe Götze, Deryl Northcott, Peter Schuster, 2007). Therefore it is important to understand which stakeholders will be affected by these decisions in order to receive the appropriate buy-in from the entire organization.

2.6 Investment Uncertainty

It is important to mention that, with any investment, there is a level of uncertainty that needs to be accounted for (Uwe Götze, Deryl Northcott, Peter Schuster, 2007). There typically are not any investments that have certain or known effects since investments take place over a period of time rather than instantaneously. However, there are different levels of uncertainty and some investments can have effects that are more or less certain depending on the complexity of the investment. We can plan for certain disruptions; however, not everything can be anticipated. Bienstock and Shapiro (1988) for example advise that there are uncertainties in the external environment that are relative to prices, capital markets, government policies and competition that there is no control over.

2.7 Financial Analysis

The company's strategy could include a gated process (see *Figure 2*) whereby different decisions will be made at each gate in the process that hopefully align with the company's goals, ruling out projects or ideas that are not worth investing time and energy in. The gated process is displayed in *Figure 2* below. Ultimately, the NPV analysis can provide us with a framework to make our decisions but should also be supplemented with qualitative analysis of the investment decision.

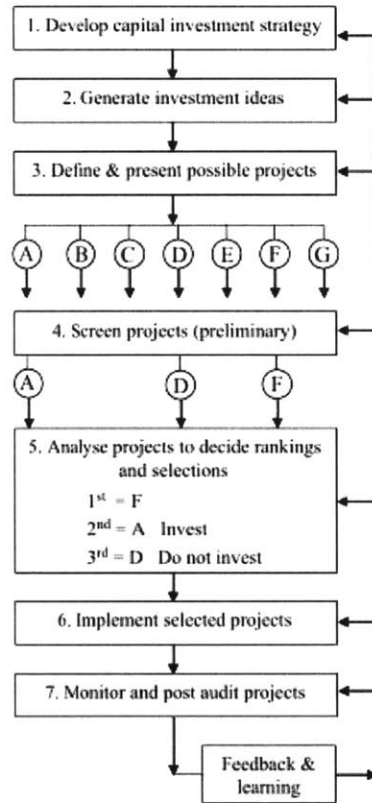


Figure 2: Gated Process for Investing (Uwe Götze, Deryl Northcott, Peter Schuster, 2007)

2.8 Capacity Planning of a Multi-Module System

Some benefits to building a secondary module can be related to strategic capacity planning. In the case of multi-site problems, there are two options: capacity expansion without new site installation and capacity expansion with new site installation as was mentioned by Chen et al., (2013). The former includes the detail of bottleneck machines or tools purchase decisions at a particular site. The latter problem involves decisions such as when and with what capacities new plants should be constructed. This confirms that one of the key challenges that decision makers routinely encounter is to ensure the availability of enough production capacity to meet the demands of products through efficient capacity planning (Arul Sundaramoorthy, Xiang Li, James M.B. Evans, Paul I. Barton, 2012).

2.9 Evaluating Risk

Fox, Birt, James, Kokko, Salverson and Soflin (2009) mention that shortages in material may occur, which is another form of risk that pharmaceutical companies need to have full control over and visibility into. Shortages occur as a result of raw material unavailability, manufacturing/regulatory issues, inventory practices, unexpected

increases/shifts in demand, and natural disasters. According to Swaminathan (2002), risks associated with making any decision need to be reduced. One way of doing this is to make sure that there are constraints that limit the amount of shortages.

2.10 Impacts on Inventory

A major dilemma resides in determining the optimal level of buffer stocks to adopt which allows a reduction of the total incurred cost and ensures a high level of customer satisfaction (Assid, Gharbi, Dhouib, 2015). An investment that can reduce inventory becomes a lot more attractive; however, there is a tradeoff between managing inventory levels and maintaining an optimized supply chain. Pharmaceutical companies are continually seeking to improve the planning and control of the supply chain as well as the efficiency of their production process as Assid, Gharbi, and Dhouib (2015) mention.

2.11 Summary

The bulk of our research and analysis will involve analyzing different investments through NPV analysis and studying different scenarios of the investment by adjusting our input parameters. The literature just referenced will supplement the quantitative analysis that we will provide and will reiterate the importance of analyzing the broader spectrum of factors that may or may not be influenced by the investment decision. At the initial stages of the study, the analysis is performed at a low level and at the final stages, we will introduce additional parameters that may influence investment decisions differently.

In summary, this literature demonstrates the importance of having qualitative analysis that can supplement the quantitative analysis that we will present in the data analysis and results section of this thesis paper. A great deal of research has been done to discuss whether investment decisions are feasible through MILP analysis. Our sponsor company prefers to have guidelines and procedures supplement such quantitative analysis in order to consider internal customers and stakeholders. Next, we will explore the specific case study of our sponsor company.

3. Data Collection

This section describes the data collection necessary to answer the questions posed the sponsor company. We initiated data gathering with formal meetings with the sponsor to better understand the cost breakdown of their operations and their expectations of the thesis project. For instance, we inquired about the typical COGS, labor costs, operating costs, capital and equipment costs that any production module incurs. The

breakdown of the cost elements that were studied were listed below. See Appendix C for details on cost breakdown that was discussed with the sponsor company.

Direct Labor: The direct labor in this case is the labor cost associated with the hourly wages of employees producing the material in the different stages of production. The salary for the direct labor force ranges between £50K and £110K and the number of employed salary workers is about 8 employees per module. In our analysis, the annual salary is estimated to be £60K.

Material Cost: The material cost is used for inventory valuation. It begins with the cost to procure raw material from suppliers and increases in each of the four different stages of production as variable costs accumulate. For example, in Stage 1, the cost increases from £400/kg to £450/kg. In stage 2, the cost increases from £450/kg to £500/kg. In stage 3, the cost increases from £500/kg to £550/kg. Finally, in stage 4, the cost increases from £550/kg to £600/kg.

Fixed Overhead: The fixed overhead cost includes indirect labor, distribution, waste management and repair and maintenance. The indirect labor is associated mainly with management as well as personnel that is responsible for the changeover from one production stage to the next. The personnel include: production supervisors and quality control staff. Total fixed overhead is estimated to be between £700K and £1.5 million. In our analysis, the fixed overhead is estimated to be £960K per module.

Variable Overhead: The variable overhead includes energy, consumables and overtime. It is estimated to be between £300K and £3 million. In our analysis, the variable overhead is set at £300K.

Operating Expenses: The operating expenses cost element is the sum of the variable overhead and fixed overhead cost.

Equipment Cost: Production equipment that has a capacity of 5 tons per week was assumed to cost £30M. This was the equipment necessary to produce the finished goods for the base scenario. In our analysis, we assumed that the equipment cost is proportional to the capacity. For example, if the capacity was 4 tons per week, then the equipment cost would be £24M. Finally, the equipment was assumed to have a life of 10 years.

Module Cost: The module cost was £10M which was equitable to the cost of the primary facility. The module was assumed to have a life of 40 years.

Discount & Tax rate: The discount rate is 9% and the tax rate is 20%.

Depreciation: We assumed a straight-line depreciation method for the equipment that was used in the facility over 10 years.

Inventory: The inventory value was calculated to be the average of the weekly inventory levels. In other words, the general equation used to calculate the inventory value is:

$$\text{Inventory value} = \frac{\sum(\text{average weekly inventory values})}{52 \text{ weeks/year}}$$

The total average inventory cost for one module was calculated to be £8.24M (See Appendix D for details). The same analysis was done for the two-module scenario. The inventory was calculated to be £4.28M, a reduction of approximately 48%.

Inventory Holding Cost: The cost of capital for inventory was implicitly included in the free cash flow analysis. Other components of inventory holding cost were assumed to be negligible as the company owns the warehouse space and believes the holding cost will not be of concern.

Changeover cost: The changeover cost was not provided to us as it was difficult for the sponsor company to quantify exactly what the cost would be. Instead, we assume that the changeover cost is directly correlated to the initial equipment cost. Please refer to section 4 for details.

Accounts Payable and Accounts Receivable: The accounts payable and accounts receivable were disregarded for the purposes of this analysis and were not used when analyzing working capital. This was discussed and agreed upon with the sponsor company.

Revenues: Revenues were calculated with the help of the financial statements of the company. Over a period of 3 years between 2012 and 2014, the COGS of the company averaged to be 24% of the revenues, yielding a 76% gross margin. Since we knew the COGS of the product considered in this case, we assumed that the revenues would be COGS/0.24, which in this case was calculated to be £88M. Please refer to *Table 1* for details.

Year	2012	2013	2014
COGS/Revenues	23.06%	24.96%	24.10%

Table 1: Calculation the Cost of Goods Sold as a percentage of Revenues

The revenues for the two smaller modules were assumed to be equal to the revenues of the large module since the two smaller modules produce the same tonnage at the end of the year. We assumed that finished products that were produced in Stage 4 were sold at a certain and constant rate of 1 ton/week or 52 tons/year. We assumed this in order to simplify our analysis.

4. Methodology and Approach

This section of the paper discusses how analyzed the data that were given to us along with the questions that we asked ourselves as we explored the data. The first part of this section looks at the two different investments: (1) One large module investment (2) Two smaller modules investment. The second part explains the methodology we used to analyze the data. In section 5 of this paper we use this methodology to find results and use them to propose recommendations in section 6. We used net present value as a primary metric to identify whether one opportunity was more attractive than the other. We looked pros and cons of making either investment. Finally, we proposed different scenarios to study how different situations affect key performance indicators.

At first, we had multiple discussions with the sponsor company to distill the exact resources that would be needed to invest in the new module. Initially, we came to understand that our sponsor company's pharmaceutical production line is comprised of four key stages. Each stage of production cannot be initiated before the prior stage is complete. Traditionally, pharmaceutical manufacturing is composed of primary manufacturing facilities where raw materials are converted into active pharmaceutical ingredients and of secondary manufacturing facilities where the active pharmaceutical ingredients are developed into the finished products. More recently, pharmaceutical companies, including our sponsor company, have made the switch to continuous manufacturing where raw materials are converted into active pharmaceutical ingredients and finally into the finished products, all in one facility. This allows for a more efficient manufacturing process and hence a more efficient supply chain. The production process is illustrated in *Figure 3*:

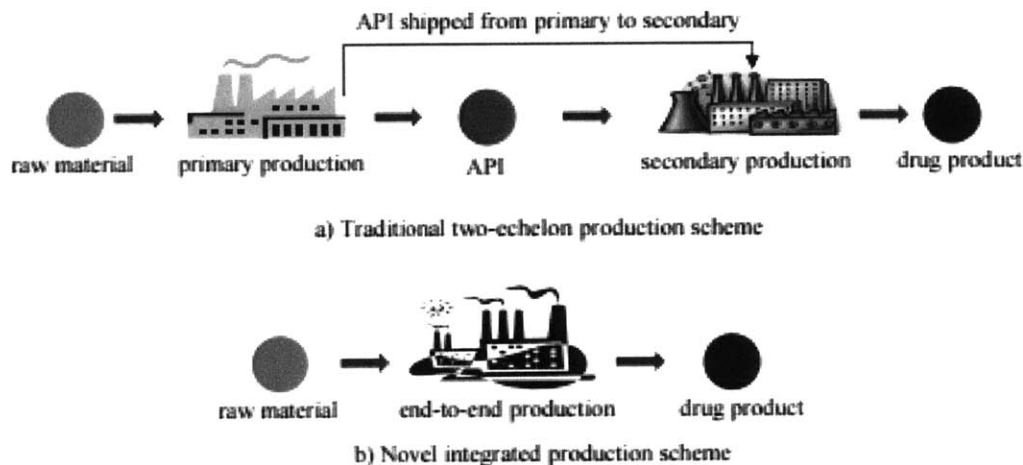


Figure 3: API Production process (Arul Sundaramoorthy, Xiang Li, James M.B. Evans, Paul I. Bartona, 2012)

With the help of the sponsor company, we were able to identify what an investment in a new module would entail. There are a few assumptions that needed to

be considered when breaking down the cost. First, we assumed that the investment was going to be located near the primary facility. This means that the tax rate and discount rate remain the same. This also means that transportation cost from one facility to the incumbent facility will be small relative to the total cost, so we assumed it to be negligible. The transportation here is referring to the movement of goods from one facility to another. For example, if Stage 1 was complete in the primary facility and management decided there was not enough capacity in one module, the material would be transported to the second module in order to produce Stage 2. This will be done to reduce lead-time of the finished product and to increase production flexibility, which will be discussed in section 5.7.

The second assumption is that the number of direct labor employees needed for a large module is 8. On the other hand, the number of direct labor employees needed for two small modules is 16, double the number of employees in the large module investment. On that same note, the number of indirect labor employees at one large module is 8 and is the same for two small modules.

The third assumption was that the fixed overhead is proportional to the number of modules, and thus the fixed overhead of two modules doubles that of one module. However, for both the large module and two smaller modules, the variable overhead cost remains the same since the total volume produced is constant.

4.1 Production Scheduling

For the base scenario, the production schedule information was provided to us by the sponsor company.

The production runs that are needed to for the one large module investment can be found in *Figure 4* below:

	c/o	c/o	c/o	c/o
Stage	1	2	3	4
Quarter	Q1	Q2	Q3	Q4

Figure 4: Production schedule for one large module (base scenario)

The raw material is delivered to the production facility and in Q1, Stage 1 begins to be produced. After the completion of the stage 1 material production, a changeover process occurs (C/O), at which point the facility is prepared for the second stage. The changeover process takes about 2 weeks on average and there are 4 changeovers per year. Stage 2 material is produced in Q2, Stage 3 in Q3 and Stage 4 in Q4. The next year, the same cycle is initiated all over again. According to the sponsor company, this creates large batch sizes and little room for flexibility. In other words, if in Q1, the customer needed finished product, assuming there was no inventory of finished product in-house,

the lead-time for the finished product would be 39 weeks starting from Raw Material. This calculation will be explained in detail in section 4.3.

The production runs that are needed to for the two-module investment can be found in *Figure 5* and *Figure 6* below:

	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o
Stage	1	2	1	2	1	2	1	2	1	2	1	2
Quarter	Q1			Q2			Q3			Q4		

Figure 5: Production schedule for first small module (base scenario)

	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o	c/o
Stage	3	4	3	4	3	4	3	4	3	4	3	4
Quarter	Q1			Q2			Q3			Q4		

Figure 6: Production schedule for second small module (base scenario)

This production run for the two-module investment would require that the first small module produce Stage 1 material, changeover, produce Stage 2 material, changeover, and then produce Stage 1 material all in Q1. Simultaneously, the second small module would need to produce Stage 3 material, changeover, produce Stage 4 material, changeover, and then produce Stage 4 material, all in Q1 as well. This essentially means that we can produce Stage 1, Stage 2, Stage 3 and Stage 4 material all in Q1 as compared to the one large module scenario where you could only produce Stage 1 and some Stage 2 material in Q1. As a result, in this production run format, the lead-time of the finished goods would be shorter and more adaptable should there be a spike in customer demand. However, the changeover frequency is comparatively higher.

In general, the objective of production is to match supply with demand and, in the real world, production scheduling is subject to many constraints such as demand forecast, set-up cost (time), equipment capacity, labor availability, etc. In our analysis, we simplify the production scheduling process by only considering the below constraints:

Demand constraint (D): Let D be the demand rate per year. In the base scenario, we assumed that the demand rate is certain and constant at 1 ton per week or 52 tons per year, and we need to produce exactly 52 tons of finished goods annually. So the production quantity per year equals D.

Changeover lead time constraint: Each changeover takes 2 weeks. It takes two weeks to have the appropriate personnel to disinfect the module and prepare it for the next stage of production.

Changeover frequency constraint (CF): Let CF be the total number of changeovers per year, then the total available time that the equipment can actually be used to produce the product (AT) equals:

$$AT = 52 - CF * 2 \quad (1)$$

Once the above constraints are set, the production schedule can be determined, as shown in Appendix A.

Production Time for each batch (PT) is determined by the total production time and the number of batches running in each module. In other words, PT is the time in weeks that it takes to produce each batch. The number of batches equals the number of changeovers there are in each module. For example, if the changeover frequency is 4 times per year, the number of batches would be 4. Therefore, in one module, the PT equals:

$$PT^* = \frac{52 - CF * 2}{CF} \quad (2)$$

**The company assumes an integer value for PT.*

The Average Production Quantity (APQ) per batch is determined by the total production quantity and the total number of batches per stage:

$$APQ = \frac{\text{Total Production Quantity (Tons/Stage)}}{\text{Number of Batches/Stage}} \quad (3)$$

The equipment capacity (EC) measures the maximum tonnage of material that the equipment produces per unit of time. Integer values for the weekly production capacity were assumed to simplify calculations and were agreed upon with the sponsor company. The EC is therefore the average production quantity per batch, rounded up and divided by the production time for each batch:

$$EC = \text{roundup}\left(\frac{APQ}{PT}\right) \quad (4)$$

As the production duration and production quantity is determined, the production schedule is thus settled.

4.2 Inventory

Once we set the demand rate, changeover lead time and changeover frequency, the production schedule is determined. Once the production schedule and demand rate is known, we can easily calculate the average inventory.

One Large Module Inventory: In the base scenario, we produce 52 tons of finished goods annually, with inventory levels varying between each production stage. In week 1, we assume that 52 tons of finished product (Stage 4) was being held in stock from the previous year's production and is slowly being shipped to the customer to meet demand. At the same time, in week 1, Stage 1 production begins and gradually produces stage 1 product until it reaches a maximum of 52 tons at the end of week 11 which is also equal to the total demand level that is needed at every production stage. Between week 12 and week 14, production halts and the changeover process begins, at which point quality personnel are tasked to disinfect the area and prepare it for the next stage of production (stage 2). As soon as stage 2 begins, stage 1 material begins to be consumed, producing stage 2 material, until it reaches a maximum of 52 tons in week 26. The same can be said about stage 3 and 4. Notice that as soon as stage 4 production begins in week 41, the stage 4 inventory level rises while the stage 3 inventory level drops (See *Figure 7* for details).

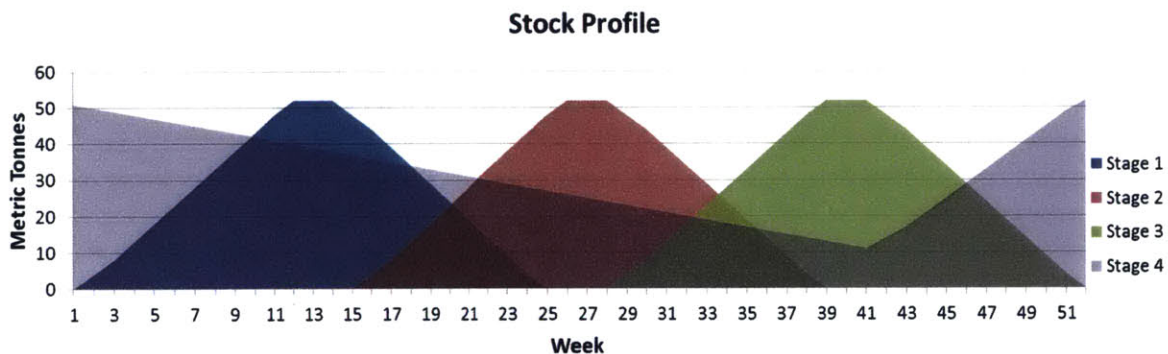


Figure 7: Stock profile of one module

According to the sponsor company, this large module scenario creates large batch sizes and little room for flexibility. In other words, if in Q1, the customer needed finished product, assuming there was no inventory of finished product in-house, the lead-time for the finished product would be 39 weeks starting from Raw Material. This calculation will be explained in detail in section 4.3.

Two smaller modules Inventory: In the two smaller modules investment, the work in process inventory is reduced. The output per module annually is the same at 52 tons. However, notice that the stage production runs are taking place more frequently. Stage 1, throughout the year, is being produced in batches of 8, 8, 8, 8, 10, 10 tons respectively, producing an output of 52 tons in total (See *Figure 8* for details)

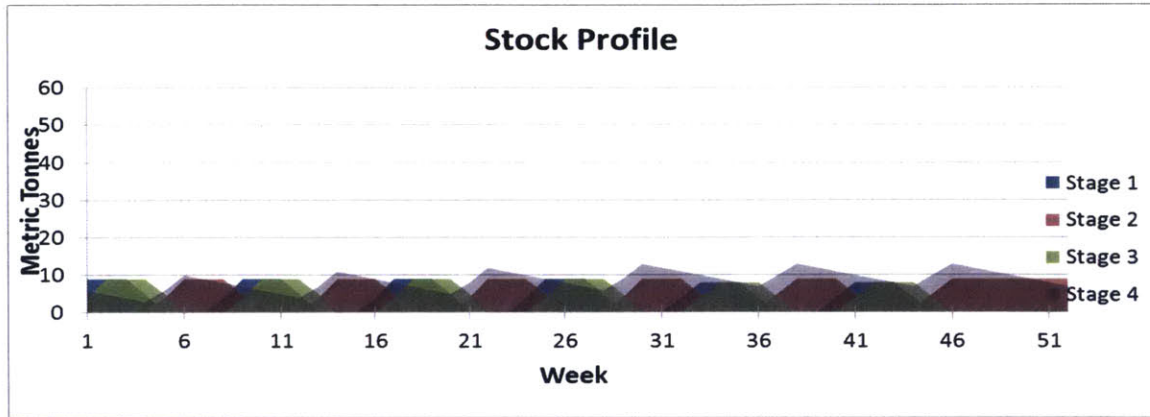


Figure 8: Stock profile for two smaller modules investment

4.3 Lead Time

Lead time is defined as the amount of time it takes to produce one unit of finished goods from raw material. The lead time (LT) equals the amount of time the previous stages take up until the current point in time plus the time spent on changeovers:

$$LT = (SG - 1) * PT + SG * 2 \quad (5)$$

In the base scenario, with one-module investment, the lead time to start producing finished goods equals:

$$LT = (4 - 1) * 11 + 4 * 2 = 39 \text{ weeks} \quad (6)$$

With a two-module investment, the lead time equals:

$$LT = (4 - 1) * 2 + 4 * 2 = 14 \text{ weeks} \quad (7)$$

4.4 Changeovers

In the base scenario, the production process in the two-module investment requires a total of 6 changeovers in one quarter and, consequently, 24 changeovers in one year as compared to 4 changeovers in the one large module investment. The 24 changeovers is equivalent to:

$$24 \text{ changeovers} \times 2 \text{ weeks/changeover} = 48 \text{ weeks required for changeover annually}$$

In the same manner, the 4 changeovers in the one large investment is equivalent to:

$$4 \text{ changeovers} \times 2 \text{ weeks/changeover} = 8 \text{ weeks required for changeover annually}$$

This is why it is important to incorporate the changeover cost into our model. With more frequent changeover, there is more wasted time during which the equipment does not produce any material. In order to achieve the same production output, more

production capacity is needed. We define equipment capacity as the maximum amount of products that can be produced during a certain period of time. The higher the capacity of equipment is, the larger the size of the equipment, and the higher the equipment capital investment. For simplicity, we assume that equipment cost is proportional to equipment capacity. In the one module investment, the maximum output is 5 tons per week and the equipment costs £30 million. In two modules, the maximum output is 4 tons per week for each equipment and thus 8 tons per week for both modules. The total equipment for both modules then costs £48 million. Production capacity is increased in exchange for the inventory reduction and increased flexibility.

In section 5 of this paper we look at different scenarios in which we adjust the production schedule to look at the impact on inventory level, production capacity and NPV. For instance, we studied whether it would make sense to have 2 changeovers in one quarter as opposed to 3 changeovers, and how that impacts the total cost of the investment as well as on other KPI's.

Changeover frequency also affects the utilization rate of production equipment. The higher the utilization rate, the higher the output that can be produced per module. However, the tradeoff is flexibility; the higher the utilization rate, the lower the excess capacity available to handle fluctuations in demand. The utilization rate is defined as:

$$\text{Production Utilization Rate} = \frac{\text{Actual Annual Production Volume}}{\text{Maximum Annual Production Capacity}} \quad (8)$$

For example, for the base scenario and for one module:

$$\text{Actual Annual Production Volume} = \frac{52 \text{ tons}}{\text{stage}} * \frac{4 \text{ stages}}{\text{year}} \quad (9)$$

$$\text{Maximum Annual Production Capacity} = 52 \text{ weeks} * \frac{5 \text{ tons}}{\text{week}} \quad (10)$$

$$\text{Production Utilization Rate} = \frac{52 * 4}{52 * 5} = 80\% \quad (11)$$

4.5 Free Cash Flows and Net Present Value

The cost breakdown spreadsheet that we had was linked to an Income Statement spreadsheet. We set it up this way in order for us to test how changes in any of the elements would impact the NPV.

Using the company's financial statements, we were able to estimate the revenues and ultimately calculate the free cash flows (FCF). Using the free cash flows, we were able to calculate the Net Present Value (NPV) of the investment decisions. Although this analysis is not enough to make an expensive investment decision, it gives us and the sponsor company a framework to work with and informs us as to whether an investment is or is not favorable. Furthermore, should the cost breakdown not be fully accurate, at the very least, it provides us with a technique to comparatively analyze the investments. The projected free cash flows are demonstrated in

Assumptions			
Tax Rate		20%	
Discount Rate		9%	

Incremental Income Statement	Periods:	0	1	2	3	...	10
Revenue			£ 88.52	£ 88.52	£ 88.52		£ 88.52
- COGS		£ -	£ 21.76	£ 21.76	£ 21.76		£ 21.76
= Gross Income		£ -	£ 66.76	£ 66.76	£ 66.76		£ 66.76
- Operating Expenses		£ 0.00	£ 2.22	£ 2.22	£ 2.22		£ 2.22
= Operating Income (EBITDA)		-£ 0.00	£ 64.54	£ 64.54	£ 64.54		£ 64.54
- Depreciation & Amortization		£ -	£ 5.05	£ 5.05	£ 5.05		£ 5.05
<i>Depreciation</i>			£ 5.05	£ 5.05	£ 5.05		£ 5.05
= Operating Income (EBIT)		-£ 0.00	£ 59.49	£ 59.49	£ 59.49		£ 59.49
- Income Tax		-£ 0.00	£ 11.90	£ 11.90	£ 11.90		£ 11.90
= Net Operating Profit After Taxes (NOPAT)		-£ 0.00	£ 47.59	£ 47.59	£ 47.59		£ 47.59
Adjustments					<i>Salvage</i>		<i>Salvage</i>
+ Depreciation (not a cash flow)			£ 5.05	£ 5.05	£ 5.05		£ 5.05
- Net Capital Expenditures		£ 58.00	£ -	£ -	£ -		£ -
<i>Equipment</i>		£ 48.00					
<i>Module</i>		£ 10.00					
- Net Working Capital Investment		£ 4.28	£ -	£ -	£ -		£ -
+ <i>Net Increase in Accounts Receivable</i>							
+ <i>Net Increase in Inventory</i>		£ 4.28	£ -	£ -	£ -		£ -
- <i>Net Increase in Accounts Payable</i>							
Free Cash Flow		-£ 62.28	£ 52.64	£ 52.64	£ 52.64		£ 52.64

NPV £ 275.58

Figure 9:

Assumptions			
Tax Rate		20%	
Discount Rate		9%	

Incremental Income Statement	Periods:	0	1	2	3	...	10
Revenue			£ 88.52	£ 88.52	£ 88.52		£ 88.52
- COGS		£ -	£ 21.28	£ 21.28	£ 21.28		£ 21.28
= Gross Income		£ -	£ 67.24	£ 67.24	£ 67.24		£ 67.24
- Operating Expenses		£ 0.00	£ 1.26	£ 1.26	£ 1.26		£ 1.26
= Operating Income (EBITDA)		-£ 0.00	£ 65.98	£ 65.98	£ 65.98		£ 65.98
- Depreciation & Amortization		£ -	£ 3.25	£ 3.25	£ 3.25		£ 3.25
= Operating Income (EBIT)		-£ 0.00	£ 62.73	£ 62.73	£ 62.73		£ 62.73
- Income Tax		-£ 0.00	£ 12.55	£ 12.55	£ 12.55		£ 12.55
= Net Operating Profit After Taxes (NOPAT)		-£ 0.00	£ 50.19	£ 50.19	£ 50.19		£ 50.19
Adjustments							
+ Depreciation (not a cash flow)			£ 3.25	£ 3.25	£ 3.25		£ 3.25
- Net Capital Expenditures		£ 40.00	£ -	£ -	£ -		£ -
<i>Equipment</i>		£ 30.00					
<i>Module</i>		£ 10.00					
- Net Working Capital Investment		£ 8.24	£ -	£ -	£ -		£ -
+ <i>Net Increase in Accounts Receivable</i>							
+ <i>Net Increase in Inventory</i>		£ 8.24	£ -	£ -	£ -		£ -
- <i>Net Increase in Accounts Payable</i>							
Free Cash Flow		-£ 48.24	£ 53.44	£ 53.44	£ 53.44	...	£ 53.44

NPV £ 294.70

Assumptions			
Tax Rate		20%	
Discount Rate		9%	

Incremental Income Statement	Periods:	0	1	2	3	...	10
Revenue			£ 88.52	£ 88.52	£ 88.52		£ 88.52
- COGS		£ -	£ 21.76	£ 21.76	£ 21.76		£ 21.76
= Gross Income		£ -	£ 66.76	£ 66.76	£ 66.76		£ 66.76
- Operating Expenses		£ 0.00	£ 2.22	£ 2.22	£ 2.22		£ 2.22
= Operating Income (EBITDA)		-£ 0.00	£ 64.54	£ 64.54	£ 64.54		£ 64.54
- Depreciation & Amortization		£ -	£ 5.05	£ 5.05	£ 5.05		£ 5.05
<i>Depreciation</i>			£ 5.05	£ 5.05	£ 5.05		£ 5.05
= Operating Income (EBIT)		-£ 0.00	£ 59.49	£ 59.49	£ 59.49		£ 59.49
- Income Tax		-£ 0.00	£ 11.90	£ 11.90	£ 11.90		£ 11.90
= Net Operating Profit After Taxes (NOPAT)		-£ 0.00	£ 47.59	£ 47.59	£ 47.59		£ 47.59
Adjustments					<i>Salvage</i>		<i>Salvage</i>
+ Depreciation (not a cash flow)			£ 5.05	£ 5.05	£ 5.05		£ 5.05
- Net Capital Expenditures		£ 58.00	£ -	£ -	£ -		£ -
<i>Equipment</i>		£ 48.00					
<i>Module</i>		£ 10.00					
- Net Working Capital Investment		£ 4.28	£ -	£ -	£ -		£ -
+ <i>Net Increase in Accounts Receivable</i>							
+ <i>Net Increase in Inventory</i>		£ 4.28	£ -	£ -	£ -		£ -
- <i>Net Increase in Accounts Payable</i>							
Free Cash Flow		-£ 62.28	£ 52.64	£ 52.64	£ 52.64		£ 52.64

NPV £ 275.58

Figure 9: Free Cash Flow Analysis for the One Module Baseline Scenario

The FCF is calculated using the following formula:

$$FCF = NOPAT + Depreciation - Net Capital Expenditures - Net Working Capital Investment \quad (12)$$

As mentioned earlier in the paper, we calculated the FCF for the investment over 10 years with the assumption that the tax rate was 20% and the discount rate was 9%. Here we assumed annuity but no perpetuity. This same FCF analysis was done for all 11 scenarios.

Next we calculated the NPV for the investments in our base scenarios as well as the additional scenarios we had proposed. This was important because not only did we want to identify whether this type of investment is profitable but also use NPV as a benchmark to compare the different scenarios. For instance, is there a big difference between the NPV, and how much flexibility do we have to make the first investment more attractive than the second and vice versa? This will be important for our scenario testing section of this paper.

4.6 Key Performance Indicators

We performed this comparative analysis by focusing on how different scenarios impacted key performance indicators. The KPI's that we thought would be most useful to the sponsor company are:

Net-present value (NPV): The NPV here would be crucial since it is important for key stakeholders at the company to decide from the very start whether to proceed with an investment. The NPV is also important when comparing the different investments. It becomes a lot easier to recommend specific types of investments based on the NPV alone but should also be supported by other metrics.

Finished Goods Lead-time (L/T): Assuming a four-stage production process and no finished goods inventory available at the start of the year, the finished goods do not become readily available until the fourth quarter (Q4) when stage 3 is complete, changeover takes place and then Stage 4 is initiated. This means that it takes approximately 39 weeks to go from raw materials to finished goods. Should there be a sudden surge in demand, it would take approximately 39 weeks to provide the customer with the product assuming there is no finished goods inventory available in-house. Depending on the urgency of the matter, this could be manageable or it could be an operational bottleneck.

Machine Operating Time Rate (MOT): The machine operating time rate varies significantly between the first and second investment. This rate is inversely correlated to the changeover frequency; as the changeover frequency increases, the MOT rate decreases. In the first investment we studied, there were four changeovers per year at a duration of two weeks per changeover. This implied that the production facility was utilized 84% of the entire year. Assuming there are no changeovers whatsoever, which is not likely, the MOT increases to 100%. It is important to understand that it is not uncommon to find low MOT rates in the pharmaceutical industry.

Equipment Capacity (EC): This measures the maximum production rate of equipment. In the one-module case under the base scenario, the maximum output of one equipment is 5 tons per week. Maximum output is the maximum tonnage of material that the equipment can produce per unit of time. This rate, multiplied by the amount of time the equipment is scheduled for production, determines the total production capacity.

Equipment Investment (EI): Equipment investment takes up the majority of upfront capital investment, and thus has the highest influence on the capital expenditure in our NPV analysis. The higher the EI is, the lower the NPV will be. EI is proportional to the EC of the equipment.

Allowable demand variation (DV): The maximum production quantity under the existing production schedule equals the maximum output times the production time. So DV equals:

$$DV = \frac{MO * PT}{D} \quad (13)$$

Work in process Inventory (WIP): In the base scenario, the average work-in-process inventory is £8.24 million for the one-module investment but is reduced to about £4.28 million for the two-module investment, which is a major advantage. The sponsor

company has had an objective for the last couple of years to reduce inventory, so this is an important metric to pay attention to, but will also come at a cost.

Profitability Index (PI): The Profitability Index here is an important metric that will provide us with a better understanding as to whether the investment is able to generate earnings, as compared to the initial investment that was made. The profitability index equation is as follows:

$$Profitability\ Index = \frac{NPV}{Initial\ Investment} \quad (14)$$

4.7 Scenario Testing

It is not enough to say that either of the investments is more attractive than the other solely based on the NPV. Therefore, it is important to experiment with the results, generate different scenarios to identify when any of the investments move from being less attractive to being more attractive and vice versa. In order to do this we have set up 12 different scenarios that vary the changeover frequency and consider both 4 stage production and 2 stage production. As mentioned earlier, we assumed demand to be constant at 52 tons a year. A summary of the scenario analysis that we have done can be found in *Figure 10* below:

Scenario	Number of Modules	Number of Stages in Production	Changeover Frequency (times/year)	Changeover Time (Weeks)
Base Scenario	One Module	4	4	8
Base Scenario	Two Modules	4	12	24
Scenario 2	Two Modules	4	8	16
Scenario 3	Two Modules	4	4	8
Scenario 4	One Module	2	12	24
Scenario 5	One Module	2	8	16
Scenario 6	One Module	2	6	12
Scenario 7	One Module	2	4	8
Scenario 8	One Module	2	2	4
Scenario 9	Two Modules	2	4	8
Scenario 10	Two Modules	2	2	4
Scenario 11	Two Modules	2	0	0
Scenario 12	Two Modules	2	0	0

Figure 10: Scenario Assumption Summary

Changeover Frequency: We have varied changeover frequency which, as we have mentioned earlier, has a direct correlation to the equipment investment.

Number of production stages: We varied the number of production stages from 4 stages to 2 stages. The sponsor company advised that it is not likely to find a production facility with more than four stages or less than 2 stages. On the contrary, it might be possible to find a production facility with two stages that produces a different product. We varied the production stages and studied the impact on WIP and NPV. From the base scenario

to scenario 3, we looked at products that take 4 stages to produce. Scenario 4 to scenario 12 require only two stages and produce a different set of products.

4.7.1 Base Scenario

For the base scenarios, the product takes 4 stages to produce and changeover frequency is 4 times per year for one module 12 times per year for two modules.

4.7.2 Scenario 2 to 3

For these scenarios, all else remains the same as base scenario, except the changeover frequency. In scenario 2, the changeover frequency for two modules is 12 times a year. For scenario 3, the frequency drops to 8 times a year. Stage 1 and 2 are produced in the first module, and stage 3 and 4 are produced in in the second module in parallel. See *Figure 11* and *Figure 12* for details.

	C/O	C/O	C/O	C/O	C/O	C/O	C/O	C/O	C/O
Stage	1	2	1	2	1	2	1	2	
Quarter	Q1		Q2		Q3		Q4		

Figure 11: Production schedule for scenario 2 - first module

	C/O	C/O	C/O	C/O	C/O	C/O	C/O	C/O
Stage	3	4	4	3	3	4	4	3
Quarter	Q1		Q2		Q3		Q4	

Figure 12: Production schedule for scenario 2 - second module

In scenario 3 we further reduce the changeover frequency to 4 times a year. See *Figure 13* and *Figure 14* for the schedule layout.

	C/O	C/O	C/O	C/O
Stage	1	2	1	2
Quarter	Q1	Q2	Q3	Q4

Figure 13: Production schedule for scenario 3 - first module

	C/O	C/O	C/O	C/O
Stage	3	4	3	4
Quarter	Q1	Q2	Q3	Q4

Figure 14: Production schedule for scenario 3 - second module

4.7.3 Scenario 4 to Scenario 12

From scenario 4 to 12, we assume another type of product that only takes 2 production stages. Scenarios 4 to 8 test how the KPI's will change for a one module investment.

In scenario 4, we set the changeover frequency to 12 times a year. For scenarios 5 to 8, we set the frequency at 8, 6, 4 and 2 times per year.

Scenarios 9 to 12 examine a two-module investment and we set the changeover frequency at 4, 2, and 0 times per year respectively. Note that scenario 11 is a special case in which each module can only produce one stage throughout the year, so the changeover frequency is reduced to zero. Scenario 12 uses double the capacity as compared to scenario 11.

5. Data Analysis and Results

In the previous sections, we collected cost data (labor, material, overhead, and depreciation), estimated revenue, net capital expenditures and net working capital. The data are all inputs into the free cash flow and net present value analysis model. The aim of the model is to identify the net present value as well as all the KPIs we mentioned in section 4 in order to compare all the scenarios.

In this section, we present the results and insights we gained from the analysis and breakdown of the different scenarios discussed in the previous section.

5.1 Scenario Analysis

We tested 12 different scenarios and identified how these KPIs varied with different scenario settings: Net-present value (NPV), finished goods Lead-time (L/T), production Utilization Rate (UR), Equipment Capacity (EC), Equipment investment (EI), allowable Demand Variation (DV), Work-In-Process inventory (WIP), Profitability Index (PI) etc. The two key variables that we changed are changeover frequency (CF) and the number of stages (SG) in the production process.

The summary of the scenario testing results are shown in *Table 2 and Table 3* below.

	4 Stages			
	One Module	Two Modules		
	Base Scenario	Base Scenario	Scenario 2	Scenario 3
Changeover Frequency (CF) (times/year)	4	12	8	4
Number of Stages/module	4	2	2	2
Changeover Time (Weeks)	8	24	16	8
Number of batches/module	4	12	8	4
Total Production Time	44	28	36	44
AVG production quantity for each batch	52.0	8.7	13.0	26.0
Production time for each batch (Week/batch)	11.0	2.3	4.5	11.0
Equipment Capacity (Tons/week)	5	4	3	3
Maximum Annual Production Capacity (Tons)	260	208	156	156
Actual Annual Production Volume (Tons/year)	208	104	104	104
Production Utilization Rate (%)	80%	50%	67%	67%
Machine Operating Time Rate (%)	85%	54%	69%	85%
Actual Production Volume (Tons)	52	52	52	52
Maximum Production Quantity (Tons)	55	56	54	66
Allowable Demand Fluctuation %	6%	8%	4%	27%
Inventory Investment (£M)	8.24	3.68	4.32	6.22
Lead Time (weeks)	39	14	20	41
Profitability Index (%)	610.9%	447.8%	571.4%	547.0%
Module Investment (£M)	10	10	10	10
Equipment Investment (£M)	30	48	36	36
Total Capital Investment (£M)	48.24	61.68	50.32	52.22
NPV	294.70	276.18	287.53	285.64

Table 2: Four-stage production process KPI Results

	2 Stages								
	One Module					Two Modules			
	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
Changeover Frequency (CF) (times/year)	12	8	6	4	2	4	2	0	0
Number of Stages/module	2	2	2	2	2	2	2	1	1
Changeover Time (Weeks)	24	16	12	8	4	8	4	0	0
Number of batches/module	12	8	6	4	2	4	2	0	0
Total Production Time	28	36	40	44	48	44	48	52	52
AVG production quantity for each batch	8.7	13.0	17.3	26.0	52.0	26.0	52.0	+∞	+∞
Production time for each batch (Week/batch)	2.3	4.5	6.7	11.0	24.0	11.0	24.0	+∞	+∞
Equipment Capacity (Tons/week)	4	3	3	3	3	2	2	1	1
Max Annual Production Capacity (Tons)	208	156	156	156	156	104	104	52	104
Actual Annual Production Volume (Tons/year)	104	104	104	104	104	52	52	52	52
Production Utilization Rate (%)	50%	67%	67%	67%	67%	50%	50%	100%	50%
Machine Operating Time Rate (%)	54%	69%	77%	85%	92%	85%	92%	100%	100%
Actual Production Volume (Tons)	52	52	52	52	52	52	52	52	52
Maximum Production Quantity (Tons)	56	54	60	66	72	88	96	52	104
Allowable Demand Fluctuation %	8%	4%	15%	27%	38%	69%	85%	0%	100%
Inventory Investment (£M)	4.53	4.60	5.22	5.85	8.01	5.84	7.87	3.40	3.40
Lead Time (weeks)	6	8	10	15	28	15	28	1	1
Profitability Index (%)	790%	952%	932%	913%	852%	748%	707%	1230%	803%
Equipment Investment (£M)	24	18	18	18	18	24	24	12	24
Total Capital Investment (£M)	38.53	32.60	33.22	33.85	36.01	39.84	41.87	25.40	37.40
NPV	304.40	310.34	309.72	309.09	306.93	298.01	295.98	312.46	300.46

Table 3: Two-stage production process KPI Results

5.2 Impact on Production Capacity

Changeover frequency and the number of stages determines the maximum output which in turn decides what the equipment capital investment should be. Assuming the number of stages remains unchanged, the equipment investment increases as the changeover frequency increases. Furthermore, assuming the changeover frequency remains unchanged, the equipment investment increases as the number of stages increases. This can be inferred from the formula of maximum output. Recall from section 4 that the maximum output of equipment (EC) is the roundup of the demand divided by the production time:

$$EC = \text{roundup}\left(\frac{APQ}{PT}\right) \quad (15)$$

EC is based on both the number of stages (SG) and the number of changeovers (CF). Since the equipment investment is proportional to EC, then we can conclude from the formula that the capital investment in equipment is directly affected by the number of stages that production requires, as well as the changeover frequency determined when designing the modules.

5.3 Impact on Inventory

The WIP is calculated as the average of the weekly average inventory values that the company incurs throughout the year. The inventory on hand (IOH) at one point in time is equal to the ending stock level from the previous period (which is the same as the initial inventory of the current period) plus inventory produced during this period less the inventory consumed.

$$\text{IOH} = \text{Initial Inventory} + \text{Inventory Produced} - \text{Inventory Consumed} \quad (16)$$

When the consumption rate is the same, the higher the changeover frequency, the more batches are carried out, and the smaller the batch size. Consequently, the work-in-process inventory is reduced as batch size becomes smaller.

Assuming changeover frequency remains unchanged at 4 times per year, the more stages the product requires, and the larger the batch size. So the WIP inventory here increases as the number of stages required to produce the product increases.

In scenario 11, the changeover frequency drops to zero, and the batch size in theory becomes infinitely large. We can picture this scenario as that with 2 sets of equipment, each responsible for producing one stage with no changeover at all. Additionally, since inventory is determined by both production and demand, the WIP of stage 1 and stage 2 equals zero because the demand rate at any particular time equals the production rate. The only inventory in stock is the raw material inventory. This scenario is similar to the just-in-time manufacturing philosophy where waste in inventory is minimized. In reality, it is not likely to find a production process that has no changeover at all; an allotted period of time greater than 0 is needed to halt production and disinfect the module.

In summary, the inventory generally decreases as changeover frequency increases or as the number of stages required decreases.

5.4 Inventory vs. Production Capacity

From the analysis above, we know that for one particular product with a constant number of stages, the higher the changeover frequency, the lower the inventory, and the higher the production capacity (or equipment investment). This is a trade-off that companies have to live with. The question then is: what is the tradeoff between production capacity and inventory that can maximize NPV?

There were a lot of considerations taken when finding these tradeoffs. Under a few assumptions, we were able to test our model and find the tipping points. We define the tipping points as those situations when an investment goes from being less attractive

to more attractive or vice versa. These tipping points can be used during company meetings to help management decide how much flexibility it may have with an investment.

In our analysis, for a product that requires a four-stage production process, we observe that as changeover frequency decreases from 12 times to 4 times per year, the NPV first increases and then drops. When the CF is 8, the EC reaches a tipping point, and the investment suddenly drops from £24 million to £18 million. One-module investment is always more attractive in terms of NPV than the two-module investment. This is because even though the higher changeover frequency can reduce the inventory value by £3.96 million from the one module investment to the two module investment, the capital investment increase in equipment is much higher at £18 million, which more than offsets the benefits of inventory reduction. However, the gap is narrowed as we change the changeover frequency in the two-module investment.

For a product that requires a two-stage production process, in the one module investment, we can see that the NPV increases first as changeover frequency decreases, reaching a maximum of £310 million at changeover frequency of 8 times per year, and then drops. This is because when changeover frequency is at 8 times per year, the maximum output reaches a tipping point, and then drops from 4 tons per week to 3 tons per week. This reduction in EC greatly reduces the equipment investment from £24 million to £18 million. At the same time, the inventory increase is minimal, from £4.53 million to £4.61 million.

In the two-module investment, the NPV reaches its highest when we produce stage 1 entirely in one facility and stage 2 in another. This is the scenario with the lowest changeover frequency and equipment investment. In the same way, since the consumption rate is equal to the production rate, inventory is also minimized. The resulting NPV reaches £312.46, which is the highest NPV that can be attained with the inputs and constraints that we have outlined.

5.5 Impact on Lead Time

For a product that requires a four-stage production process, when the changeover frequency increases, the lead time decreases. In the base scenario, the two-module investment offers a much shorter lead time of 14 weeks, while the one-module investment requires a lead-time as high as 39 weeks. See *Table 2* for the 4-stage production process detailed results.

Similarly, for a product that requires a two-stage production process, when the changeover frequency increases, the lead time is also shortened. Notice that Scenario 11 is an exception. The changeover frequency is zero, but since each module only produces

one stage's worth of material throughout the year, the lead time is reduced to only 1 week. See *Table 3* for lead-time results.

5.6 Safety Stock

The sponsor company did not include finished goods safety stock in the scope of this study. However, the production lead time reductions among the scenarios considered could have a significant impact on safety stock levels. Further analysis that incorporates safety stock could identify further working capital reductions. Safety stock should be incorporated into future research for the sponsor company.

5.7 Other Considerations

Let us discuss other things to consider, in terms of risk and flexibility, which need to be accounted for when deciding between all the investment scenarios that we have described. These considerations will be an essential supplement to our scenario testing, outlining the risk implications and operational bearings:

Flexibility:

1. More flexibility and adaptability to demand variation can lead to more responsive supply chains.
2. Centralized operations can be an advantage for efficiency of knowledge and communication exchange
3. A more flexible supply chain/operation allows for an opportunity to reduce safety stock inventory levels.

Risk:

1. Owning only one production facility can lead to a single point of failure within the pharmaceutical supply chain.
2. A less flexible supply chain forces a company to invest in safety stock levels to maintain good customer service levels.
3. Less production flexibility in the event that there is demand variation can be a risk for the company, especially in the pharmaceutical industry.
4. Safety stock inventory needs to be high when the operations are not as flexible.
5. Owning multiple facilities might lead to an increase in workload for the quality and inspection personnel that ensure coordinated changeovers.

These considerations reiterate the point that quantitative analysis is not sufficient to make strategic decisions. Ultimately, there will be different circumstance under which the company would be able to utilize our analysis to better understand how sensitive KPI's are to a certain parameter changes.

6. Discussion

6.1 Relationships

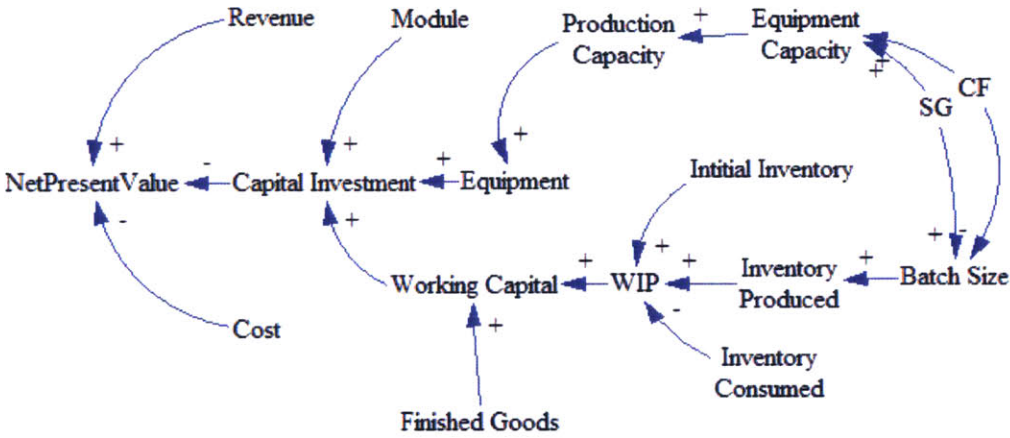


Figure 15: Causal loop diagram of the production system

In the above causal loop diagram, we have listed the key parameters that are affected by our system. The main inputs are going to be SG (number of stages) and CF (changeover frequency). These two inputs ultimately affect the NPV of the investment. For simplicity, we have drawn out the diagram to clarify the relationships and discuss the tradeoffs in this section. This relationship is explained via the polarities of the arrows displayed in the diagram.

For example, as SG increases, the EC (Equipment Capacity) increases which, in turn, requires an increase in capital investment. The higher capital investment ultimately lowers the final NPV metric. In the same manner, as SG increases, the batch size increases which increases the amount of work-in-process inventory produced. In this case, as inventory produced rises, the working capital increases, increasing the required capital investment ultimately driving down the NPV. The same dynamic applies for CF.

As CF increases, the EC increases, increasing the required production capacity. As capacity increases, the required equipment investment increases which means that the overall capital investment increases. As the capital investment increases, the NPV decreases. In the same manner, as CF increases, the batch size decreases which consequently lowers the WIP inventory. As the working capital decreases, the capital investment required decreases, which ultimately raises the NPV.

The relationship that is displayed in the causal loop diagram can be summarized as such:

$$SG \nearrow \Rightarrow \begin{cases} \text{Production Capacity} \nearrow \\ \text{WIP} \nearrow \end{cases}$$

$$CF \nearrow \Rightarrow \begin{cases} \text{Production Capacity} \nearrow \\ \text{WIP} \searrow \end{cases}$$

6.2 Tradeoffs

The main observation in section 5 was that there is trade-off between production capacity and inventory, and that the production capacity has a much higher impact on the NPV than the inventory. The best NPV is achieved when the production capacity reaches its tipping point.

The results among each of the Four-stage and Two-stage investment scenarios depends on the changeover frequency that is selected. Often, the changeover frequency that can reduce the maximum output generates a high NPV. Take the two-stage production process for example: the relationship between changeover frequency, capital investment and NPV is illustrated in *Figure 16*. The capital investment consists of three parts: equipment investment, module investment and the working capital investment. The module investment remains the same for all of the investment scenarios. Furthermore, the working capital is negatively correlated with changeover frequency and the module investment is positively correlated with CF.

The maximum output is calculated with a roundup function and, as such, is only triggered to increase when the changeover frequency reaches its tipping point: in this case 8 times per year. We consider the changeover frequency of 8 to be the point at which NPV is maximized. Please refer to *Table 3* for details. The same can be said about the four-stage production process. The best NPV can be found in scenario 2, whereby the changeover frequency is 8. Notice that the inventory in scenario 2 is not the lowest. This is the type of tradeoff that will depend on the company's main objective. Please refer to *Table 2* for details on this type of tradeoff.

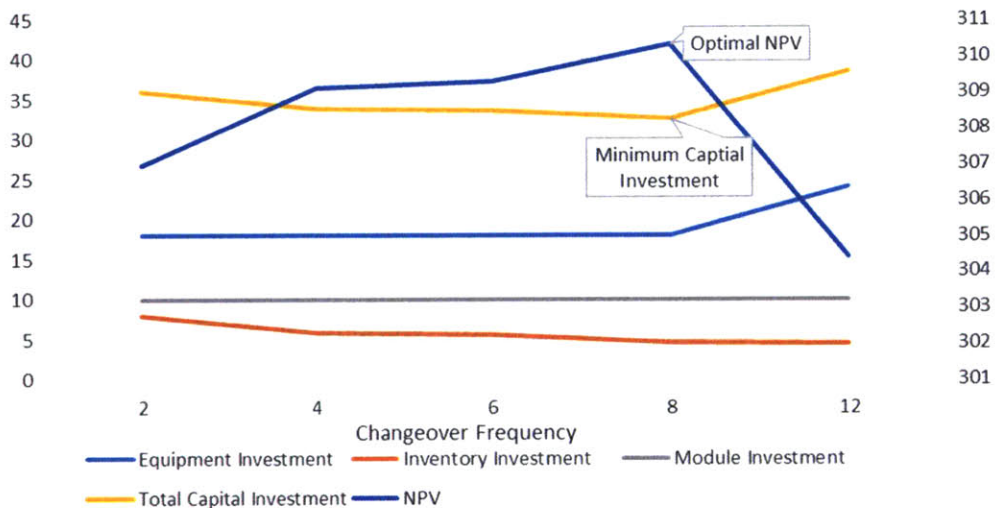


Figure 16: Graph illustrating relationships between different parameters

7. Opportunities for Future Research

Our research demonstrates the types of important considerations when making tradeoffs between the production capacity and working capital. These tradeoffs will depend on what the company would like to achieve and if it has the appropriate backing and funding in order to do so. The research tries to provide different scenarios to mimic real life situations for companies where the decisions to invest in new facilities become challenging. As our sponsor company noted, it is not sufficient to only focus on NPV when making investment decisions. Additional factors and multiple scenarios should guide stakeholders to make decisions. Our research describes key considerations in designing the pharmaceutical supply chain.

Moreover, although pharmaceutical companies are reluctant to tamper with finished goods safety stock levels, our analysis indicates that those inventory levels can be reduced. Shorter production lead times should enable lower finished goods inventory without jeopardizing the customer service levels that the companies heavily cares about. Future research should consider this broader scope. In addition, we also propose including demand variation, multiple SKUs, and/or considering new product introductions.

Appendices

Appendix A. Production Scheduling

Base Scenario: One-Module

RM	Stage 1				Stage 2				Stage 3				Stage 4			
	OS*	Make	Supply	CS**	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS
1	0	52	0	52	0	0	0	0	0	0	0	0	52	1	51	
2	52	0	52	0	0	0	0	0	0	0	0	0	51	1	50	
3	52	4	48	0	4	0	4	0	0	0	0	0	50	1	49	
4	48	4	44	4	4	0	8	0	0	0	0	0	49	1	48	
5	44	5	39	8	5	0	13	0	0	0	0	0	48	1	47	
6	39	5	34	13	5	0	18	0	0	0	0	0	47	1	46	
7	34	5	29	18	5	0	23	0	0	0	0	0	46	1	45	
8	29	5	24	23	5	0	28	0	0	0	0	0	45	1	44	
9	24	5	19	28	5	0	33	0	0	0	0	0	44	1	43	
10	19	5	14	33	5	0	38	0	0	0	0	0	43	1	42	
11	14	5	9	38	5	0	43	0	0	0	0	0	42	1	41	
12	9	5	4	43	5	0	48	0	0	0	0	0	41	1	40	
13	4	4	0	48	4	0	52	0	0	0	0	0	40	1	39	
14	0	0	0	52	0	52	0	0	0	0	0	0	39	1	38	
15	0	0	0	52	0	52	0	0	0	0	0	0	38	1	37	
16	0	0	0	52	4	48	0	4	0	4	0	0	37	1	36	
17	0	0	0	48	4	44	4	4	0	8	0	0	36	1	35	
18	0	0	0	44	5	39	8	5	0	13	0	0	35	1	34	
19	0	0	0	39	5	34	13	5	0	18	0	0	34	1	33	
20	0	0	0	34	5	29	18	5	0	23	0	0	33	1	32	
21	0	0	0	29	5	24	23	5	0	28	0	0	32	1	31	
22	0	0	0	24	5	19	28	5	0	33	0	0	31	1	30	
23	0	0	0	19	5	14	33	5	0	38	0	0	30	1	29	
24	0	0	0	14	5	9	38	5	0	43	0	0	29	1	28	
25	0	0	0	9	5	4	43	5	0	48	0	0	28	1	27	
26	0	0	0	4	4	0	48	4	0	52	0	0	27	1	26	
27	0	0	0	0	0	0	52	0	52	0	0	0	26	1	25	
28	0	0	0	0	0	0	52	0	52	0	0	0	25	1	24	
29	0	0	0	0	0	0	52	4	48	0	4	4	24	1	23	
30	0	0	0	0	0	0	48	4	44	4	4	0	23	1	22	
31	0	0	0	0	0	0	44	5	39	8	5	0	22	1	21	
32	0	0	0	0	0	0	39	5	34	13	5	0	21	1	20	
33	0	0	0	0	0	0	34	5	29	18	5	0	20	1	19	
34	0	0	0	0	0	0	29	5	24	23	5	0	19	1	18	
35	0	0	0	0	0	0	24	5	19	28	5	0	18	1	17	
36	0	0	0	0	0	0	19	5	14	33	5	0	17	1	16	
37	0	0	0	0	0	0	14	5	9	38	5	0	16	1	15	
38	0	0	0	0	0	0	9	5	4	43	5	0	15	1	14	
39	0	0	0	0	0	0	4	4	0	48	4	0	14	1	13	
40	0	0	0	0	0	0	0	0	0	52	0	52	13	1	12	
41	0	0	0	0	0	0	0	0	0	52	0	52	12	1	11	
42	0	0	0	0	0	0	0	0	0	52	4	48	11	4	1	14
43	0	0	0	0	0	0	0	0	0	48	4	44	14	4	1	17
44	0	0	0	0	0	0	0	0	0	44	5	39	17	5	1	21
45	0	0	0	0	0	0	0	0	0	39	5	34	21	5	1	25
46	0	0	0	0	0	0	0	0	0	34	5	29	25	5	1	29
47	0	0	0	0	0	0	0	0	0	29	5	24	29	5	1	33
48	0	0	0	0	0	0	0	0	0	24	5	19	33	5	1	37
49	0	0	0	0	0	0	0	0	0	19	5	14	37	5	1	41
50	0	0	0	0	0	0	0	0	0	14	5	9	41	5	1	45
51	0	0	0	0	0	0	0	0	0	9	5	4	45	5	1	49
52	0	0	0	0	0	0	0	0	0	4	4	0	49	4	1	52

*OS: Opening stock

**CS: Closing Stock

Base Scenario: Two-Module

	RM				Stage 1				Stage 2				Stage 3				Stage 4			
	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS
1	0	52	4	48	0	4	0	4	10	4	4	6	0	4	0	4	5	1	1	4
2	48		4	44	4	4	0	8	6	4	2	4	4	0	8	4	1	1	3	
3	44		0	44	8	0	0	8	2	0	2	8	0	0	8	3	1	1	2	
4	44		0	44	8	0	0	8	2	0	2	8	0	0	8	2	1	1	1	
5	44		0	44	8	4	4	4	2	4	0	6	8	4	4	1	4	1	4	
6	44		0	44	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
7	44		0	44	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
8	44		0	44	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	
9	44		4	40	0	4	0	4	10	4	6	0	4	0	4	5	1	1	4	
10	40		4	36	4	4	0	8	6	4	2	4	4	0	8	4	1	1	3	
11	36		0	36	8	0	0	8	2	0	2	8	0	0	8	3	1	1	2	
12	36		0	36	8	0	0	8	2	0	2	8	0	0	8	2	1	1	1	
13	36		0	36	8	4	4	4	2	4	0	6	8	4	4	1	4	1	4	
14	36		0	36	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
15	36		0	36	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
16	36		0	36	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	
17	36		4	32	0	4	0	4	10	4	6	0	4	0	4	5	1	1	4	
18	32		4	28	4	4	0	8	6	4	2	4	4	0	8	4	1	1	3	
19	28		0	28	8	0	0	8	2	0	2	8	0	0	8	3	1	1	2	
20	28		0	28	8	0	0	8	2	0	2	8	0	0	8	2	1	1	1	
21	28		0	28	8	4	4	4	2	4	0	6	8	4	4	1	4	1	4	
22	28		0	28	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
23	28		0	28	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
24	28		0	28	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	
25	28		4	24	0	4	0	4	10	4	6	0	4	0	4	5	1	1	4	
26	24		4	20	4	4	0	8	6	4	2	4	4	0	8	4	1	1	3	
27	20		0	20	8	0	0	8	2	0	2	8	0	0	8	3	1	1	2	
28	20		0	20	8	0	0	8	2	0	2	8	0	0	8	2	1	1	1	
29	20		0	20	8	4	4	4	2	4	0	6	8	4	4	1	4	1	4	
30	20		0	20	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
31	20		0	20	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
32	20		0	20	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	
33	20		3	17	0	3	0	3	10	3	7	0	3	0	3	5	1	1	4	
34	17		3	14	3	3	0	6	7	3	4	3	3	0	6	4	1	1	3	
35	14		4	10	6	4	0	10	4	4	0	6	4	0	10	3	1	1	2	
36	10		0	10	10	0	0	10	0	0	0	10	0	0	10	2	1	1	1	
37	10		0	10	10	0	0	10	0	0	0	10	0	0	10	1	1	1	0	
38	10		0	10	10	3	7	0	0	3	10	3	7	0	3	0	3	1	2	
39	10		0	10	7	3	4	3	3	3	0	6	7	3	4	2	3	1	4	
40	10		0	10	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
41	10		0	10	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
42	10		0	10	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	
43	10		3	7	0	3	0	3	10	3	7	0	3	0	3	5	1	1	4	
44	7		3	4	3	3	0	6	7	3	4	3	3	0	6	4	1	1	3	
45	4		4	0	6	4	0	10	4	4	0	6	4	0	10	3	1	1	2	
46	0		0	0	10	0	0	10	0	0	0	10	0	0	10	2	1	1	1	
47	0		0	0	10	0	0	10	0	0	0	10	0	0	10	1	1	1	0	
48	0		0	0	10	3	7	0	0	3	10	3	7	0	3	0	3	1	2	
49	0		0	0	7	3	4	3	3	3	0	6	7	3	4	2	3	1	4	
50	0		0	0	4	4	0	0	6	4	0	10	4	4	0	4	4	1	7	
51	0		0	0	0	0	0	0	10	0	10	0	0	0	0	7	1	1	6	
52	0		0	0	0	0	0	0	10	0	10	0	0	0	0	6	1	1	5	

Appendix B. Production Scheduling

Scenario 2

RM	Stage 1				Stage 2				Stage 3				Stage 4							
	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS				
1	0	52	3	49	0	3	0	3	14		3	11	0	3	0	3	7	1	6	
2	49		3	46	3	3	0	6	11		3	8	3	3	0	6	6	1	5	
3	46		3	43	6	3	0	9	8		3	5	6	3	0	9	5	1	4	
4	43		3	40	9	3	0	12	5		3	2	9	3	0	12	4	1	3	
5	40		0	40	12		0	12	2		0	2	12		0	12	3	1	2	
6	40		0	40	12		0	12	2		0	2	12		0	12	2	1	1	
7	40		0	40	12		3	9	2	3	0	5	12		3	9	1	3	3	
8	40		0	40	9		3	6	5	3	0	8	9		3	6	3	3	1	5
9	40		0	40	6		3	3	8	3	0	11	6		3	3	5	3	1	7
10	40		0	40	3		3	0	11	3	0	14	3		3	0	7	3	1	9
11	40		0	40	0		0	0	14		0	14	0		0	0	9	1	8	
12	40		0	40	0		0	0	14		0	14	0		0	0	8	1	7	
13	40		3	37	0	3	0	3	14		3	11	0	3	0	3	7	1	6	
14	37		3	34	3	3	0	6	11		3	8	3	3	0	6	6	1	5	
15	34		3	31	6	3	0	9	8		3	5	6	3	0	9	5	1	4	
16	31		3	28	9	3	0	12	5		3	2	9	3	0	12	4	1	3	
17	28		2	26	12	2	0	14	2		2	0	12	2	0	14	3	1	2	
18	26		0	26	14		0	14	0		0	0	14		0	14	2	1	1	
19	26		0	26	14		0	14	0		0	0	14		0	14	1	1	0	
20	26		0	26	14		3	11	0	3	0	3	14		3	11	0	3	1	2
21	26		0	26	11		3	8	3	3	0	6	11		3	8	2	3	1	4
22	26		0	26	8		3	5	6	3	0	9	8		3	5	4	3	1	6
23	26		0	26	5		3	2	9	3	0	12	5		3	2	6	3	1	8
24	26		0	26	2		2	0	12	2	0	14	2		2	0	8	2	1	9
25	26		0	26	0		0	0	14		0	14	0		0	0	9	1	8	
26	26		0	26	0		0	0	14		0	14	0		0	0	8	1	7	
27	26		3	23	0	3	0	3	14		3	11	0	3	0	3	7	1	6	
28	23		3	20	3	3	0	6	11		3	8	3	3	0	6	6	1	5	
29	20		3	17	6	3	0	9	8		3	5	6	3	0	9	5	1	4	
30	17		3	14	9	3	0	12	5		3	2	9	3	0	12	4	1	3	
31	14		0	14	12		0	12	2		0	2	12		0	12	3	1	2	
32	14		0	14	12		0	12	2		0	2	12		0	12	2	1	1	
33	14		0	14	12		3	9	2	3	0	5	12		3	9	1	3	1	3
34	14		0	14	9		3	6	5	3	0	8	9		3	6	3	3	1	5
35	14		0	14	6		3	3	8	3	0	11	6		3	3	5	3	1	7
36	14		0	14	3		3	0	11	3	0	14	3		3	0	7	3	1	9
37	14		0	14	0		0	0	14		0	14	0		0	0	9	1	8	
38	14		0	14	0		0	0	14		0	14	0		0	0	8	1	7	
39	14		3	11	0	3	0	3	14		3	11	0	3	0	3	7	1	6	
40	11		3	8	3	3	0	6	11		3	8	3	3	0	6	6	1	5	
41	8		3	5	6	3	0	9	8		3	5	6	3	0	9	5	1	4	
42	5		3	2	9	3	0	12	5		3	2	9	3	0	12	4	1	3	
43	2		2	0	12	2	0	14	2		2	0	12	2	0	14	3	1	2	
44	0		0	0	14		0	14	0		0	0	14		0	14	2	1	1	
45	0		0	0	14		0	14	0		0	0	14		0	14	1	1	0	
46	0		0	0	14		3	11	0	3	0	3	14		3	11	0	3	1	2
47	0		0	0	11		3	8	3	3	0	6	11		3	8	2	3	1	4
48	0		0	0	8		3	5	6	3	0	9	8		3	5	4	3	1	6
49	0		0	0	5		3	2	9	3	0	12	5		3	2	6	3	1	8
50	0		0	0	2		2	0	12	2	0	14	2		2	0	8	2	1	9
51	0		0	0	0		0	0	14		0	14	0		0	0	9	1	8	
52	0		0	0	0		0	0	14		0	14	0		0	0	8	1	7	

Scenario 3

	RM				Stage 1				Stage 2				Stage 3				Stage 4			
	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS	OS	Make	Supply	CS
1	0	52	2	50	0	2	0	2	26	2	24	0	2	0	2	13	1	12		
2	50		2	48	2	2	0	4	24		2	22	2	2	0	4	12		1	11
3	48		2	46	4	2	0	6	22		2	20	4	2	0	6	11		1	10
4	46		2	44	6	2	0	8	20		2	18	6	2	0	8	10		1	9
5	44		2	42	8	2	0	10	18		2	16	8	2	0	10	9		1	8
6	42		2	40	10	2	0	12	16		2	14	10	2	0	12	8		1	7
7	40		2	38	12	2	0	14	14		2	12	12	2	0	14	7		1	6
8	38		3	35	14	3	0	17	12		3	9	14	3	0	17	6		1	5
9	35		3	32	17	3	0	20	9		3	6	17	3	0	20	5		1	4
10	32		3	29	20	3	0	23	6		3	3	20	3	0	23	4		1	3
11	29		3	26	23	3	0	26	3		3	0	23	3	0	26	3		1	2
12	26		0	26	26		0	26	0		0	0	26		0	26	2		1	1
13	26		0	26	26		0	26	0		0	0	26		0	26	1		1	0
14	26		0	26	26	2	24	0	2	26	2	24	0	2	24	0	2	1	1	1
15	26		0	26	24	2	22	2	2	24	2	22	2	2	22	1	2	1	2	2
16	26		0	26	22	2	20	4	2	22	2	20	4	2	20	2	2	1	3	3
17	26		0	26	20	2	18	6	2	20	2	18	6	2	18	3	2	1	4	4
18	26		0	26	18	2	16	8	2	20	2	16	8	2	16	4	2	1	5	5
19	26		0	26	16	2	14	10	2	20	2	14	10	2	14	5	2	1	6	6
20	26		0	26	14	2	12	12	2	20	2	12	12	2	12	6	2	1	7	7
21	26		0	26	12	3	9	14	3	20	3	9	14	3	9	7	3	1	9	9
22	26		0	26	9	3	6	17	3	20	3	6	17	3	6	9	3	1	11	11
23	26		0	26	6	3	3	20	3	20	3	3	20	3	3	11	3	1	13	13
24	26		0	26	3	3	0	23	3	20	3	0	26	3	0	13	3	1	15	15
25	26		0	26	0	0	0	26	0	26	0	0	26	0	0	15		1	14	14
26	26		0	26	0	0	0	26	0	26	0	0	26	0	0	14		1	13	13
27	26		2	24	0	2	0	2	26	2	24	0	2	24	0	2	13	1	12	12
28	24		2	22	2	2	0	4	24	2	22	2	2	22	2	2	12	1	11	11
29	22		2	20	4	2	0	6	22	2	20	4	2	20	4	2	11	1	10	10
30	20		2	18	6	2	0	8	20	2	18	6	2	18	6	2	10	1	9	9
31	18		2	16	8	2	0	10	18	2	16	8	2	16	8	2	9	1	8	8
32	16		2	14	10	2	0	12	16	2	14	10	2	14	10	2	8	1	7	7
33	14		2	12	12	2	0	14	14	2	12	12	2	12	7		1	6	6	6
34	12		3	9	14	3	0	17	12	3	9	14	3	9	6		1	5	5	5
35	9		3	6	17	3	0	20	9	3	6	17	3	6	5		1	4	4	4
36	6		3	3	20	3	0	23	6	3	3	20	3	3	4		1	3	3	3
37	3		3	0	23	3	0	26	3	3	0	23	3	0	3		1	2	2	2
38	0		0	0	26	0	0	26	0	0	0	26	0	0	2		1	1	1	1
39	0		0	0	26	0	0	26	0	0	0	26	0	0	1		1	0	0	0
40	0		0	0	26	2	24	0	2	26	2	24	0	2	0	2	1	1	1	1
41	0		0	0	24	2	22	2	2	24	2	22	2	2	2	2	1	2	2	2
42	0		0	0	22	2	20	4	2	22	2	20	4	2	2	2	2	1	3	3
43	0		0	0	20	2	18	6	2	20	2	18	6	2	18	3	2	1	4	4
44	0		0	0	18	2	16	8	2	20	2	16	8	2	16	4	2	1	5	5
45	0		0	0	16	2	14	10	2	20	2	14	10	2	14	5	2	1	6	6
46	0		0	0	14	2	12	12	2	20	2	12	12	2	12	6	2	1	7	7
47	0		0	0	12	3	9	14	3	20	3	9	14	3	9	7	3	1	9	9
48	0		0	0	9	3	6	17	3	20	3	6	17	3	6	9	3	1	11	11
49	0		0	0	6	3	3	20	3	20	3	3	20	3	3	11	3	1	13	13
50	0		0	0	3	3	0	23	3	20	3	0	26	3	0	13	3	1	15	15
51	0		0	0	0	0	0	26	0	26	0	0	26	0	0	15		1	14	14
52	0		0	0	0	0	0	26	0	26	0	0	26	0	0	14		1	13	13

Appendix C. Cost Breakdown

	Composition of the cost	1 module			2 module		
		Quantity (ton)	Value	Total	Quantity (ton)	Value	Total
Production cost	Direct labor	8 Persons	£0.06 M/Person	£ 0.48	16 Persons	£0.06	£ 0.96
	Material cost	52,000 KG	£400/KG	£20.80	52,000 KG	£400/KG	£20.80
	Variable overhead			£ 0.30			£ 0.30
	Fixed overhead			£ 0.96			£ 1.92
	COGS			£21.28			£21.76
	Operating expenses			£ 1.26			£ 2.22
Inventory		Quantity (ton)	Value	Total	Quantity (ton)	Value	Total
	RM	50,000 KG	400	£ 20	10,000 KG	400	£ 4.00
	Stage 1	50,000 KG	450	£ 23	10,000 KG	500	£ 5.00
	Stage 2	50,000 KG	500	£ 25	10,000 KG	600	£ 6.00
	Stage 3	50,000 KG	550	£ 28	10,000 KG	700	£ 7.00
	Stage 4	50,000 KG	600	£ 30	10,000 KG	800	£ 8.00
Depreciation	Equipment	£30 M	10 Years	£ 3.00	£48 M	10 Years	£ 4.80
	Module	£10 M	40 Years	£ 0.25	£10 M	40 Years	£ 0.25
	Total			£ 3.25			£ 5.05

Appendix D. Inventory Value Calculation

Cost (\$/kg)	Raw mats					Average Inv/Wk
	Stage 1	Stage 2	Stage 3	Stage 4	600	
1	20800	0	0	0	30600	10280
2	20800	0	0	0	30000	10160
3	20800	1800	0	0	29400	10400
4	20800	3600	0	0	28800	10640
5	20800	5850	0	0	28200	10970
6	20800	8100	0	0	27600	11300
7	20800	10350	0	0	27000	11630
8	20800	12600	0	0	26400	11960
9	20800	14850	0	0	25800	12290
10	20800	17100	0	0	25200	12620
11	20800	19350	0	0	24600	12950
12	20800	21600	0	0	24000	13280
13	20800	23400	0	0	23400	13520
14	20800	23400	0	0	22800	13400
15	20800	23400	0	0	22200	13280
16	19200	21600	2000	0	21600	12880
17	17600	19800	4000	0	21000	12480
18	15600	17550	6500	0	20400	12010
19	13600	15300	9000	0	19800	11540
20	11600	13050	11500	0	19200	11070
21	9600	10800	14000	0	18600	10600
22	7600	8550	16500	0	18000	10130
23	5600	6300	19000	0	17400	9660
24	3600	4050	21500	0	16800	9190
25	1600	1800	24000	0	16200	8720
26	0	0	26000	0	15600	8320
27	0	0	26000	0	15000	8200
28	0	0	26000	0	14400	8080
29	0	0	24000	2200	13800	8000
30	0	0	22000	4400	13200	7920
31	0	0	19500	7150	12600	7850
32	0	0	17000	9900	12000	7780
33	0	0	14500	12650	11400	7710
34	0	0	12000	15400	10800	7640
35	0	0	9500	18150	10200	7570
36	0	0	7000	20900	9600	7500
37	0	0	4500	23650	9000	7430
38	0	0	2000	26400	8400	7360
39	0	0	0	28600	7800	7280
40	0	0	0	28600	7200	7160
41	0	0	0	28600	6600	7040
42	0	0	0	26400	8400	6960
43	0	0	0	24200	10200	6880
44	0	0	0	21450	12600	6810
45	0	0	0	18700	15000	6740
46	0	0	0	15950	17400	6670
47	0	0	0	13200	19800	6600
48	0	0	0	10450	22200	6530
49	0	0	0	7700	24600	6460
50	0	0	0	4950	27000	6390
51	0	0	0	2200	29400	6320
52	0	0	0	0	31200	6240
						9,276,923.08

References

- Assid, M., Gharbi, A., & Dhouib, K. (n.d.). *Joint production and subcontracting planning of unreliable multi-facility multi-product production systems*. OMEGA, 54-69, 2014.
- Bienstock, D., Shapiro, J.F. *Optimizing resource acquisition decisions by stochastic programming*. *Manag. Sci.* 34 (2), 215–229, 1988.
- Chen, Y.Y., Chen, T.L., Liou, C.D. *Medium-term multi-plant capacity planning problems considering auxiliary tools for the semiconductor foundry*. *Int. J. Adv. Manuf. Technol.* 64 (9–12), 1213–1230, 2013.
- E. R. Fox, A. Birt, K. B. James, H. Kokko, S. Salverson, and D. L. Soflin. *ASHP guidelines on managing drug product shortages in hospitals and health systems*. *American Journal of Health-System Pharmacy*, 66:1399–1406, 2009.
- Flores, J., Montagna, J., & Vecchiotti, A. *An optimization approach for long term investments planning in energy*. *Applied Energy*, 162-178, 2014.
- Götze, U., Northcott, D., & Schuster, P. (n.d.). *Investment Appraisal*. Springer Texts in Business and Economics, 2007.
- Grunow, M., Günther, H.-O., & Yang, G. (2003). Plant co-ordination in pharmaceuticals supply networks. *OR Spectrum*, 25(1), 109–141. <http://doi.org/10.1007/s00291-002-0117-z>
- Kallrath, J. (2000). Mixed Integer Optimization in the Chemical Process Industry: Experience, Potential and Future Perspectives. *Chemical Engineering Research and Design*, 78(6), 809–822. <http://doi.org/10.1205/026387600528012>
- Levis, A. A., & Papageorgiou, L. G. (2004). A hierarchical solution approach for multi-site capacity planning under uncertainty in the pharmaceutical industry. *Computers & Chemical Engineering*, 28(5), 707–725. <http://doi.org/10.1016/j.compchemeng.2004.02.012>
- Martínez-Costa, C., Mas-Machuca, M., Benedito, E., & Corominas, A. (n.d.). *A review of mathematical programming models for strategic capacity planning in manufacturing*. *International Journal of Production Economics*, 66-85, 2014.

- Oh, H.-C., & Karimi, I. A. (2004). Regulatory Factors and Capacity-Expansion Planning in Global Chemical Supply Chains. *Industrial & Engineering Chemistry Research*, 43(13), 3364–3380. <http://doi.org/10.1021/ie034339g>
- Papageorgiou, L. G., Rotstein, G. E., & Shah, N. (2001). Strategic Supply Chain Optimization for the Pharmaceutical Industries. *Industrial & Engineering Chemistry Research*, 40(1), 275–286. <http://doi.org/10.1021/ie990870t>
- Shah, N. (2004). Pharmaceutical supply chains: key issues and strategies for optimisation. *Computers & Chemical Engineering*, 28(6–7), 929–941. <http://doi.org/10.1016/j.compchemeng.2003.09.022>
- Sundaramoorthy, A., & Karimi, I. A. (2004). Planning in Pharmaceutical Supply Chains with Outsourcing and New Product Introductions. *Industrial & Engineering Chemistry Research*, 43(26), 8293–8306. <http://doi.org/10.1021/ie049857l>
- Sundaramoorthy, A., Li, X., Evans, J., & Barton, P. (n.d.). *Capacity Planning for Continuous Pharmaceutical Manufacturing Facilities*. Computer Aided Chemical Engineering 11th International Symposium on Process Systems Engineering, 1135-1139, 2010.
- Swaminathan, J.M. *Tool procurement planning for wafer fabrication facilities: a scenario-based approach*. IIE Trans. 34 (2), 145–155, 2002.
- Verderame, P. M., Elia, J. A., Li, J., & Floudas, C. A. (2010). Planning and Scheduling under Uncertainty: A Review Across Multiple Sectors. *Industrial & Engineering Chemistry Research*, 49(9), 3993–4017. <http://doi.org/10.1021/ie902009k>