Evaluating The Economic Feasibility and Design of Modular Production Systems in the Steel Industry

A Major Qualifying Project
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Abstract

Previous studies in the agriculture and pharmaceuticals industries have indicated that companies who switched to a modular production system design (MPS) have increased profitability and direct control over their respective supply chains, among other benefits. While MPS is relatively new, they have yet to be implemented in the metal or steel-making industries, which are responsible for a considerable portion of the planet’s carbon emissions. In this report, our team develops a sample MPS design that could be implemented when a company decides to begin constructing such a facility. Our design considers the different machine and equipment types necessary to process and produce finished steel products that aim to eliminate some of the limitations captured in traditional steel manufacturing. We then developed a profit and loss analysis that suggested that an MPS in steel is theoretically profitable – generating nearly $1 million annually at the end of four years. This analysis was extended into a linear programming model, proving that the mix of product demand during economic turmoil can be optimized to maximize the profits of the manufacturing operations. Furthermore, we developed risk management tools, such as a Monte-Carlo simulation and decision tree, highlighting the variables that most impact potential payoffs. These variables include sell-through, maintenance costs, and the total value-added time in the process. As proven by both the P&L and Monte-Carlo simulation, the system is cash flow positive nearly a year or two after deployment, which is significantly less time than with the traditional methods of producing steel. Ultimately, additional research is required to prove the impacts MPS might have on the steel supply chain. Similarly, there is insufficient data to draw conclusions about the amount of emissions and impact such a system has on the environment and the long-term suitability of this type of manufacturing.

Authorship Table

During the three-term duration of this project, team members (Elise Deshusses, Aaliyah Royer, Kenneth Savage, Advait Surana) contributed to performing background research, data collection approaches, formulating financial and risk management models, and other necessary procedures as needed. Every team member put forth effort in writing, formatting, creating deliverables, and editing this report.

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* The Linear Program model was constructed by Aaliyah Royer and consulted on by the team.

** The Monte Carlo Simulation was created by Elise Deshusses.

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Executive Summary

This Major Qualifying Project was completed in the 2022 - 2023 academic year in collaboration with GenH, a clean-energy startup. The main goal of this project was to evaluate whether implementing a steel-producing modular production system (MPS) was feasible in terms of process flow and economics. Our team familiarized ourselves with such technology by reading MPS case studies, researching the traditional steel production systems, and talking with our sponsors about their research. Our sponsor's goal is to use our findings to determine if and when they should build a steel MPS using their clean energy technology and apply other recommendations they should consider before construction.

The first objective of this project was to improve our team and sponsor's understanding of MPS potential in the steel and metal-making industries. From our literature review, our team developed a sample MPS design that considered a set of theoretical products to be manufactured. The design also contained a set of 6 to 8 machines which was organized into cells. We drew process flow diagrams to indicate how the products move through the system and drafted several assumptions and limitations associated with our design.

Our second objective was to determine the economic feasibility of implementing a steel-producing MPS based on a positive net profit margin and return on investment (ROI). This objective was achieved by implementing our design into a profit and loss (P&L) analysis. This analysis considered the breakdown of costs by type (equipment, production, and transportation). It demonstrated how one set of variables impacted another, and how that would impact overall profitability. This analysis also illustrated how the manufacturer can dictate the revenue created by adjusting the selling price, the types of products produced and adjusting labor and machine or cell types. Because our team lacked a comprehensive and robust data set, we decided to analyze how profitability and ROI could be impacted by making changes to our production values. Consequently, we developed a linear program and Monte-Carlo simulation tool that captured additional economic insight.

Our third objective was to identify risks, categorize them, and minimize the potential points of failure in our designated MPS. We also studied how these results could impact the supply chain. This objective was achieved through our risk management models, and developing a list of additional risk considerations that we were unable to incorporate in other ways. Through our economic and risk analyses, we learned that it is feasible to build a steel-producing MPS. With that said, we expect there to be many innovative technologies in the coming years, so it might be best to wait before deploying such a system. In the meantime, many of the constraints and future

applications we highlighted can be explored in more detail, which can place our sponsor in a position to advance strategically and perhaps capture greater control over the steel supply chain.

1.0 Introduction

1.1 Project Motivation

The steel industry is vital to the American economy, and is one of the most important industries since it serves as the material of choice for many manufacturing, construction, transportation, and consumer products. Some may argue that it is the foundation and predecessor for many industries today. Steel provides workers and businesses with widely valued employment, training, and development opportunities. A job in the steel industry can provide a person with a close connection to some of today's most advanced technology and highly efficient supply chains (*Steel Industry Profile*, n.d.). Given steel is a valued commodity, the motivation for this project is to develop a long-term, low-cost solution to produce steel more sustainably. Current steel production systems present many inefficiencies which are beyond the manufacturers' controls. Through this project, our student team at WPI planned to create a cleaner and more affordable future for people and manufacturers alike.

1.2 Background

The world produces a significant amount of steel. On average, over 240 kilograms of steel are produced per person on the planet annually. The image below illustrates the most common applications of steel as of 2019.

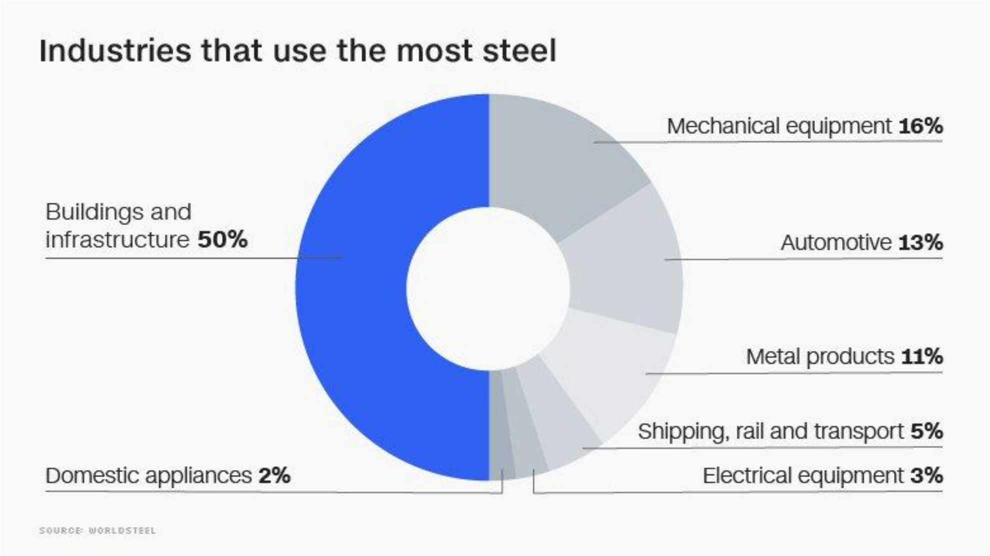


Figure 1 – Steel Applications (Frequently asked questions, 2019).

Since 1950, the amount of steel produced in the world has increased tenfold. This rate of increase is expected to remain in the coming decades (Counts, 2019). Steel production is considered to be a dirty business in terms of pollution, but no product can be created without it. In 2022, the industry employed about 100,000 people in the United States alone, a country that has seen a decline in its manufacturing industry since the early 2000s (IBIS World, 2022). Countries such as China and India, which incorporate labor-intensive production processes, employ many more people in the industry. Bridges, skyscrapers, railroads, automobiles, and appliances are all made of steel. There are currently over 3,000 catalog grades of steel available. If steel is not used in the product itself, it is used in its production process or shipment. The six main countries that produce steel, as of 2018, were China, India, Japan, the United States, South Korea, and Russia. China produced 928 million tons, more significant than the other five top countries combined.

The primary ingredient in the production of steel is iron ore. Over 2 billion tons of iron ore are mined each year, used almost exclusively by steel industries. Iron ore is the third most produced commodity trailing behind only crude oil and coal, and the second most traded commodity, following behind crude oil. When the iron ore is processed in a furnace, it releases carbon as a byproduct, leading to much pollution. The steel industry has produced 33 billion metric tons of carbon dioxide between January and October 2022 and is by far the most polluting industry on the planet. The steel industry also is the most energy-consuming industry, where every ton of steel produced requires 20 gigajoules of energy. To put that into perspective, an average household only requires about 36 gigajoules of energy annually (Tuck, 2022).

The amount of water wastage caused by the industry is also astronomical, with over 100 million tons of wastewater generated from steel mining during the same 2022 timeframe (Counts, 2019). Due to these issues, many new innovations in the industry have since been developed. For example, the ‘Hybrit’ system, a type of fossil-free steel, aims to reduce carbon emissions in its processing. This project report will reflect our student team’s efforts to design a process that offers manufacturers superior returns while reducing the industry's environmental impact.

1.3 Problem Statement

Historically, most industrial production processes can be characterized by two main challenges that have yet to be solved. First, they are known for consuming significant amounts of electrical energy from the ‘grid,’ the massive, complex network of transmission lines, generation facilities, and transformers (*What is the grid?*, n.d.). The ‘grid’ is known for being dirty and risky.

Today, much of our energy is captured by burning fossil fuels, which create over 1500 million metric tons of carbon dioxide emissions annually (*Frequently asked questions,* 2022). Furthermore, manufacturing facilities experience 800 hours of downtime annually due to outages or machine failures, which costs businesses more than $50 billion and causes extended product and machine damage. There is also a cost associated with maintaining the grid structure, and although controlled by utility companies, it presents potential physical and cyber security threats. Therefore, it is unsurprising that industries, including steel, must pay for and rely on the grid to produce their goods (Shanker, 2021).

Secondly, conventional manufacturing is a very complex system that has traditionally required multiple key partners, each with particular responsibilities. For example, there could be a company A that mines metals and produces powder, while company B takes those metals, melts them and creates a final product. Company C might store them in its warehouses or sell directly to businesses and customers. Therefore, the main manufacturer, or company B in this case, lacks control over the entire supply chain. They depend on their partners to keep short lead times and provide the products when needed. There is also a lack of flexibility regarding production. Conventional manufacturing is designed for low-cost, mass-produced parts that are susceptible to a system breakdown or bottleneck. Conventional manufacturing systems are extremely reliant on forecasting, where they carry high inventory levels to absorb fluctuations in demand. While this strategy is not always unordinary, it requires businesses to have a warehouse to store this inventory, which comes at a greater cost.

Lastly, and perhaps most notably, traditional manufacturing produces significant CO2 emissions by use of furnaces and processes requiring heating, cooling, smelting, and burning. In recent years, reducing carbon emissions has been an increasingly influential objective of national and international regulatory and trade policy (*Strategic Intelligence*, n.d.). Proposed measures to meet this objective are already emerging in the form of increased reporting requirements for public companies or carbon border tariffs and pricing. Today, many industries are looking to reduce their emissions or create products that are much more eco-friendly.

In the case of manufacturing systems, the method to eliminate these unnecessary emissions, costs, and supply chain steps can be achieved by exploring opportunities within the energy-consuming production processes. In this report, our student team will be studying the production processes within the steel industry, which is representative of the challenges industrial production faces (Freda, 2021); (Hoffman et al., 2020). We will also explore the possibility of implementing elements of a modular steel production system, which cannot currently compete with conventional factories in the commodity market due to the significant initial setup cost. The

WPI team plans to develop recommendations that could potentially put GenH ahead of their peers.

GenH is a company that specializes in clean energy. Their goal is to provide affordable and reliable clean energy to be used in various industries through hydropower. They are now looking at the feasibility of a modular production system which could be powered by their clean energy to expand and diversify. Currently, the conventional method to produce steel is through mass production. However, modular production could be an alternative system that targets smaller markets. Although they have researched the topic, they would prefer to improve their understanding of the economic feasibility of modular production systems. Through this MQP, we will aim to assist our sponsors in determining if modular production can become a reality in the near future.

1.4 Project Goals and Objectives

Our team's primary goal is to build on the research generated by our sponsor, GenH, to determine whether building a modular steel production system is feasible in terms of production, process flow, and economics. Below are three questions we would like to answer by the conclusion of this project:

1) Is a modular steel production system economically viable? What processes or parts could this theoretical system consist of?
2) What would a steel MPS look like in terms of inputs, outputs, and internal processes?
3) How might a steel MPS be evaluated, and what are some of the most important factors in deploying an MPS given a set of assumptions?

First, our team looks to further research the limitations, specifically the processes, equipment, materials, energy, and facility requirements associated with traditional steel manufacturing. This research improved both our team and sponsor's understanding of limitations in the steel industry before building any form of model or analysis. This part of the research provides our team with a baseline of the opportunities for GenH to possibly take advantage of and develop a new manufacturing production system. From this information, our team constructed and implemented a sample modular design. Secondly, our team measured the economic feasibility of implementing a modular production system for steel on the basis of net profit margin and return on investment. Developing an economic model will suggest whether developing such a system is profitable and provide our sponsor with a timetable of expected expenses and revenues for each period. Third, our team anticipates that any recommended production system design or economic model will have impacts on the supply chain. We have identified, categorized, and minimized the potential failure points in this production system type by constructing risk management models. Such information will serve as supplementary material that can help our sponsor make a well-informed decision.

2.0 Literature Review

2.1 Traditional Steel Production Systems

This paper refers to traditional steel production systems as those in place for much of the 20th century. Steel combines iron and carbon, yet can contain traces of other elements to achieve desired properties. Steel is a very important material. It is used in infrastructure, vehicles, tools, machines, weapons, and other products. It is known for being ductile, hard, durable, strong, and can withstand shocks (Dey, 2021). Historically, steel has been produced through integrated or mini production mills. The main difference between these two types is the proportion of recycled steel put into the system and the method of steel production. Mini mills utilize up to 99% recycled material, whereas integrated mills can only handle 91% (Jamison et al., 2015). Furthermore, integrated steel mills produce steel using blast furnaces and basic oxygen furnaces, while mini mills acquire recycled scrap and refine it via the electric arc furnace. Mini mills, however, have the advantage of flexibility in starting and stopping batches, and can be placed geographically close to markets for steel products. There are fewer transportation requirements compared to integrated mills. Additionally, incorporating this furnace results in lower carbon dioxide emissions compared to the conventional production route of blast furnaces (De Ras et al., 2019).

Essentially, a blast furnace is a cylindrical shell lined with heat-resistant brick that produces molten pig iron from iron ore. It works in partnership with the basic oxygen furnace, which takes molten pig iron or scrap steel and converts it into steel through an oxidation process. This process involves a current of air containing carbon, silicon and manganese being blown through the molten pig iron (Dey, 2021). An electric arc furnace (EAF), on the other hand, produces molten steel through generating heat from an electric arc between electrodes. Statistically, the blast furnace and basic oxygen furnace processes require nearly 7 times as much energy to produce one ton of steel as an electric arc furnace (Fruehan et al., 2000). Hence, approximately 60% of United States steel is produced using the electric arc furnace. This trend is expected to continue in the coming years, especially considering that EAF steelmakers produce 75% less carbon compared to traditional blast furnace processes (Contributor, 2022). Images of these processes can be seen in figures 2 and 3.

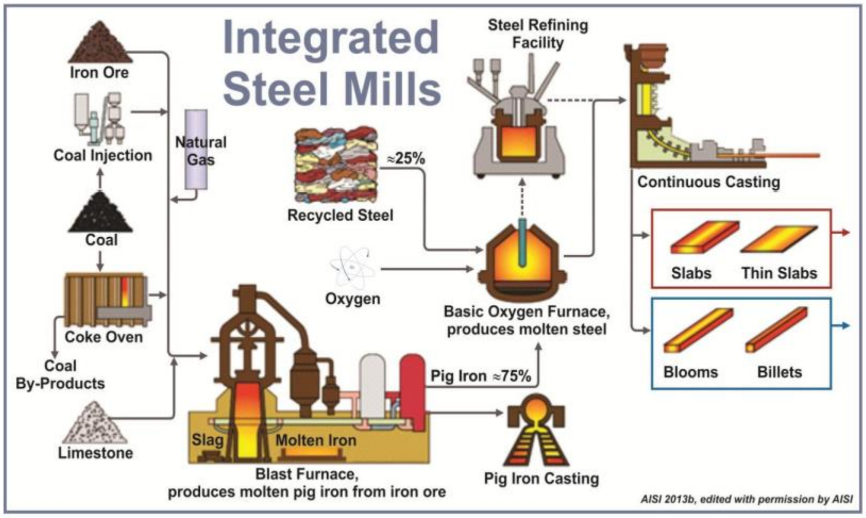


Figure 2 – Process map of Integrated Steel Mill, which harnesses energy from mostly iron ore, through blast and basic oxygen furnaces (Jamison et al., 2015); ("Steel Production," n.d.).

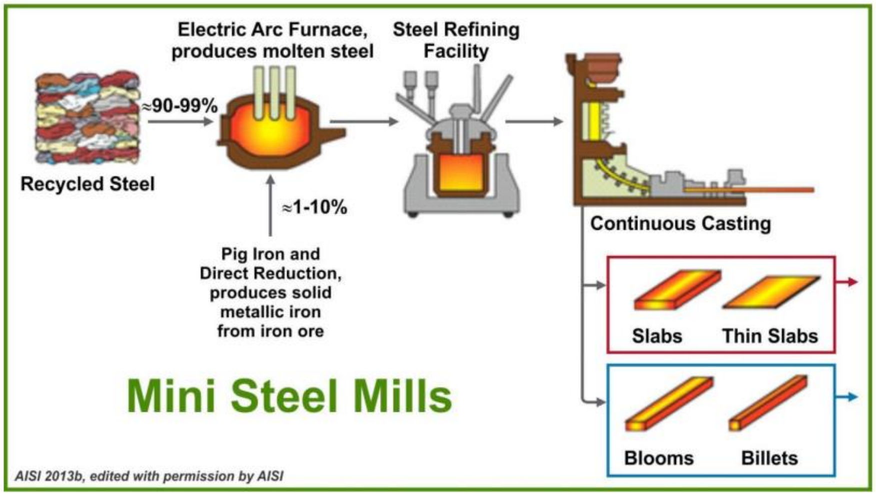


Figure 3 – Process map of Mini Steel Mill, which harnesses energy from mostly recycled steel through an electric arc furnace (Jamison et al., 2015).

As of 2015, the United States is home to 5 companies that oversee a total of 15 blast and basic oxygen furnace steelmaking facilities. The electric arc furnace, on the other hand, can be found in 112 facilities owned by over 45 companies (Jamison et al., 2015). A majority of these facilities can be found in Midwestern states, specifically Ohio, Illinois, Indiana, Pennsylvania, and Michigan, because they are geographically adjacent to most iron ore and coal suppliers. In recent years, there has been a shift in manufacturing and new mini mill construction in the southern and western regions of the United States to be closer to customers in these regions (Watson, 2022).

The following section explores the steelmaking processes more deeply and categorizes the steps into separate energy-consumption categories.

2.1.1 Steel Production Process

Table 1 – Summary of the steel production process divided into energy-consumptive steps. Note that not all steps are necessary depending on the facilities or equipment used (Jamison et al., 2015); (Fernandez-Gonzalez et al., 2017); (Fruehan et al., 2000). Steps in green occur within integrated steel mills. Steps in purple occur in mini steel mills, or in association with other plants. Steps in orange are independent of the plant or mill used in steps 1 through 4.

Process/Step	Substeps	Location
(1) Ore Agglomeration	Sintering, Pelletizing, Briquetting	Near mining site
(2) Cokemaking		Integrated Steel Plants, or Merchant Plants
(3) Ironmaking	Blast Furnace, Direct Reduction	Integrated Steel Plants, Gas-based Direct Reduction Plants
(4) Steelmaking	Basic Oxygen Furnace or Electric Arc Furnace	Integrated Steel Plants or Mini Steel Mills
(5) Casting	Continuous Casting, Molten Steel -> Ingots	Steel Refining Facility
(6) Rolling	Hot Rolling, Cold Rolling	Hot Strip Mill, Plate Mill, or Cold Rolling Mill

The first step is ore agglomeration. This step aims to improve the physical properties and quality of the iron ore. This may require sintering, which is mixing ore pellets, coal fines, limestone, and coke, and then heating it to form a porous sinter (Jamison et al., 2015). It may also require pelletizing, which is the physical crushing of iron ore or grading it to remove impurities. The powder is then formed into small, round pellets to be heated and hardened. Alternatively, a briquetting technique could be implemented in which iron briquettes are formed from ore and are hardened at high temperatures. It should be noted that ore agglomeration is typically managed not at the mill, but at the mining site to reduce transportation and waste costs (Fernandez-Gonzalez et al., 2017). However, this process is very expensive because of the amount of energy required to heat the furnace, particularly the sintering stage.

The next step of the process is called coke-making. This process requires placing coal into a coke oven, heating it to intensely warm temperatures in a ‘vacuum-like,’ airless environment. The resulting product possesses greater carbon purity. The heating process does not require significant energy since the oxidation of coal fuels it. In fact, volatile chemicals are produced as byproducts to provide power for other plant operations (*Coal to Make Coke*, 2022).

The third step is ironmaking. Unlike the first two steps, which do not occur within either furnace type, traditional ironmaking occurs in the blast furnace. This is where the iron ore, coke, and limestone material are passed into the system. This material reacts to the heated stream of air to remove excess oxygen, resulting in a product called pig iron. Please note that the coke quality will highly influence the process energy consumption (Jamison et al., 2015). Lower quality, although cheaper to purchase, requires a greater amount of coke to achieve pig iron with high carbon content. Pig iron tends to contain 88-90% iron by weight, 5% carbon, 2.5% manganese and 4% silicon, phosphorus or sulfur (Fruehan et al., 2000; Rellick et al., 1971). After reacting, the resultant pig iron accumulates into a liquid puddle where a slag-like shell forms due to air oxidation. It is then tapped at regular 8 hour intervals to remove hot metal and remaining slag from the furnace which improves hearth drainage efficiency and to prevent unstable furnace operations (Agrawal et al., 2017).

The fourth process is steelmaking, where the pig iron is converted to steel, though the process differs depending on the furnace in use. In basic oxygen steelmaking, oxygen is ‘injected’ to remove carbon from pig iron (Jamison et al., 2015). This process does not require significant energy since the molten pig iron contains considerable heat in addition to the heat provided from burning the carbon content. With that said, energy is lost through radiation and conduction (*AIST Steel Wheel*, 2022), resulting in potentially significant yield loss. Cold steel straps, which are part of the furnace, lower the temperature if necessary. These processes can be monitored by looking at the flame coming from the mouth of the converter (Dey, 2021). During the oxidation phase, the flame is short, though it grows in luminosity as the blow continues and carbon becomes eliminated.

In electric arc steelmaking, the raw steel is produced from a ‘feedstock of recycled steel or iron’. There is an electric arc formed among both the graphite electrode and feedstock, where the electrode is the part responsible for melting the recycled steel. It should be noted that these processes can be accelerated if carbon fines or oxygen are added (Jamison et al., 2015). This also saves on carbon emissions, as the previous steps of iron ore agglomeration, cokemaking and ironmaking are unnecessary (Sinha-Spinks, 2015).

The fifth process is casting, where molten steel is casted into several different forms, including billets, ingots, beams or continuous metal slabs. While there are multiple casting methods, nearly 97% of steel is cast using continuous casting processes. Upon transporting the steel from the furnaces to a converter and then to a ladle, the steelmaker might make some changes or adjustments to the temperature or composition (*Steel Supply Chain*, n.d.). They would do this by stirring the metal with gas. The steel must be cooled to not only prevent cracking, but segregate chemicals and to allow for a metallurgical steel structure. There is minimal yield loss in the casting process, given that most of the product can be salvaged, other than what remains in the ladle.

After being casted, the steel is moved to its final process, rolling, which occurs in one or both rolling mill types, hot and cold. In hot-rolling mills, the steel slabs are reheated in furnaces to a uniform temperature before being rolled to reduce thickness (*Rolling Process for Steel*, n.d.). In cooling mills, the steel is allowed to cool to air temperature, however it may require reheating if the temperature is too cool, which would require additional energy consumption (Jamison et al., 2015). Final heat treatments are performed, such as annealing, which softens steel and quenching, which increases the strength of steel. Yield loss is very common at this step since the steel can oxidize and crack while rolled and cropped at the end of the slabs. After this process, steel is ready to be cut and customized.

2.1.2 Personnel and Labor

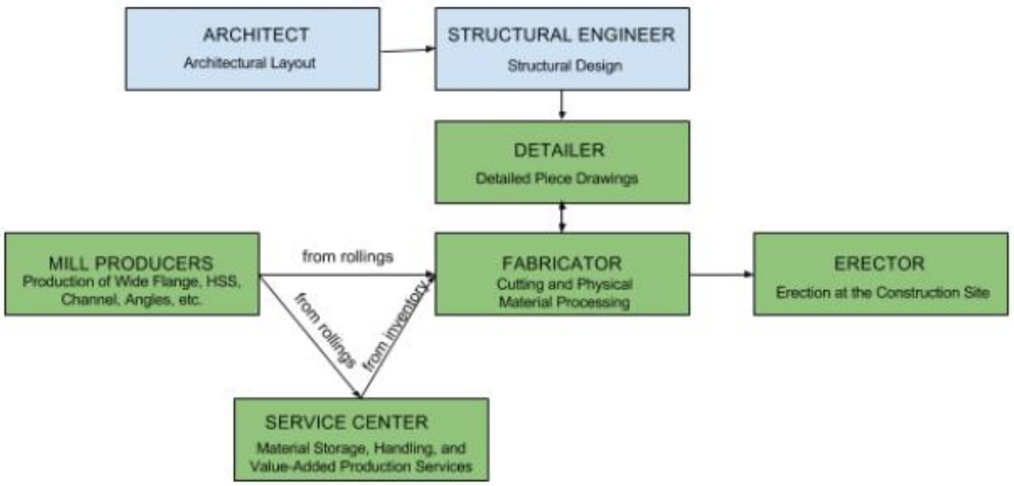


Figure 4 – Process Map of the different personnel jobs in the steel production process (Steel Supply Chain | American Institute of Steel Construction, n.d.).

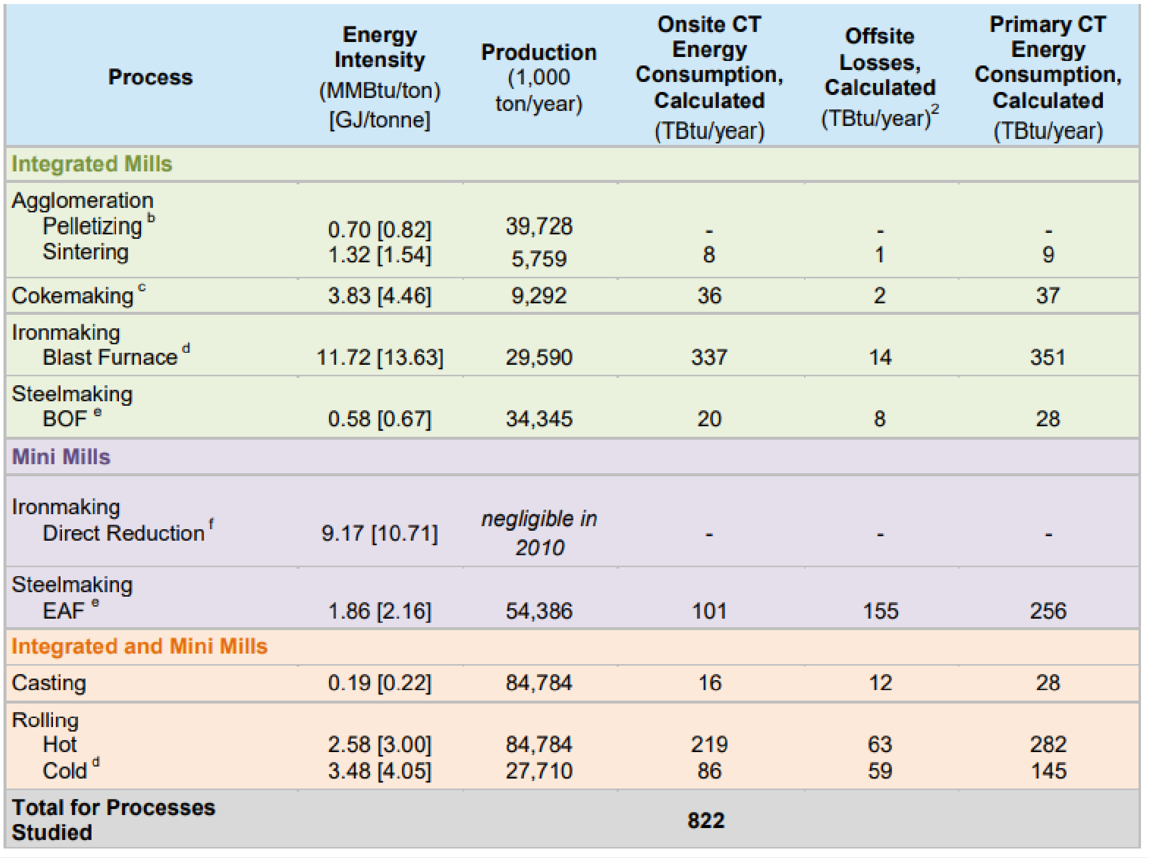
Key personnel are responsible for different processes in the supply chain. For example, producers roll structural shapes and beams. Currently, there are three major structural steel producers that develop over 90% of steel in five different locations (*Steel Supply Chain*, n.d.). On average, it takes producers approximately half an hour to produce one ton of steel. The product then sits in the service center for two to three months, essentially functioning as a steel warehouse. Fabricators cut and physically process the material. They prepare each piece of structural steel based on the drawings provided by the detailer, who develops these drawings. The fabricator either performs detailing in-house or contracts someone else to manage this process. Next, the steel is sent to the erector, who physically constructs the structural frame. Steel packaging has a material cost that accounts for 25% - 30% of the total cost, whereas the fabricator and erector processes cost 70% - 75% of the total price (*Steel Supply Chain*, n.d.).

In 2021, United States steel mills employed nearly 80,000 workers. About 65% of these workers work directly with the steel product manufacturing systems, which accounts for 40% of total steel industry employment (Watson, 2022). The number of process workers required at any one facility varies between 15 and 30 (Jamison et al., 2015). The American Iron and Steel Institute (AISI) has found that approximately 2.1 labor hours were required to produce one ton of steel in 2020 on average. However, that number fluctuates depending on the furnace type and customization of steel (*Quarterly Census of Employment*, 2022).

2.1.3 Energy Consumption

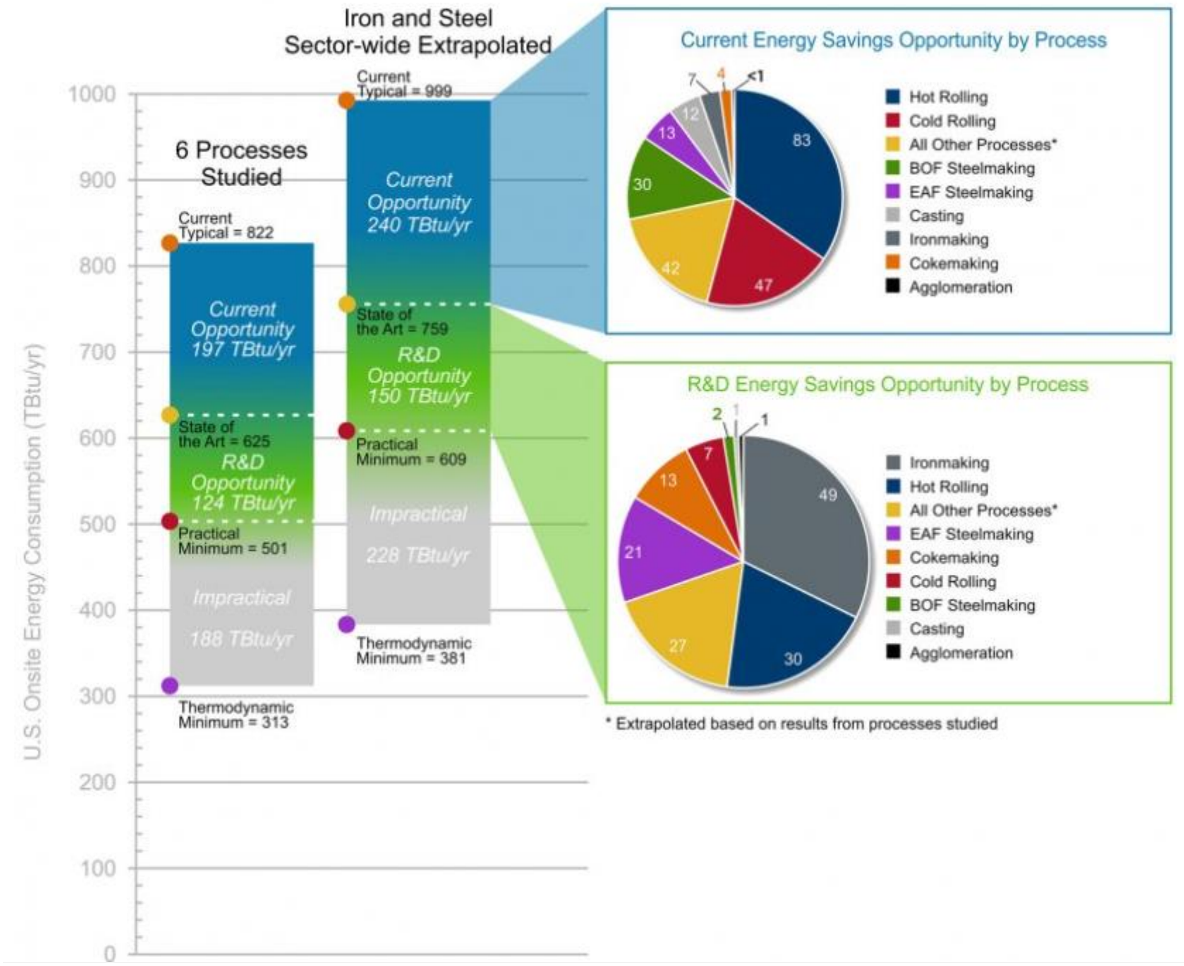
The total amount of energy required to develop steel varies considerably depending on the processes involved in addition to the age, design and layout of the steelmaking facility. In this report, average energy consumption amounts were borrowed from (Jamison et al., 2015) that were based on mid-2010s data from steel mills exclusively in the United States. Please note the true energy consumption will depend on the aforementioned factors. The column labeled ‘energy intensity’ measures the amount of energy required to produce consistent steel quality among the different manufacturing facilities. Table 2 shows this performance reported in Btu per unit ton (Watson, 2022).

Table 2 – Data collected by the Bandwidth study on Energy Use and Potential Energy Saving Opportunities from a 2010s report shows the energy intensity, production and yield loss calculated from each process separately (Jamison et al., 2015).



Process	Energy Intensity (MMBtu/ton) [GJ/tonne]	Production (1,000 ton/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated (TBtu/year)[2]	Primary CT Energy Consumption, Calculated (TBtu/year)
Integrated Mills					
Agglomeration					
Pelletizing [b]	0.70 [0.82]	39,728	-	-	-
Sintering	1.32 [1.54]	5,759	8	1	9
Cokemaking [c]	3.83 [4.46]	9,292	36	2	37
Ironmaking					
Blast Furnace [d]	11.72 [13.63]	29,590	337	14	351
Steelmaking					
BOF [e]	0.58 [0.67]	34,345	20	8	28
Mini Mills					
Ironmaking					
Direct Reduction [f]	9.17 [10.71]	*negligible in 2010*	-	-	-
Steelmaking					
EAF [e]	1.86 [2.16]	54,386	101	155	256
Integrated and Mini Mills					
Casting	0.19 [0.22]	84,784	16	12	28
Rolling					
Hot	2.58 [3.00]	84,784	219	63	282
Cold [d]	3.48 [4.05]	27,710	86	59	145
Total for Processes Studied			**822**		

Table 3 – Potential opportunities for improving energy efficiency and consumption in steelmaking processes (Jamison et al., 2015); (Domestic Steel Manufacturing, n.d.).



2.1.4 Steel Production Costs

While the demand for steel operates under a regular cycle, it is highly influenced by sectors sensitive to current interest rates. Domestic steel consumption was about 98 million metric tons in 2021. The construction and automotive industries were the two largest end markets for steel in 2021, at 47% and 25%, respectively (*Domestic Steel Manufacturing*, n.d.).

The price of steel is calculated using a manufacturer-suggested retail price (MSRP). This amount considers markups and margins throughout the different levels of the supply chain and is influenced by several factors. Steel grade increases as steel become more specialized. Typically, the higher the grade, the more expensive it becomes since specialized steel requires additional processes, such as quenching, adding alloys, or changing thickness (*US & International Steel*, 2022). Furthermore, the type of process or furnace used will impact pricing too. Recall that each process has different energy consumption which is passed to the customer. Typically, the order quantity has an influence as well. Buying in bulk will lower the average cost per unit due to the efficiencies of speed or human resources. The timeline to receive the steel, the country of origin, the material location and warehouses, the supplier's niche, market regulation, and supply and demand are other factors influencing steel pricing (*How Much Does Steel*, n.d.).

In recent years, United States domestic steel prices have been far higher than those in international markets. In December 2021, hot-rolled steel in the United States averaged $1855 per metric ton, whereas the prices were $646 in China and $1031 in Europe for steel of the same quality. The price in the United States has since decreased to $1481 in March 2022 due to unsustainable production levels (*SteelBenchmarker*^{TM}, n.d.). Domestic prices of steel are traditionally greater than foreign prices because of US significant restrictions on steel imports maintained by the United States. These restrictions prevent foreign competition in the domestic market by limiting the imported volume. These restrictions have been commonplace for the past 50 years due to domestic steelmaker complaints (Casey, n.d.).

Many steel producers now specialize in low-cost, high-demand products to better compete in the domestic market and avoid cheaper steel imports. These changes are demonstrated in the gap between import and export prices. United States steel exports are averaging $1570 per metric ton compared to the average import of $1171 in 2021 (*Industries at a Glance*, n.d.).

2.2 Alternative Manufacturing Processes

Due to steel's various different properties and applications, there are many ways to manipulate the steel after the melting process. The two main methods include “forging” and “printing”.

2.2.1 Forged Processes

Many of the processes discussed in section 2.1 were considered forged processes, meaning that steel was shaped through a series of melting, cooling and purifying techniques. Most conventional factories tend to use this method because it is efficient to mass produce parts when compared to other technologies, such as printing. With that said, newer and trending forged processes include Hybrit and Molten Oxide Electrolysis, though these have not been implemented in many steel factories as of 2023. Hybrit is a process where instead of using coke to remove oxygen, which can produce harmful levels of CO2, hydrogen, and water is used to produce water vapor instead. This method, though believed to be more expensive than traditional forged processes, allows for the safe disposal of harmful wastes.

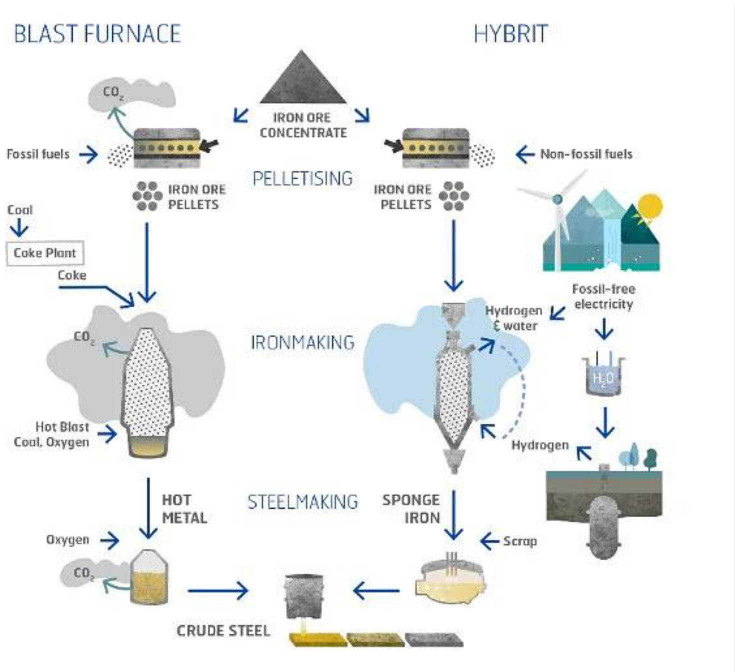


Figure 5 – A diagram comparing Hybrit's approach to the traditional blast furnace (Institute, n.d.).

Molten Oxide Electrolysis, also known as MOE, is an electro-metallurgical technique that can directly produce metal in the liquid state from ore oxide feedstock instead of first producing a solid metal which is then melted. Traditionally, the process requires a significant amount of energy and is very complex, requiring multiple machine types, tools, and handling systems. MOE, however, eliminates both of these issues. It simplifies the number of machines required while keeping energy usage to a minimum. It has many desirable qualities in terms of metal production and manufacturing and can be used in many different fields. The only drawback of this technology is that because it is new, it should be expected to be very expensive, as the technology is not necessarily commercially available.

2.2.2 Printing Processes

Metal 3D printing is a relatively new method of producing metal parts. They are mainly used to produce smaller parts that require a high degree of control and precision. Previously, smaller parts were produced using special casts through the use of injection molding. 3D printing is a potentially cheaper alternative compared to the traditional steelmaking process, as it only requires powder and printing materials. It also is more efficient for smaller batches, unlike special casts, which require high volume to be profitable.

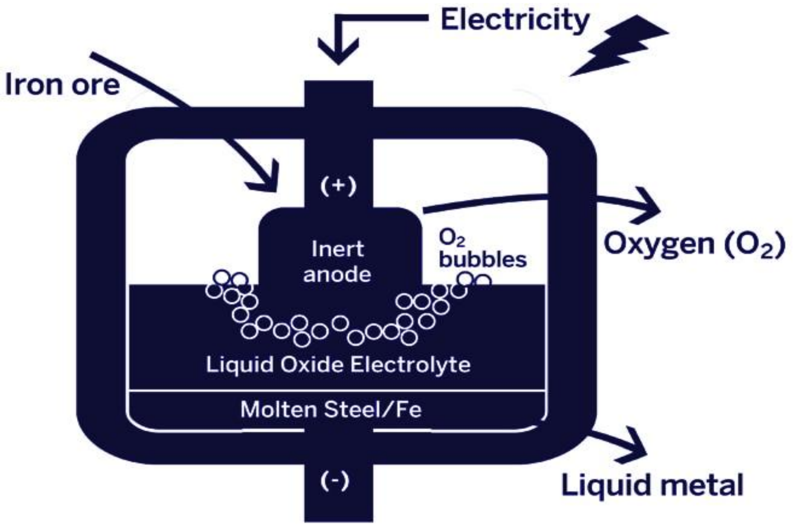


Figure 6 – A diagram of the molten oxide electrolysis energy method (Thermal Process Intensification, 2022).

Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are the two most commonly used processes for 3D printing metal. SLM and DMLS both require a laser to scan and then fuse the raw material, which contains a metal powder in granular form. The bonding process, also known as additive manufacturing, happens layer by layer, from bottom to top. The greatest difference between the two processes is the fundamental way the metal powder is bonded together to form the final shape. For example, SLM only uses one temperature setting to fuse the particles, implying only one metal type can form the finished product. The DMLS process incorporates multiple temperature settings, which allows it to fabricate parts made of metal alloys (Castells, 2023).

3D Metal printing works in 3 steps (*What Is Metal 3D*, n.d.).

- The build chamber is first heated up and filled with an inert gas to ensure no oxidation during this process.
- Metal powder is spread layer by layer using the assistance of a laser that scans and builds the part by using its cross-section data. After one layer is done, it goes on to the next layer till the part is complete.
- After this, the part is rescanned to make sure there are no errors, and the final part is recoated with another layer of powder to ensure the durability of the product.

Most of the real-world applications can be covered from aluminum, steel, titanium, and cobalt chrome. Gold and silver can also be used for 3D printing but are more limited in their application, such as jewelry making. Traditional metal manufacturing processes are not designed for high-strength parts such as nickel, but the SLM and DMLS methods can process these parts easily (*What Is Metal 3D*, n.d.). The table below summarizes the general benefits and drawbacks of 3D printing compared to traditional steel manufacturing.

Table 4 – Summary of the benefits and drawbacks of switching to a 3D printing process for steel production over traditional manufacturing methods. Data gathered from (Duda et al., 2016); (Jamison et al., 2015); (Jurmaah, 2018); (Watson, 2022); (Bhasin et al., 2014).

	Benefits	**Drawbacks**
3D Printing	- design freedom, complexity - ability to customize - faster production (small parts) - less waste material - fewer emissions (VOCs vs carbon) - combines manufacturing steps - mostly automated, little labor - requires single device - easy material or product changeover - direct control over production process - lower energy consumption - bulk of pricing comes from machine cost, implementation	- fewer material options - less economical compared to traditional in large-scale production - cannot apply batch quality testing - potential inconsistent print quality, higher variation - hazardous printing emissions - expensive to purchase, especially multiple printers - process is disconnected from conventional manufacturing (self-reliant)
Traditional Manufacturing	- well suited for mass production - good repeatability - wide material selection - ability to manage or assign processes to partners - ease of testing for quality - system already in place - excellent surface finish	- part production requires many processes, machines - longer lead times - reliance on partners/suppliers - labor intensive - higher energy consumption - volume of wasted material - not well suited for low-volume, customizable products

2.2.3 Printed Technology Applications

3D printing has a variety of applications in the steel and metal-making industries. Below are some examples taken from (*The Top 5 Metal,* 2022*)*.

- Specialty parts
    - 3D printed rocket engine fuel pump saving over 50% of the cost
- Functional Metal Prototypes

  - Internal combustion engines 25% faster than traditional methods
- Spare & Obsolete Parts
  - Classic Car parts that cannot be found in today's market
- Surgical & Dental Implants
  - Knee and hip replacements that are otherwise hard to produce
- Jewelry & Decorative Arts
  - Intricate jewelry designs

2.2.4 Printed Process Example

Since most 3D printing steel applications are similar, our team decided to focus on studying an example in industry. Markforged, an additive manufacturing company founded in 2013, specializes in 3D Printing. Their printing process consists of three main steps: printing, washing, and sintering. First, a CAD file is exported as a .STL file. It is then uploaded to a utility-based printing information software system. Based upon the user's material and shape selections, the software will configure the part as it sees fit. It coordinates with the device to level the printing bed, and maps the print appropriately (*Metal 3D Printing*, 2022). The printed material is then built from a combination of metal and ceramic release, which is safely suspended by a plastic binder, warmed, and then expelled onto the plate builder. Markforged's process is capable of printing materials including 7-4 PH stainless steel; copper; tool sheets; and a variety of other products. This process uses nearly all inputted metal powder and is known to be more cost-effective than other 3D printing systems.

Figure 7 – The required steps to produce 3D printed objects. Many manufacturers use a combination of 3D printing with other additive manufacturing processes to produce finished products (Campbell et al., 2011).

Once the part is finished printing, the user is notified via email. Simultaneously, binding material is washed away. The green-colored part then soaks for a few days before turning brown. It is then placed into a sintering process, where the metal particles fuse together to form a solid piece of material (*Metal 3D Printing*, 2022). As soon as the parts are finished, they are ready for use.

2.2.5 Implications

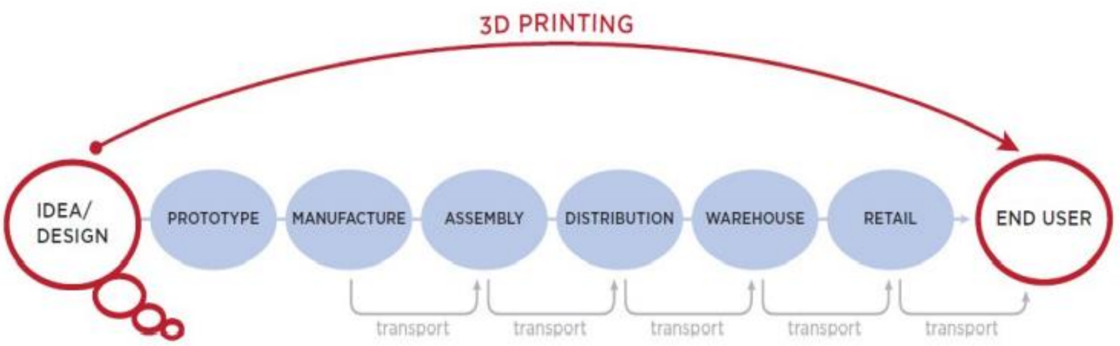


Figure 8 – Process map highlights how several processes are unnecessary and could be eliminated if an additive manufacturing technology, such as 3D printing, were implicated instead (Ozceylan et al., 2017).

In 2014, an MIT study suggested 3D printing could reduce total supply chain costs for small, custom products by between 50 and 90% (Bhasin et al., 2014). Consequently, because 3D printing technology eliminates many steps of the supply chain, the production processes are closer to the end-user. Production and distribution channels should theoretically be deglobalized and more localized. Warehouses can strategically be located close to airports or sea ports to support cargo operations (Ozceylan et al., 2017). Therefore, it can be argued that this technology is a disruptive innovation that will impact both the global supply chain and the logistics industry. Furthermore, manufacturers will possess the ability to produce products ‘on demand’ without having to store significant inventory (Jurmaah, 2018). Additive manufacturing could simplify the current complicated global supply chain and instead develop a newly structured trading economy.

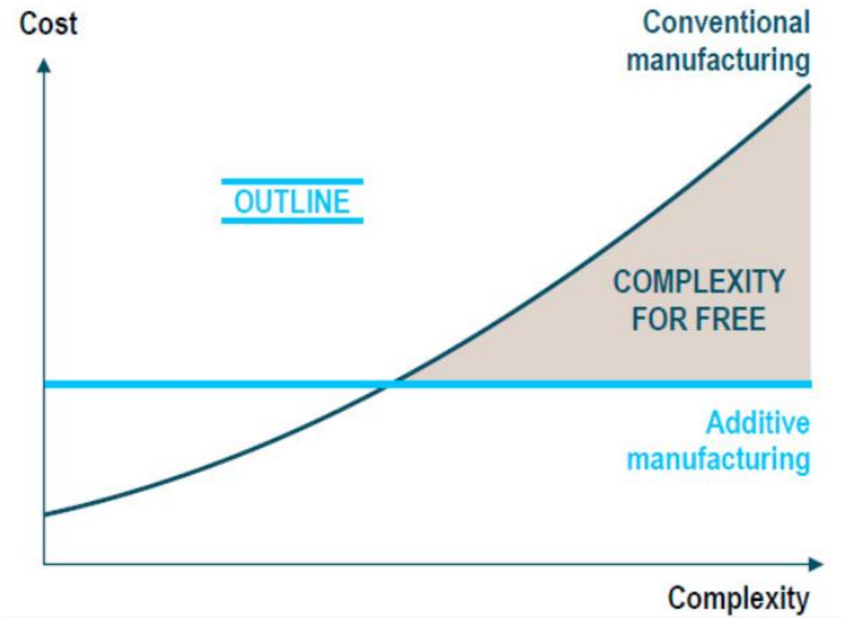


Figure 9 – Cost as a function of product complexity in conventional and additive manufacturing settings. The cost of conventional manufacturing is highly correlated to its complexity, whereas additive manufacturing remains consistent (Duda et al., 2016).

In addition to simplifying the supply chain, 3D printing is nearly as likely to lower energy requirements through eliminating unnecessary processes. Furthermore, by requiring fewer processes with lower energy requirements, it should be expected that CO2 emissions are also reduced. Location plays a critical role here as well since shipping steel over shorter distances is less expensive, and the freight trucks require less diesel through delivery. Moreover, 3D printing has the potential to reduce shipping across great distances, which should theoretically reduce carbon emissions. By printing items on-site, firms, manufacturers or other consumers could produce their own products from digital files instead of waiting on traditional providers (Nadagouda et al., 2020). (Gebler et al., 2014) predict 3D printing production lead time can be reduced while allowing users to customize their products. It should be noted, however, that depending on the types of powders used, they could release hazardous nanoparticles, carcinogens, and volatile organic compounds, which pose many health risks (Kim et al., 2015).

Like Markforged, GE utilized additive manufacturing techniques back in 2015. They became the first company to develop a 3D-printed commercial jet engine part. This served as a stepping stone for traditional manufacturers to work with GE to utilize their technology to develop new parts (Joshi et al., 2015). Consequently, in 2016 and 2017, GE built its first additive manufacturing centers in Pennsylvania and Germany (*GE Celebrates Grand*, n.d.). Process costs, quality, and speed were some of the driving factors in switching to this printing technology.

In 2021, GE redesigned the printing process to finish products in 10 months compared to the 12 to 18 months for casting (*GE Cuts Costs*, n.d.). This resulted in cost and production time reductions of 35% and 25%, respectively.

2.3 Modular Systems

As Industry 4.0 advances and becomes more normalized, the traditional manufacturing industry will radically improve. The five primary shortcomings of the current industry to be improved include the lead times for a product ‘design to market’’, the variance and quality of goods, predictability of lead times and production costs, the flexibility of production process and volume, and the feasibility of frequently introducing new products to production and thus the market (Rogers et al., 1997). As automation tools improve and become more affordable, improvements in these areas may seem more achievable. However, there are limitations and issues with depending heavily on special production process tasks because developing robots for tasks is expensive and lacks versatility. Instead, radical changes in the structure and organization of manufacturing processes, including modular production systems, may be a more reasonable way to reinvent manufacturing.

2.3.1 Modular Production Systems

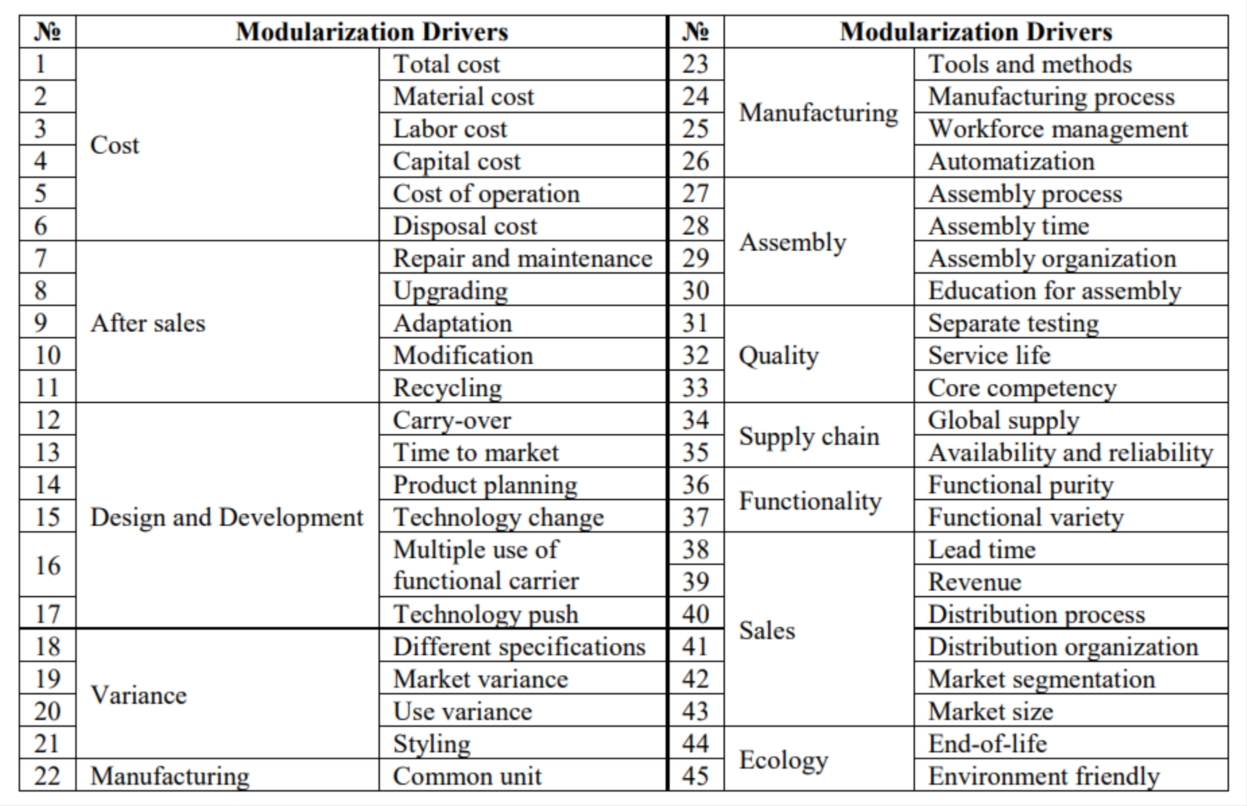
One of the main components of modular production systems is to remove the main assembly tasks to simplify the automated assembly, which can be done using the ‘just-in-sequence’ parts production method. This method eliminates many transportation and motion wastes and defects by bringing and assembling parts in sequence onto the main assembly. Another way of simplifying the production process is to decrease and limit the special-purpose automated assembly machinery and labor in favor of more elementary machines and tasks. Consequently, these costs will decrease due to lower product cycle times and greater machine utilization, suggesting production capacity could be greater.

However, to have a successful MPS, each product must be well ‘designed for manufacturing’ (DFM), requiring different design processes and assessment criteria than traditional manufacturing. MPS have shorter ‘design to market’ lead times because the manufacturing for the new product is simplified and automated. As a result, the lead times are decreased because the production process can quickly be designed and implemented, finishing construction and production sooner. Since MPS processes are simplified and generally require reliable, versatile machines, production tends to be more consistent and reliable. Therefore, if production is designed for high quality, the MPS lays out a framework for the products to be of high and consistent quality.

Another critical advantage of MPS is the flexibility of the system. Since the production processes are modular and automated, changing production quantities to match market demand through a product's life cycle is easy and does not significantly impact costs. Moreover, it becomes viable to quickly alter the production process to update the current product or launch a new product altogether to adapt to the market share. To achieve a modular production system, all products must be designed to be manufactured using the set of 'process modules', or machine units in the cells. Moreover, MPS will lean towards processes that have high reliability and accuracy. Similarly, processes such as casting do not occur because of longer cycle times which decrease manufacturing cell utilization and thus reduces the return on capital investment.

More recent publications about modular systems investigate the modularization drivers and the attributes that define good modular architecture. According to (Klushin et al., 2018), the main factors are "the economic viewpoint, the assembly, the product life cycle, [and] recycling." Over 70 attributes within these factors have been used to evaluate modular designs across many industries. Klushin et al. (2018) selected 45 modularization drivers as subsets of larger design focus, shown in Table 5.

Table 5 – General modularization drivers for an MPS (Klushin et al., 2018).



№	Modularization Drivers		№	Modularization Drivers	
1	Cost	Total cost	23	Manufacturing	Tools and methods
2		Material cost	24		Manufacturing process
3		Labor cost	25		Workforce management
4		Capital cost	26		Automatization
5		Cost of operation	27	Assembly	Assembly process
6		Disposal cost	28		Assembly time
7	After sales	Repair and maintenance	29		Assembly organization
8		Upgrading	30		Education for assembly
9		Adaptation	31	Quality	Separate testing
10		Modification	32		Service life
11		Recycling	33		Core competency
12	Design and Development	Carry-over	34	Supply chain	Global supply
13		Time to market	35		Availability and reliability
14		Product planning	36	Functionality	Functional purity
15		Technology change	37		Functional variety
16		Multiple use of functional carrier	38	Sales	Lead time
			39		Revenue
17		Technology push	40		Distribution process
18	Variance	Different specifications	41		Distribution organization
19		Market variance	42		Market segmentation
20		Use variance	43		Market size
21		Styling	44	Ecology	End-of-life
22	Manufacturing	Common unit	45		Environment friendly

By assessing a modular design and the production process in terms of modularization drivers, the quality and effectiveness of the modular system can be determined and compared to other alternatives (Hackl et al., 2017). Depending on the industry, there are many specific ways of assessing a modular design, including using different modularization metrics, quality score matrices and hierarchies, synthesis or extracted data, etc (Bonvoisin et al., 2016).

2.3.2 Developing New Modular Production Systems in Steel

While there are no MPS for metals currently, MPS will likely be deployed in the metal industry at some point. There are many different aspects to consider when evaluating a potential modular design, especially when evaluating a system in a new industry (Bonvoisin et al., 2016). For example, when speculating about a modular system in metal processing, the lead times for the various metal sub processes must be considered. Rogers et al. (1997) discuss the types of favorable and undesirable tasks in MPS, including the unfavorable cycle times for casting. On the other hand, they consider the versatility of CAD, CAM, and CNC machining. Additive manufacturing (AM), such as printing, is known for being a basic process that easily yields a variety of products (Davies et al., 2022). Additionally, machines used in AM can easily and quickly be adjusted for different product configurations and specifications (Kumar et al., 2021). This sort of flexibility in a machine is exactly what is needed for modular machines and modular cells.

2.3.3 Modular System Examples

One example of a successful modular design comes from the agricultural industry. Agro, Amplified Ag, and Freight Farms, Inc. are just some companies that have implemented a modular design in their crop production system. These systems make use of crates and freight shipping containers, where each crate is its own module. Within each module is one or two machines, conveyor belts, and storage facilities. The containers may also include a carousel system mounted for rotation about a central vertical axis within mountable growth towers. Being modular in design, farmers are able to save significantly on soil, water, and fertilizer, increase their crop yield, and have more control over the entire harvesting process (Friedman, 2021).

Similarly, Mitsubishi has recently developed a modular gas turbine package called *FT8 Mobilepac (*™*).* This turbine generates power within two days of arriving at the site. It requires very little site preparation and is transportable by land, sea, or air. It does not require a concrete foundation, notably reducing the time and costs required to complete installation. The turbine outputs a dual frequency of 60 Hz/50 Hz: 31 MW/29 MW, utilizes a fuel mix of gas and oil, an air-cooling system, and can be arranged in in-line or parallel configurations. The entire module only takes up an area just over 400 feet (Mitsubishi Power, n.d.).

2.4 Process Metrics

Another way to look into the steel supply chain is through key performance indicators (KPIs). KPIs help determine the changes needed to increase steel production efficiency and create new opportunities for advancement economically. Metrics that we plan to analyze, as will be discussed in the next sections, include labor, material, and energy costs, sell-through, and emissions. Development costs include evaluations of the initial setup of a steel production system, such as costs related to equipment, capital, and government regulations. Labor costs include changes in wages, training, efficiency, and predictions of future advancement. Material costs include the required materials for machinery such as 3D Printing or the level of quality desired for products. Energy costs come from the different sources of available energy and the kilowatt per hour usage of the machinery. Sell-through utilizes sales on inventory and the amount received from manufacturing for efficiency evaluation.

2.4.1 Economics for ROI and Margins

By looking at the economics of steel production processes, we determined that the criterion for analysis is centered on the impact of return on investment (ROI) and marginal data. Several metrics, such as initial investment for equipment and labor wages, affect the return on investment of steel supply chains. Concerning 3D Metal printing, the initial investment in equipment is higher than in other processes, such as forging, in addition to the time dedicated to labor training and acquiring software to design the products requested. With the training, the flexibility of the 3D metal printing process allows manufacturers to print products as needed and adjust capacity. Furthermore, the increase in the utilization of the use of 3D metal printing creates an opportunity to lower long-term costs (Ultimaker Bv, 2019).

In the case of evaluating marginal data, small changes can affect economic analysis immensely (Nipan, n.d.). The change in utilization affects the marginal efficiency of capital through possible changes related to ROI, manufacturing processes, and energy costs. As the product's demand changes, the utilization of the machinery will increase to full capacity. This will also increase energy costs and suggest managers invest in purchasing additional machinery and capital expansion. On the other hand, a decrease in demand will generate wasted energy and present opportunity costs. The use of marginal capital efficiency improves the decision-maker's ability to develop a thorough cost analysis. Marginal costs aid in the development of analysis concerning demand forecasting growth and efficiency. As demand changes occur, marginal costs can be used to evaluate the operations and determine the cost per unit. Additionally, sensitivity analysis can be performed to make improvements in the manufacturing process and pricing strategy.

2.4.2 Impacts on Economic Cycles

All the aforementioned metrics are interrelated and frame an outline for our economic analysis. Our economic analysis focuses on the effects of changes in supply and demand and technological substitution to understand the changes that a modular steel system will bring.

This impact is evaluated through the economic analysis of marginal data. In current steel supply chains, bottlenecks occurring due to equipment and labor constraints prevent production systems from keeping up with demand (*Using Additive Manufacturing*, n.d.). The current systems look to possibly incorporate additive manufacturing to decrease the gap in supply and demand. In terms of production, the supply can be affected by changes related to the capacity of the equipment, wages, materials, and purchase price per product (Fernando, 2021).

Product demand depends on consumer needs as well as options offered in competitive markets. With the push toward additive manufacturing, steel manufacturers have a greater opportunity to meet demand. Consumer opportunities for variation of products, batch size, and lead time create a larger consumer base (*Using Additive Manufacturing*, n.d.).

Technological changes in steel production can also affect the steel supply chain. Using 3D Metal printing versus other processes creates cost competition and variation in material usage. Upon analyzing the economic challenges of 3D printing, there are typically issues regarding the lack of quality standards, design security, and inventory management (DebRoy et al., 2019). The long-term production costs of 3D printing are presented to be less than processes like forging and casting due to the flexibility in product creation and material requirements. Changes in technology can potentially create large economic impacts in the form of production and sales forecasting.

3.0 Methods

To accomplish our project goal, our team derived the following three objectives:

Objective 1 (O1): Explore what a modular production system could look like in a defined scenario and set of assumptions, using prophetic data to help illustrate a model of a MPS in a steel industry.
Objective 2 (O2): Determine the economic feasibility of implementing a steel-producing MPS on the basis of a positive net profit margin and ROI.
Objective 3 (O3): Identify risks, categorize and minimize potential points of failure in MPS and their potential impacts on the optimal supply chain.

Method 1: Modular Production System Design (supports O1)
Method 2: MPS Implementation (supports O1, O2)
Method 3: MPS Analysis (supports O2 and O3)

- Profit and Loss (O2)
- Monte-Carlo Simulation (O2, O3)
- Linear Programming Model (O2, O3)
- Decision Tree (O3)
- Risks (O3)

3.1 Modular Production System Design

To better understand a modular production system for steel manufacturing, we designed a case study for a system and used the collected and prophetic data to analyze the system.

While there are different ways of designing and approaching the development of a MPS, some concepts stay the same. Currently, manufacturing struggles with resource efficiency, global markets, agile markets, and investment risk.

- Resources, especially metals, are limited, and their processes require significant energy, which is not sustainable and puts a strain on the systems.
- Globalization is part of the increasing demand for market variety and specialization as well as shorter lead/cycle times.
- The current infrastructure for product development and manufacturing processes is still based on fixed capacity and cannot adapt and react to the quick-changing market demands.

- The risk of failure in process development is high because economic and development decisions must be made very early in the product development stages. Production processes are not scalable and cannot change product properties very quickly, which greatly impacts the success of that product.

As a result of these production challenges, the MPS aims to address them through the following principles or concepts:

- Design for manufacturing (DFM) - increases product design time but generally lowers production investment costs and reduces design-to-market time.
- “Eliminate islands of automation” by decreasing product-specialized machines and increasing machine versatility and reuse (Rogers et al., 1997).
- Local, decentralized production and supply chains - local sourcing allows for shorter lead times, shorter distribution times/distances, economic efficiency, and possible off-grid energy sources (Becker et al., 2021).
- Process mobility - smaller, mobile production processes mean lower investment risks and more flexible responses to demand and product changes in market
- Standardized cellular manufacturing system (CMS) - standardized cell designs allow for a stable and predictable process. Different styles of cell designs can benefit different types of manufacturing.

Despite common principles and motives, our team later learned there are different types of MPS, and each type has its benefits and drawbacks. Two of the main types of MPS are transformable production (TP) and hyperconnected mobile modular production (HMMP). Transformable production is a modular production system based on ISO containers, emphasizing the system's mobility. These systems have low to no cost associated with space rental and low operation costs but higher distribution, relocation, and infrastructure costs. TP is most common in the agriculture industry, as mentioned in Section 2.3.3. On the other hand, HMMP has high space rental and purchasing costs but low distribution costs, distribution distances, and no infrastructure costs. Table 6 indicates some of the key attributes associated with both design types (Fergani et al., 2022; Becker et al., 2020). Modular production systems may also vary in their production network regarding singular or parallel production, automated or labor-managed, and central or local sourcing.

Table 6 – Types of modular production.

Transformable Production (TP)	**Hyperconnected Mobile Modular Production (HMMP)**
Summary ● Products produced in autonomous reconfigurable units ● Best suited for small production ● Significant adaptability, agility, and flexibility potential ● Flexible mobility from site to site	Summary ● Allows manufacturers to increase capacity as necessary relative to demand ● Involves a series of facilities (warehouse and production areas) ● Decentralizes production over TP
Infrastructure ● High investment, low operation Equipment Costs ● No cost of storage ● High relocation costs ● Low localization costs ● Medium cost of purchase Product Costs ● Medium production costs ● Medium to high distribution costs	Infrastructure ● Not applicable Equipment Costs ● Medium cost of storage ● Low relocation costs ● High localization costs (rental space) ● High cost of purchase Product Costs ● Medium production costs ● Low distribution costs

For the MPS design case study, we chose to follow a design closer to the hyperconnected mobile modular production since most of the steel and metal processing machines are large and emit significant heat. This feature is not ideal for fitting within the standard 8’ by 8’ by 20’ to 40’ ISO container.

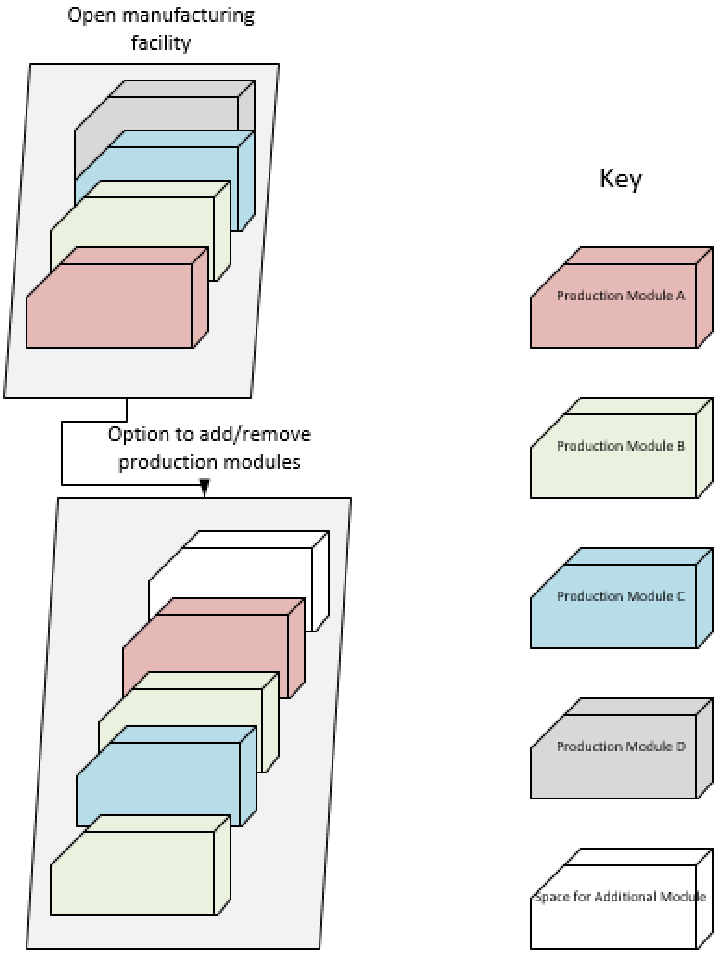


Figure 10 – An illustration displaying the interchangeability of module cells between warehouse storage units in an open warehouse (Fergani et al., 2020).

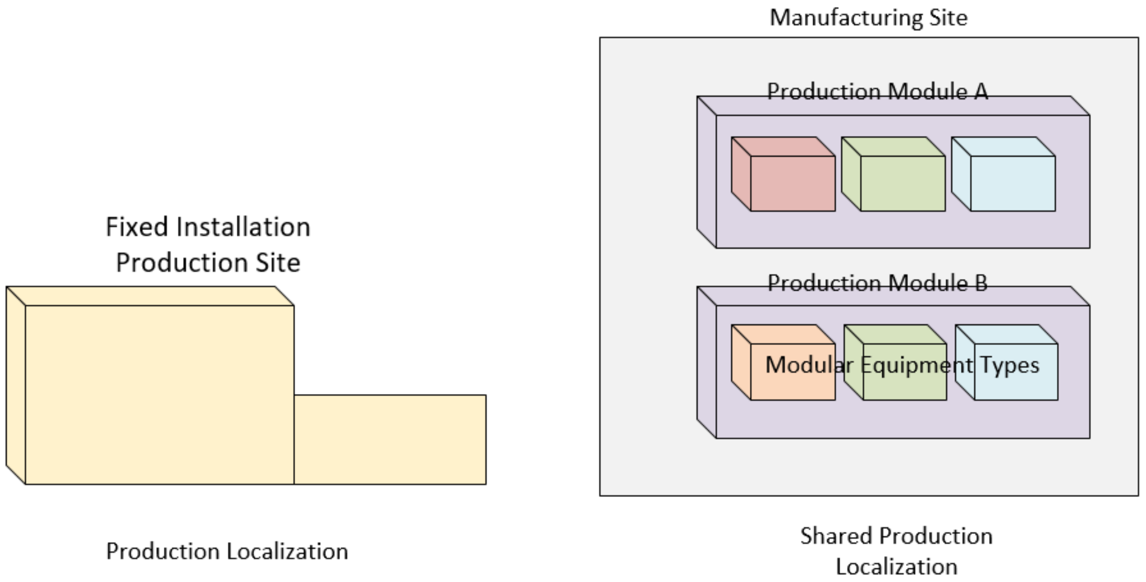


Figure 11 – Basic infrastructure associated with the TP (left) and HMMP type (right). HMMP incorporates new equipment and technology and can connect or move additional modules as needed (Fergani et al., 2022).

We decided to focus on the following principles when designing our MPS:

- Versatile machine set
- Product set will be designed for manufacture (DFM).
- Identical cells for interchangeability
- Production flexibility for market changes and demand
- Minimizing risks (market, product, energy, initial investments)

We derived the following steps for designing our MPS:

1. Derive list of modularization drivers
2. List system and scenario assumptions (product set)
3. Come up with a set of machines
4. Design a cellular layout (order and manufacturing practices, not spatial facility layout)
5. Create process maps

3.1.1 Modularization Drivers

To have a sustainable and consistent MPS, the system's design must follow and prioritize a certain set of factors and attributes, which are generally referred to as modularization drivers. Most processes will have their own unique set of modularization drivers. According to (Bonvoisin et al., 2016), a set of modularization drivers is a set of strategic objectives–or goal expectations a company has for a product or process that are connected to each other in a sort of hierarchy–

in a case where modularization can advance the main objective. The set of preliminary modularization drivers is shown in Table 7 below. Using this set of drivers, we will construct the MPS design and analyze it before determining its importance relative to the other drivers.

Table 7 – Preliminary modularization drivers for an MPS in the steel industry.

Operation cost	Utilization	Sell through rate
Material cost	Separate testing	Education for assembly
Labor cost Set up / installation time	Lead time	Dependency on energy
Product changeover/ flexibility in production / changes in product	Global supply of product / product availability and reliability	Selling price (supply vs. demand)
Time to market	Type of product distribution process	Market variance
Technology Change	Market size	Different specification / variance
Maintenance and repair	Environmental emissions	

3.1.2 System Assumptions

As with any case study or model, assumptions must be made. Since modular steel production in the steel industry is not yet well established, we had to create a set of assumptions and scenario parameters to approach the modular design. Due to the flexible nature of an MPS, these systems tend to thrive in medium-low demand markets for semi-specialized products (Bieringer et al., 2013). In the case study we explored, we determined a set of assumptions about the entire process, the facility, the hyperconnected mobile modular production system, as well as the product set and their corresponding market assumptions. These can be seen in Table 8.

Table 8 – Assumptions about our steel-producing MPS.

1. The factory, not including the machinery or equipment, will not use more than 5.5 kWh of energy per hour.
2. The factory will operate 16 hours a day, 7 days a week.

3. A constant energy supply will be powered by the grid or a reliable renewable energy source. In all likelihood, this might not necessarily be accurate.
4. Each module fits the designed cells. They fit inside shipping containers with average widths of under 9 feet.
5. Cells can be adjusted as necessary, although there is a cost associated with adding or removing them.
6. Demand is expressed as total steel required, but it is separated into production ratios per product type.
7. Each product is manufactured in its own respective cell type.
8. Machines and equipment will be financed or leased instead of purchased in quarter 1.
9. Total production and equipment costs will increase by a variable percentage each period or quarter.
10. Raw materials are purchased as needed, though we are not considering the cost of importing materials.
11. The cost of business is stagnant between quarters.
12. There will be a constant demand growth for each product in the regular P&L. In the linear programming and Monte-Carlo simulations, the growth rate will change depending on outside economic factors. The production ratios and selling prices will also adjust.
13. There is a learning curve associated with each product. We suspect the number of defective units will decrease once production for a product type begins.
14. Each product is designed for manufacture.
15. Handling time is ignored since it does not add value to the product.
16. Machines are financed by a constant rate per quarter. In real-world applications, they likely need to make a down payment or initial investment with quarterly payments.

3.1.3 Machine Set

One objective when determining the set of machines for the MPS was to find a balance between the desirable functionality types and options each machine offers. We plan to minimize the number of different machine types since one of the key MPS principles is machine versatility and reuse. To help us determine the machine set for our cells, we developed a list of machine attributes to consider, as shown in Table 9. We used these criteria to compare our machine lists to help us narrow down the set. Note that these attributes are listed in no order or relevance.

Table 9 – Machine attributes and drivers.

Cost	Prerequisites	Functionalities	Material inputs
Labor (per machine)	Labor (per day)	Labor education	Set up time
Maintenance failure rate	Maintenance costs	Product cycle times	Production scrap efficiency
Quality specifications	Size, mobility	Energy consumption	

3.1.4 Cellular Layout

There are many cellular layout styles, each of which benefits different types of manufacturing. For example, in job shop (process layout) manufacturing (Figure 13), products are moved from one machine/task area to the next, so the cells are made up of fixed non-moving machines (Süer et al., 2010). On the other hand, in flow shop (product layout) manufacturing (Figure 12), the product is fixed, and the machines are brought to the products to be worked on in sequential, linear moving cells. As previously stated, there are different advantages for various types of cell layouts depending on the manufacturing style. We focused on creating an identical cell that we could replicate and multiply for multiple reasons. For example, if a machine breaks in one of the five or six cells in a facility, the other four or five cells remain unaffected. On the other hand, if market demand suddenly increases an unexpected amount, production in some cells can be adjusted accordingly to match the product’s increased demand and better satisfy demand, thus providing more economic benefits.

Once we determined the machine set and the cell layouts, based on our product assumptions, we created process maps for each product. Process maps greatly illustrate the tasks and sequence of tasks required in producing a product. They also help demonstrate how products move throughout a cell and facility throughout its product life cycle.

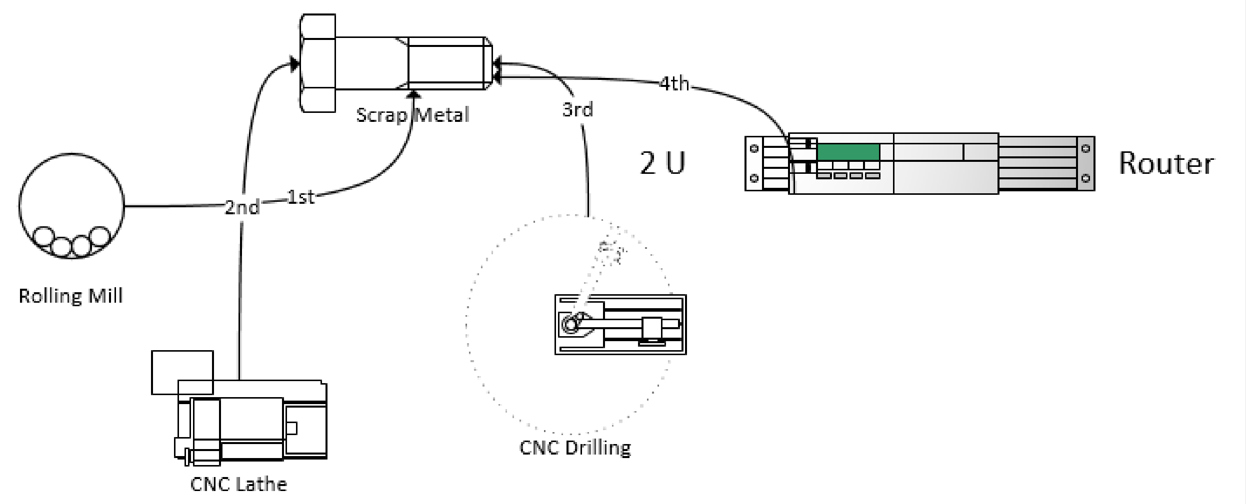


Figure 12 – Example of how a flow shop (product layout) would operate. The portable rolling machine would be brought to a collection of scrap metal first (located in a fixed area of the shop), followed by the lathe, drill and router.

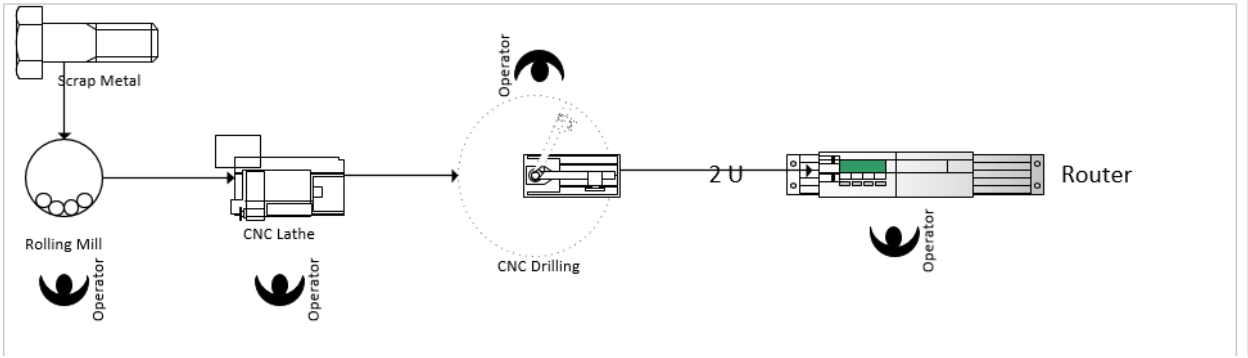
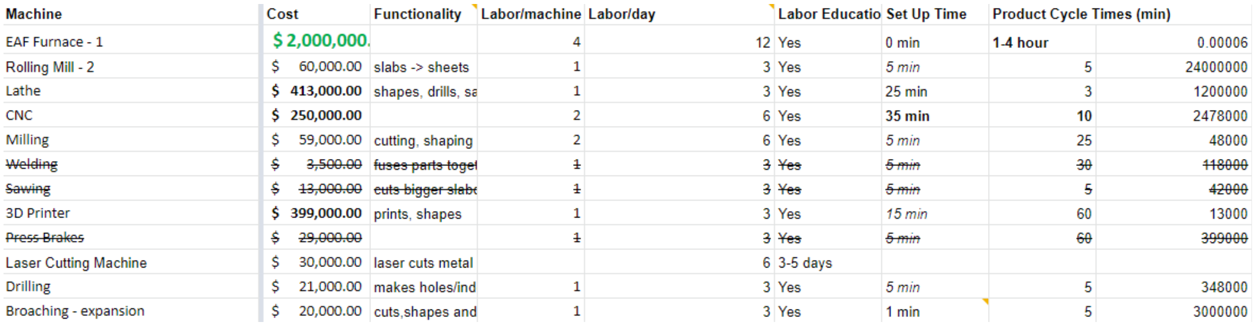


Figure 13 – Example of a job shop (process layout) where each worker performs assigned tasks and the product flows from one machine to another.

3.2 Modular Production System Implementation

Using our design method detailed above, we developed a set of steps that would help us build a modular concept system. Our first step was to determine which products could be a good fit for the system we were developing. We considered many industries that produce specialized steel products that cannot be mass-produced. For example, we considered parts from the automotive, medical and construction industries, such as electric parking brake brackets, medical scissors, tooling, metal roofing and cladding. Products such as these are small enough to be manufactured efficiently through a modular system, including printing, machining, and refining applications. We believe these products are suitable for a modular production system because there is a lack of significant constant demand. By definition of being a modular production system, we desire the ability to change over or pivot from one product to another. This advantage allows us to start producing new and temporarily high-demand products that consumers need to obtain quickly. We studied the products' current manufacturing process, including manufacturing types, machines and process times. We then developed a list of theoretical products (see Figure 15) with similar characteristics. We estimated the amount of time and order of machines each part would go through under a modular format.

Next, we constructed a set of machines (see Figure 14) that would be required to manufacture these hypothetical products. We determined the set of machines based on machines that were common in traditional or additive steel manufacturing, such as CNC lathes, milling machines, printers, drills, routers and laser cutters. Information such as electricity and energy requirements, purchase price, throughput time, manufacturer, and machine functions were recorded in a spreadsheet, as part of our profit and loss models. We also considered other required processes, such as using a furnace or heating process to melt powder and raw material to create pig iron, rolling to compress the steel, and handling and storage systems to allow the product to cool and wait before moving on to the next process. We then created a sample process map to detail better the production process and its requirements of how each module could be used most effectively. The crossed cells suggest machine types we dropped since their functionalities were too similar to others on the list.



Machine	Cost	Functionality	Labor/machine	Labor/day	Labor Educatio	Set Up Time	Product Cycle Times (min)	
EAF Furnace - 1	$ 2,000,000.		4	12	Yes	0 min	**1-4 hour**	0.00006
Rolling Mill - 2	$ 60,000.00	slabs -> sheets	1	3	Yes	*5 min*	5	24000000
Lathe	**$ 413,000.00**	shapes, drills, sa	1	3	Yes	25 min	3	1200000
CNC	**$ 250,000.00**		2	6	Yes	**35 min**	**10**	2478000
Milling	$ 59,000.00	cutting, shaping	2	6	Yes	*5 min*	25	48000
~~Welding~~	~~$ 3,500.00~~	~~fuses parts toget~~	~~1~~	~~3~~	~~Yes~~	~~*5 min*~~	~~30~~	~~118000~~
~~Sawing~~	~~$ 13,000.00~~	~~cuts bigger slab~~	~~1~~	~~3~~	~~Yes~~	~~*5 min*~~	~~5~~	~~42000~~
3D Printer	**$ 399,000.00**	prints, shapes	1	3	Yes	*15 min*	60	13000
~~Press Brakes~~	~~$ 29,000.00~~		~~1~~	~~3~~	~~Yes~~	~~*5 min*~~	~~60~~	~~399000~~
Laser Cutting Machine	$ 30,000.00	laser cuts metal		6	3-5 days			
Drilling	$ 21,000.00	makes holes/ind	1	3	Yes	*5 min*	5	348000
Broaching - expansion	$ 20,000.00	cuts,shapes and	1	3	Yes	1 min	5	3000000

Figure 14 – Sample machine list.

3.2.1 Process Map

To create the process map, we shortlisted a small group of machines from our initial selection. We then assigned every product a different process based on our research of real products. Each product would be worked on at various machines and have a different process time from each other. Some products might also be processed on the same machine multiple times during the process. We also factored in the cooling and waiting time for each product. Bottlenecks were ignored because our team was not considering batch sizes or individual defect rates, at least in this stage of design. We view these processes from a very high-level perspective, and the details are irrelevant in our scenario. As shown in Figure 15, we considered 6 different products in this production system.

3.2.2 Cell Layout

One of our goals was to make sure that the modular production system was as efficient as possible, considering the greatest strength lies in possessing the ability to pivot between products and adjust the capacity as we expect changes in demand. Developing cells is advantageous since it allows machines to be grouped together to allow for a more efficient process flow and to avoid potential bottlenecking or any other forms of waste when it comes to lean manufacturing. These wastes include defects, excess processing, overproduction, waiting, inventory, transportation, motion, and non-utilized talent. The design and cell system speed will complement these strengths. A cell can be focused on the production of one product type, so different cells will involve different products. The only required step is to simply disable the cell to stop the production of a product type. To change the type of production, as will be discussed in greater detail later in this report, changes to the machines need to be made prior to production. To increase the capacity of producing a product type, additional cells will need to be installed or converted since it is difficult to increase machine productivity. Figure 15 shows the product types and necessary machines. Figure 16 displays the layout if all the cells were connected.

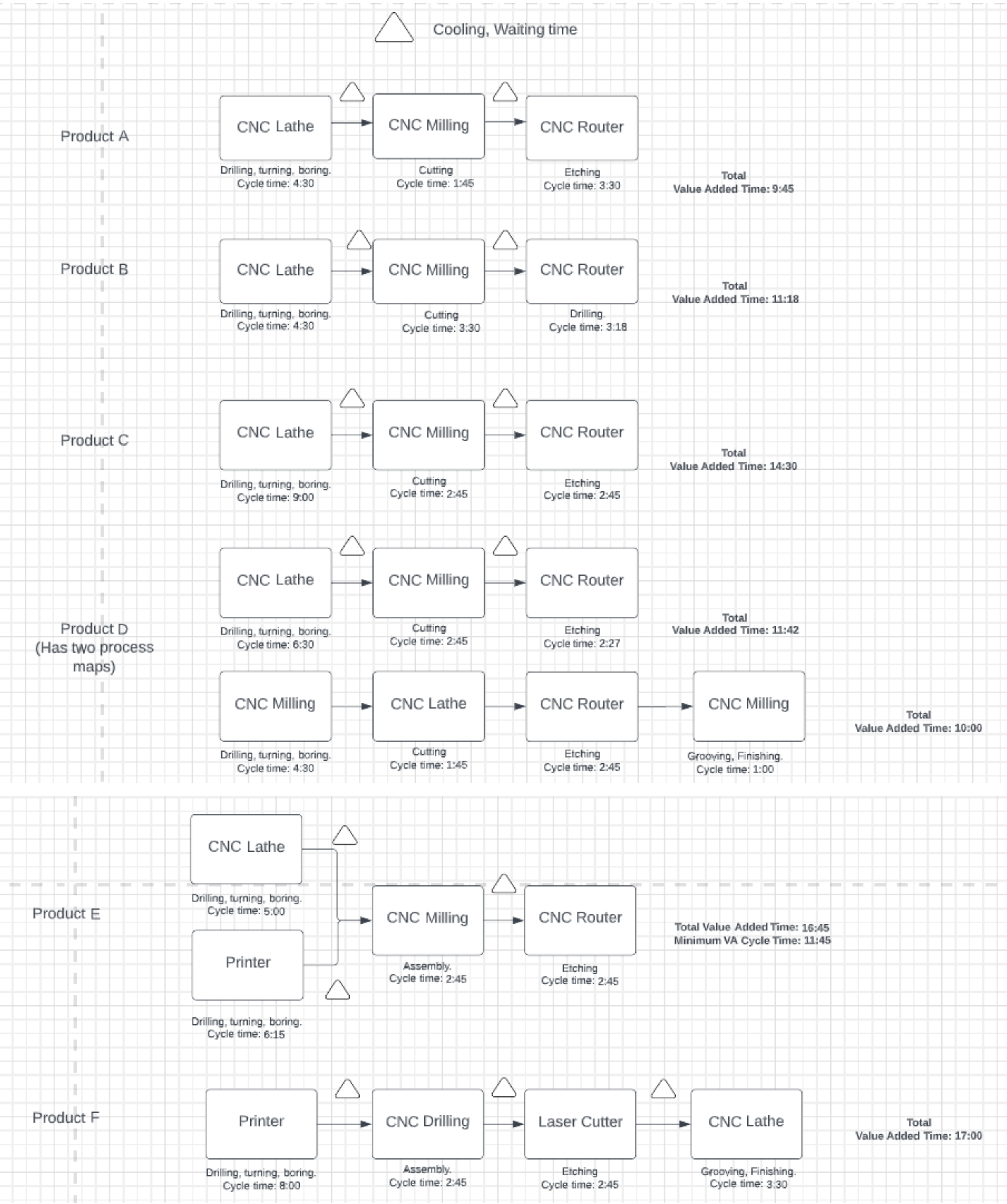


Figure 15 – Screenshots of sample product process flow charts.

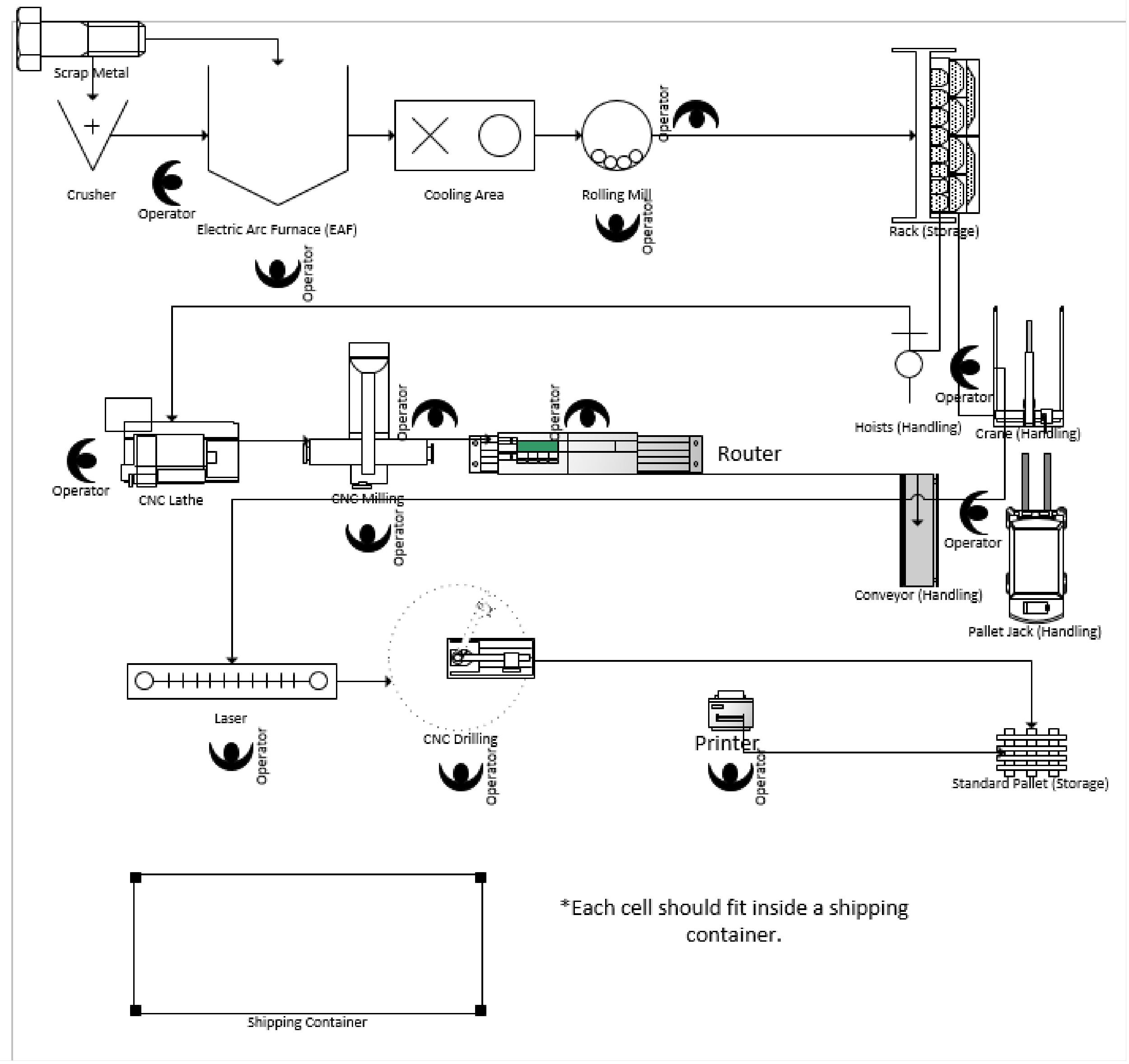


Figure 16 – Cell layout.

Below are other advantages to using a cell, some of which consider principles of lean manufacturing and waste. The formal process map is shown in Figure 17.

- Having cells can lead to shorter lead times as there is less transportation inside the factory. Every machine required for the process is in the same location.
- There is less inventory wastage as the amount of production is based directly on demand and the amount produced will always be equal to or less than the demand
- There is less motion of workers in the system due to the entire process being completed in the cell

- The cell promotes better communication between the workers and fosters an environment where teamwork is appreciated (Rellick et al., 1971)

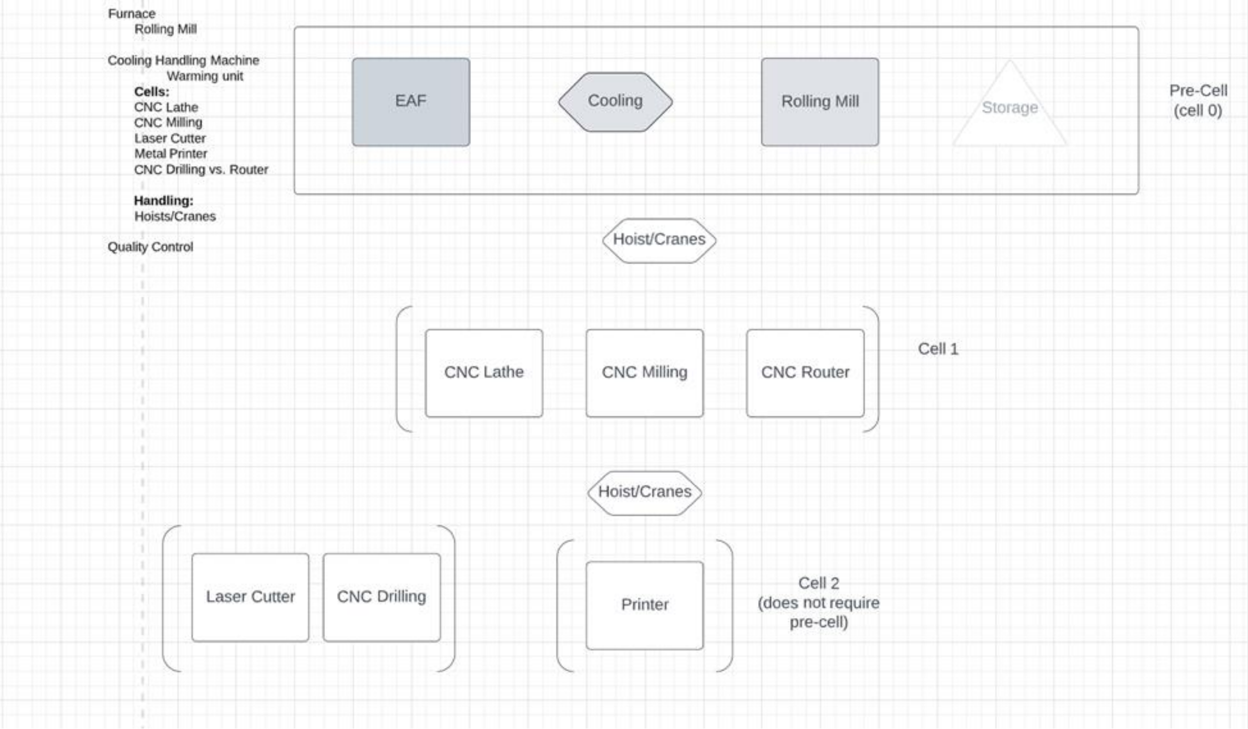


Figure 17 – Process map (developed by our team) that indicates possible cell group based on machine characteristics.

3.2.3 Process Failure Mode and Effect Analysis

Most steel manufacturers do not aim to produce products 24 hours a day, 7 days a week. Manufacturers don't operate in this manner due to insufficient demand, and their processes are designed to accommodate machine downtime for upgrades, maintenance, and free usage. While revenue is generated from selling goods, significant overhead and breakdown repair often limit total profit. Hence, this is why companies aim to reduce machine and other process failures or defects, in addition to striving for high customer satisfaction. This is where Process Failure Mode and Effect Analysis (PFMEA) comes in. The PFMEA can be used to identify potential problems in the process prior to implementing a new design and to give some potential solutions to fix the current issue. This analysis should be conducted in scenarios that involve producing new technology or equipment, changing process location, or modifying an existing process in any way. The ultimate goal of this analysis is to result in fewer breakdowns and a higher utilization rate for the machines. While the process we are designing does not currently exist, we have created a mock PFMEA chart to demonstrate how failure modes could be detected, why they might occur, and how they could be overcome. This analysis could be more beneficial once a modular steel production system is finalized and integrated, but is something that should be considered nonetheless. The mock PFMEA is shown in Table 10.

3.3 MPS Analysis

We analyzed the hypothetical modular production system we designed to gain insight on what could have been done differently, the MPS economic success, and the risks and benefits of the MPS as well as characteristics and trends we may be able to generalize for all MPS for steel. Analyzing these topics and speculating a precedent for MPS analytics in terms of economic feasibility required analyzing the process from multiple angles.

First, in Section 3.3.1, we target the profit margins and ROI over a four-year production period through a profit and loss analysis. Then, building on top of the P&L, we account for uncertainty and prophetic data through a Monte Carlo Simulation of the P&L (Section 3.3.2). In this simulation, we look closer at the probabilities of economic success, defined by the break-even point, cash flows, and annual ROI. We also use growth rates of the profit margin for a deeper analysis. Next, we consider the potential impact of a recession. Many starting businesses struggle to earn a return on their investment in a timely manner. Because recessions result in less consumer spending, businesses expect to generate lower profits, therefore lengthening the time required to achieve a net positive ROI. To explore the capabilities and benefits of a modular production system, in Section 3.3.3, we construct a linear program to optimize production ratios and cell switching between products in order to maximize profits, and minimize labor or capital–depending on the shortcomings during a recession similar to the recession of 2008. Finally, we consider the risks of an MPS through a decision tree from the perspective of discrete probabilities (Section 3.3.4), and we discuss the potential risks of these systems (Section 3.3.5).

Table 10 – An example of what a completed PFMEA would look like in our modular production system design.

Item #	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/Mechanisms of Failure	Occur	Current Process Controls Prevention	Current Process Controls Detection	Detect	RPN	Recommended Action(s)	Responsibility and Target Completion Date
1	Remove slag through the furnace door	Failure to completely remove slag	Low quality of steel produced, reduces malleability and ductility	8	Operator error	1	Process, training	Verification	3	24	Retrain workers to properly remove slag and explain consequences if not	6/1/2023
2	Cooling of molten steel	The cooling system does not cool to desired temp	Deformed parts, steel must be reheated or corrected before continuing process	6	Defective equipment, operator error	2	Process, Training, Frequent maintenance	Verification	9	108	Contact cooling systems service company to acquire new equipment, implement better insulation from external environment	6/15/2023
3	Rolling Metal into desired dimensions	non-uniform hardness, excessive residual stress,	improper cooling system, unreasonable design of rolls and the roll grooves, excessive single pass deformation, deep fire cracks, fatigue and spalling	5	Defective machine, machine life span ended, problem with material in previous processes	3	Process,, maintenance	Verification	6		Contact Manufacturer, Conduct regular testing and maintenance	6/17/2023
4	Rolling Metal into desired dimensions	Damaged part	Non-conforming part, cannot continue process	3	Machine misaligned, no proper handling system	4	Bucket that collects part	Scanner	2	24	Lock storage systems in place	6/22/2023
5	Rolling Metal into desired dimensions	Broken lathe machine	Parts unable to be shaped properly	5	Not enough/ poor electricity connection	1	Quality checks	Verification	3	15	Temporarily move product to another cell with working lathe	7/1/2023
6	Rolling Metal into desired dimensions	Not enough electricity to power all modules	Inability to produce finished parts	10	Renewable energy source	3	None	Verification	1	10	Implement alternative power methods or sources	1/1/2024

3.3.1 Profit and Loss

3.3.1.1 P&L Analysis

The first step to determine if a modular steel production system is feasible is to conduct an economic analysis. A significant advantage of developing such a system that compacts the resource-to-product processes is that they can achieve positive cash flow operations more quickly compared to their traditional-style counterparts. Developing an economic model allows us to determine if, in fact, it is worth building such a system and to predict at what period it should become profitable. While such projects are initially very expensive, the first four years are important in determining whether the investor can expect to earn a significant return or even cover their investment. Therefore, we can say that the main economic drivers or key performance indicators used to determine the profitability of such projects are the return on investment and the total profit margin.

The primary method that utilizes such indicators is to develop a profit and loss analysis. This financial statement typically separates the operating revenues and expenses from the nonoperating revenues and expenses. It includes a profit margin or net income for a described period. Return on investment is calculated by dividing the net income by the total cost of the investment. These calculations are typically straightforward for the investor to calculate for a period (either by-hand or through spreadsheet software) when previous or current demand and sales data is available. However, when such data is unavailable, making estimates for one period may not indicate how profitable a business or company is performing. As is the case in this project, developing a P&L that considers multiple periods is needed, especially as a start-up where capital and assets must be initially invested. Given the nature of modular production systems, we should expect profitability to change from month to month, so looking at a multi-period P&L is essential.

To improve our understanding of how to construct a P&L for a modular system, we referred to our sponsor, who previously created such a model, but for forged cast glass. The profit and loss statement was broken into different sections: overall financial performance, products, systems, handling, materials, transportation, and staff. The overall financial performance consisted of periodical determinations of units sold, revenue, cost of equipment, cost of goods, gross margin, cost of business, profit margin, and cash flow. This table utilized the data referenced in the products and other tables and would reflect any changes made in the spreadsheet.

Furthermore, each product type was listed as a percentage of total demand in the product table. Each product has its own price, thickness, start number, and an associated growth rate between periods. Product revenue was calculated by taking the product quantity produced and multiplying it by the price. Each successive periodical revenue was calculated by multiplying the previous period's revenue by the expected increase or growth rate.

Similarly, the other tables include systems, handling, materials, transportation, and staff costs. Each system type was associated with a different description (such as furnace, forge, quench), the expected price for purchasing and installing such a system, and a finance ratio. The finance ratio indicates that the investor prefers to finance or lease each system, since it is very expensive to own. Furthermore, since modular systems are designed to be built up or taken down as demand requires, it saves the investor from spending a fortune. The periodical cost was calculated by taking the system price and multiplying by this ratio. Like the product table, each successive period's expenses were calculated by taking the previous period's expenses and multiplying by the growth rate.

One advantage to the profit and loss analysis created by our team is that it was built using a spreadsheet model. Therefore, as actual costs are realized or change, the spreadsheet can be updated and will indicate the updated profitability in live time. Our team recognizes the benefit of including a screenshot of the entire P&L in this report, however, due to the size of the spreadsheet and limited space in this document, our team opted to include screenshots as we explore each table in more detail. We recommend the reader read Appendix E to view a summary of all the table types before reading section 3.3.1.2. This reference material may prove beneficial in following the next few sections.

3.3.1.2 Table Analysis

To recap, the machine and product drivers were used to select the machine and product set to be incorporated into our design. The data values associated with these sets were then used to find our profit margins and return on investment. Our initial approach to the profit and loss analysis was to gather daily production data from current steel production systems to develop accurate estimates of the capacity and utilization of the machines and products used for production. The daily data would also show the energy and demand fluctuations from different companies to predict data to be accurate representations of the demand in the current supply chain. After reaching out to steel production companies and failing to receive adequate data about processes in steel manufacturing over an hour, day, or weeks, we had to resort to other sources. We were able to find sample data on traditional steel production processes from Cleveland-Cliffs and the American Iron and Steel Institute, through company reports (*United States Steel Profit*). We were able to find sample data online based on traditional steel production for variables including the number of machines needed, energy usage, predicted demand and material cost. We also derived mock data from machine statistics on company websites, where we estimated machine capacity, product, demand, and utilization. Product production assumptions were derived from research and listed as a separate sheet in our P&L analysis.

The first phase of the construction of the P&L was to develop a list of costs and revenues that could model the quarterly costs of cells, machines, production of products, and process economic resilience. The cell's and machine's cost analysis utilized selected variables from the list of machine drivers. The product production cost analysis incorporates the process cycle time and machine operating costs.

To determine the profit margin, we developed interrelated tables that incorporated information such as facility, product, materials composition and costs. This information was then organized into quarterly production costs, quarterly machine financing costs, quarterly transportation costs and quarterly sales and revenue. Each table in the P&L analysis focuses on one aspect to determine the chosen machines' economic feasibility and outline the production process of each product produced in the system. The list of the equations for the tables and their relations can be seen in Appendix E. The rest of Section 3.3.1.2 will be dedicated to examining the contents of each table, and their connections to the other tables. Figure 18 presents the flow of information and dependencies between the tables.

The facility assumptions and constants table (P&L Table A) estimated the costs of running the MPS facility. It includes information such as price of rent, the facility cost per kWh, the number of workday hours, the number of workers, and the material costs to produce each product. P&L Table B shows the estimated area requirements for a facility, where the product module or cell requirements are broken into their total squared area. It evaluates the square footage needed to house the products for inventory and all of the machine's floor space needs. P&L Table C combines the information from both of these tables, suggesting a quarterly amount the owner or company producing steel in a MPS would need to pay. These three tables are shown below.

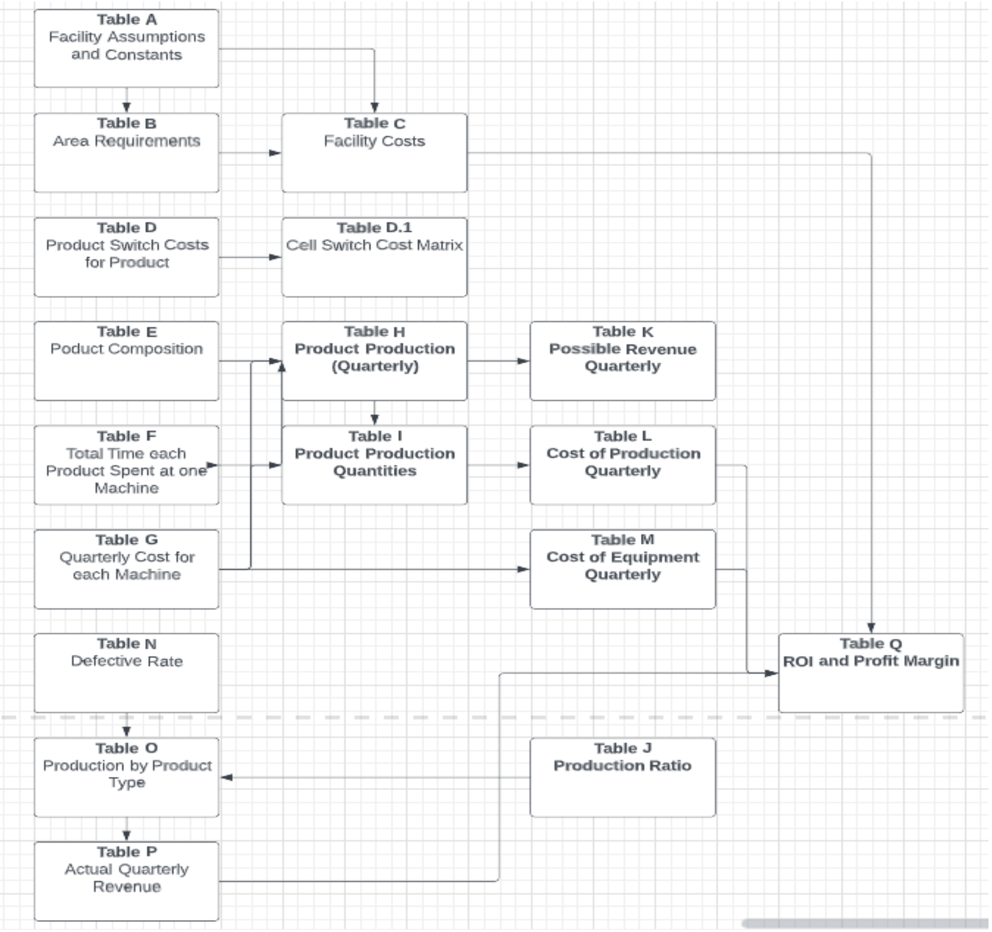


Figure 18 – Diagram of the tables and their relationships in the P&L.

P&L Table A – Facility costs including the variables that create the quarterly cost for the facility to function.

Facility	Labor	Metals Cost ($ per lb)
Rent price (annually per sq ft)	Workers per shift	Iron Ore
6.89	28	0.042
Facility kWh Cost ($ per sq ft per quarter)	Workdays Annually	Coal
5.5	340	0.005
kWh Rate	Hours per Workday	Scrap Steel
0.12	16	0.04
kWh required	Hours of Operation (Quarterly)	Other
216	1360	0.05

Annual growth rate	Quarterly work hours	
0.030	38080	

P&L Table B – Area requirements includes the area/size of each product in square feet and the necessary space of each machine that sums to the Total Area.

Product Module	Width (ft)	Length (ft)	Area (sq ft)
A	8.5	30	255
B	8.5	45	382.5
C	8.5	35	297.5
D1	8.5	30	255
D2	8.5	30	255
E	8.5	40	340
F	8.5	25	212.5
Extra Space (handling/storage/equipment)			898.875
EAF			300
Rolling			400
		Total Area (sq ft)	**3,596.375**

P&L Table C – Facility costs table that determines the facilities expenses each quarter.

Facility sq ft	Rent (quarterly)	electricity cost (quarterly)	overhead cost (quarterly)	**sum of costs (quarterly)**
3,596.375	$6,194.76	$2,373.61	$1,200.00	**$9,768.36**

The product switch cost table (P&L Table D) outlines the setup and disassembly costs of the cells. The estimated setup cost includes the cost of labor and installation for all the machines in the cells. In the development of the switch costs, we wanted to account for the potential changes in demand for products changes in the future. For example, if product demand were to decrease to a level that production has become unprofitable, removal/change of a product cell is an option. Therefore, the disassembly cost estimates the cost of removing a cell from the lines of a product.

The cell switch cost matrix (P&L Table D.1) is an extension of Table D depicting the cost from changing between products. The matrix utilizes the cell setup and disassembly cost to develop the total cost of changing the production of products.

P&L Table D – The product switch costs table.

Product	Cell Disassembly Cost	Cell Set-up Cost
A	$1,200.00	$1,400.00
B	$1,350.00	$1,900.00
C	$850.00	$1,000.00
D1	$575.00	$800.00
D2	$750.00	$1,000.00
E	$1,400.00	$2,050.00
F	$1,200.00	$1,000.00

P&L Table D.1 – An extension of Table D. Cell switch cost matrix.

(FROM)	cell set up for product (TO)						
disassembly for product	A	B	C	D1	D2	E	F
A	--	$3,100.00	$2,200.00	$2,000.00	$2,200.00	$3,250.00	$2,200.00
B	$2,750.00	--	$2,350.00	$2,150.00	$2,350.00	$3,400.00	$2,350.00
C	$2,250.00	$2,750.00	--	$1,650.00	$1,850.00	$2,900.00	$1,850.00
D1	$1,975.00	$2,475.00	$1,575.00	--	$1,575.00	$2,625.00	$1,575.00
D2	$2,150.00	$2,650.00	$1,750.00	$1,550.00	--	$2,800.00	$1,750.00
E	$2,800.00	$3,300.00	$2,400.00	$2,200.00	$2,400.00	--	$2,400.00
F	$2,600.00	$3,100.00	$2,200.00	$2,000.00	$2,200.00	$3,250.00	--

The product composition table (P&L Table E) evaluates the materials needed to produce each product. The products chosen are theoretical due to the need for a product set with varying specifications to display the flexibility of the modular production system. The products contain varying levels of iron ore, coal, scrap steel, and other materials to depict different grades of steel produced in the facility. This table outlines the weight per unit and the demand ratio of the products, which presents the levels of production occurring in the facility to match the demand.

P&L Table E – Product composition includes the materials needed to produce each product and the weight. The table also includes the predicted production in the facility to match demand.

Product	Iron Ore	Coal	Scrap Steel	Other	Total Composition	Total Weight (lbs per unit)	Production Ratio
A	0.8	0.2	0	0	1	2	0.4
B	0.75	0.15	0.1	0	1	1.5	0.2
C	0.7	0.15	0.1	0.05	1	0.5	0.1
D1	0.85	0.1	0.05	0	1	1	0.1
D2	0.6	0.1	0.15	0.15	1	0.75	0.05
E	0.9	0	0.1	0	1	0.5	0.1
F	0.8	0.1	0	0.1	1	0.75	0.05

Each product has a different set of refinery and manufacturing requirements (as seen in section 3.2). Therefore, we organized the product times by machine into a table shown in P&L Table F.

P&L Table F – Product-machine times table.

Products	A	B	C	D1	D2	E	F
(Lathe)	4.5	4.5	9	6.5	1.75	5	3.5
(Milling)	1.75	3.5	2.75	2.75	5.5	2.75	
(Router)	3.5	3.3	2.75	2.45	2.75	2.75	
(Laser Cutter)							2.75
(Metal Printer)						6.25	8
(CNC Drilling)							2.75

Total Value Added	9.75	11.30	14.50	11.70	10.00	16.75	17.00

Next, we organized the quarterly costs for each machine (P&L Table G), including the number of machines, electricity usage in kWh, number of laborers, labor costs, energy consumption and maintenance costs per week. The price of each machine, finance coefficient, and expected price increase coefficient were also included to forecast the cost for each machine as demand changes.

P&L Table G – Machine costs.

Machine	# Machines	kWh	Labor (required	Labor costs ($/hour)	Energy Consumption costs ($/hour)	Maintenance costs ($/week)	Total (week)	Price	finance	Expected Price Increase (per quarter)
(Lathe)	4	4	1	$30	$1.92	$20.00	$3,595	$40,000	3%	1%
(Milling)	4	5.5	2	$60	$2.64	$14.00	$7,029	$50,000	3%	1%
(Router)	4	1	1	$30	$0.48	$16.00	$3,429	$35,000	3%	1%
(Laser Cutter)	2	0.5	1	$30	$0.12	$12.00	$3,385	$46,000	3%	1%
(Metal Printer)	2	11	1	$30	$2.64	$36.00	$3,691	$80,000	3%	1%
(CNC Drilling)	2	4.5	1	$30	$1.08	$44.00	$3,524	$28,000	3%	1%
Handling	1	10	2	$60	$1.20	$65.00	$6,919	$30,000	3%	1%
EAF	1	30	2	$60	$3.60	$35.00	$7,158	$500,000	3%	1%
Rolling	1	20	2	$60	$2.40	$25.00	$7,013	$60,000	3%	1%
Sum	16.94	134	28							

We then discussed as a team the costs that go into production. P&L Table H suggests that production costs are a combination of labor, inventory, material, quality, and scrapping costs. It borrows the data from Tables E, F, and G.

P&L Table H – Production costs.

Products	Labour Cost ($/unit)	Inventory Cost ($/unit*$1.75)	Material Cost ($/unit)	Quality Control ($/nondefective unit)	Scrapping costs ($/unit)	Sum of Production cost per unit
A	$5.75	$3.50	$0.069	$0.28	$0.009	$10.57
B	$7.40	$2.63	$0.055	$0.10	$0.007	$11.21
C	$8.63	$0.88	$0.018	$0.05	$0.002	$10.53
D1	$7.23	$1.75	$0.038	$0.09	$0.005	$10.02
D2	$7.75	$1.31	$0.029	$0.18	$0.004	$10.21
E	$9.75	$0.88	$0.021	$0.11	$0.003	$11.83
F	$8.50	$1.31	$0.029	$0.05	$0.004	$10.88

Likewise, P&L Table I displays the product production quantities. It takes the total time at each machine from P&L Table F, the quarterly costs for each machine in P&L Table G, and the production costs in P&L Table H to calculate the number of produced units. It also calculates the cost to produce such units, their selling prices, and expected demand growth for future quarters.

P&L Table I – Product production quantities.

Products	Full Capacity Units Produced (per quarter)	**Units in production (quarterly)**	Quarterly Cost	Selling Price ($/unit)	Demand Growth Rate
A	234338	93735	$990,646.43	$13.21	0.03
B	202195	40439	$453,155.54	$14.01	0.04
C	157572	15757	$165,846.67	$13.16	0.02
D1	195282	19528	$195,655.30	$12.52	0.07
D2	228480	11424	$116,584.87	$12.76	0.01
E	136406	13641	$161,376.07	$14.79	0.04
F	134400	6720	$73,142.54	$13.61	0.03
			Profit markup	25.00%	

Unrelated to the other tables thus far, we created P&L Table J to illustrate how the production ratio could change in future quarters. This table is used as part of the linear programming model and will be explored more later in this report.

P&L Table J – Production ratios.

Quarter	**1**	**2**	**3**	**4**	**…**	**16**
A	0.2	0.2	0.2	0.2	…	0.2
B	0.2	0.2	0.2	0.2	…	0.22
C	0.05	0.05	0.05	0.05	…	0.05
D1	-	-	-	-	…	
D2	0.4	0.4	0.4	0.4	…	0.4
E	0.05	0.05	0.05	0.05	…	0.05
F	0.05	0.05	0.05	0.05	…	0.05
Total	0.95	0.95	0.95	0.95	…	0.97

Next, we have P&L Table K, which calculates the quarterly revenue. It multiplies the number of units produced, per P&L Table I, by the selling price. In subsequent periods, the revenue is multiplied by the demand growth rate.

P&L Table K – Potential quarterly revenue.

Quarter	**1**	**2**	**3**	**4**	**…**	**16**
A	$478,286.01	$508,799.62	$549,600.64	$587,442.45	…	$960,715.37
B	$483,050.26	$503,589.68	$541,151.66	$577,561.00	…	$1,126,668.35
C	$95,144.35	$95,163.13	$99,139.55	$102,832.66	…	$139,179.34
D1	$-	$-	$-	$-	…	$-
D2	$977,326.37	$977,374.91	$1,025,615.83	$1,067,353.30	…	$1,342,458.68
E	$81,804.86	$81,868.63	$89,775.42	$97,290.84	…	$181,642.21

F	$75,336.82	$75,370.07	$81,349.33	$86,908.33	…	$141,872.97
Total	**$2,190,948.67**	**$2,242,166.03**	**$2,386,632.42**	**$2,519,388.57**	**…**	**$3,892,536.92**

The cost of production was organized into a separate table (P&L Table L). The cost of production is calculated by multiplying the sum of production costs in P&L Table H, by the demand ratio from P&L Table J, assuming operations are at full capacity (P&L Table I).

P&L Table L – Production costs.

Products	**1**	**2**	**3**	**4**	**…**	**16**
A	$495,323.21	$510,182.91	$525,488.40	$541,253.05	…	$771,697.43
B	$453,155.54	$471,281.76	$490,133.03	$509,738.35	…	$816,107.52
C	$82,923.33	$84,581.80	$86,273.44	$87,998.91	…	$111,603.89
D1	$-	$-	$-	$-	…	$-
D2	$932,679.00	$942,005.79	$951,425.85	$960,940.10	…	$1,082,811.36
E	$80,688.03	$83,915.55	$87,272.18	$90,763.06	…	$145,314.59
F	$73,142.54	$75,336.82	$77,596.92	$79,924.83	…	$113,953.70
						$3,041,488.49

The weekly machine costs were organized from P&L Table G and combined into quarterly projections, along with the costs of financing and forecasted price increases. These quarterly costs can be found in P&L Table M.

P&L Table M – Equipment costs.

Machines	**1**	**2**	**3**	**4**	**…**	**16**
(Lathe)	$4,800.00	$4,848.00	$4,896.48	$4,945.44	…	$5,572.65
(Milling)	$6,000.00	$6,060.00	$6,120.60	$6,181.81	…	$6,965.81
(Router)	$4,200.00	$4,242.00	$4,284.42	$4,327.26	…	$4,876.07
(Laser Cutter)	$2,760.00	$2,787.60	$2,815.48	$2,843.63	…	$3,204.27

(Metal Printer)	$4,800.00	$4,848.00	$4,896.48	$4,945.44	…	$5,572.65
(CNC Drilling)	$1,680.00	$1,696.80	$1,713.77	$1,730.91	…	$1,950.43
Handling	$900.00	$909.00	$918.09	$927.27	…	$1,044.87
EAF	$15,000.00	$15,150.00	$15,301.50	$15,454.52	…	$17,414.53
Rolling	$1,800.00	$1,818.00	$1,836.18	$1,854.54	…	$2,089.74
Total	**$41,940.00**	**$42,359.40**	**$42,782.99**	**$43,210.82**	**…**	**$48,691.04**

Our team also incorporated a learning curve and defective rate equation to be used when considering changes for a defective product. To reiterate, we expect the new production system to have more problems immediately after construction compared to after it has been established for many periods. This equation assumed that approximately 81% of the total defects would happen in the successive quarter. These estimates are shown in P&L Table N.

P&L Table N – Defective rates.

Starting Defective Rate	Defect Rate	Product	**1**	**2**	**3**	**4**	**…**	**16**
0.25	0.03	A	0.250	0.203	0.164	0.133	…	0.011
0.18	0.01	B	0.180	0.146	0.118	0.096	…	0.008
0.1	0.005	C	0.100	0.081	0.066	0.053	…	0.004
0.14	0.01	D1	0.140	0.113	0.092	0.074	…	0.006
0.17	0.02	D2	0.170	0.138	0.112	0.090	…	0.007
0.22	0.01	E	0.220	0.178	0.144	0.117	…	0.009
0.2	0.005	F	0.200	0.162	0.131	0.106	…	0.008

Because there might be some form of defective products and to understand how production could be impacted, we developed P&L Table O. It combines the production ratio (P&L Table J), the full capacity units (P&L Table I), and the non-defective percent (P&L Table N) to determine the production by product per quarter.

P&L Table O – Production by product type.

Product	1	2	3	4	…	16
A	35150	37376	39180	40640	…	46370
B	33159	34542	35663	36570	…	44143
C	7090	7240	7361	7459	…	7845
D1	0	0	0	0	…	0
D2	75855	78807	81198	83135	…	90733
E	5319	5604	5835	6022	…	6756
F	5376	5631	5838	6005	…	6663

A few additional assumptions not present in P&L Table K should be considered when calculating revenue. First, the possible revenue multiplies by the sell-through rate, indicating that not all good products produced are sold. In our case, the sell-through rate was 85%. We then took the proportion of goods that did not sell and listed them at half the selling price to incentivize sales of these units. We assumed products that were not sold in the quarter produced will be sold at half-price. With these changes, the ‘actual quarterly revenue’ is a bit lower, but our team prefers this conservative model to prevent the decision-maker from feeling too confident in the possible profit margin. These values were calculated in P&L Table P.

P&L Table P – Expected quarterly revenue.

Product	1	2	3	4	…	16
A	$442,414.56	$470,639.65	$508,380.59	$543,384.27	…	$748,692.69
B	$446,821.50	$465,820.45	$500,565.28	$534,243.92	…	$755,719.75
C	$88,008.52	$88,025.89	$91,704.08	$95,120.21	…	$126,145.25
D1	$-	$-	$-	$-	…	$ -
D2	$904,026.89	$904,071.79	$948,694.64	$987,301.80	…	$1,414,622.85

E	$75,669.49	$75,728.48	$83,042.26	$89,994.03	…	$122,108.75
F	$69,686.56	$69,717.31	$75,248.13	$80,390.20	…	$110,795.46
Total Revenue	**$2,026,627.52**	**$2,074,003.58**	**$2,207,634.98**	**$2,330,434.43**	**…**	**$ 3,278,084.74**
Sell Through	0.85	0.85	0.85	0.85	…	0.85

Lastly, we summarized the findings of P&L tables C (cost of facility), L (cost of production), M (cost of equipment), and P (revenue) into a new table to allow for easy comparison between quarters. We also added a row for transportation cost, which calculates the total weight of the products produced, and added a $0.75 fee per pound of product purchased. Please note that we omitted the concept of mileage and distance to customers, as this would add additional complexity to our model. The profit margin was calculated by subtracting the four major costs from the revenue. The cash flow represents the total amount of money flowing into or out of the manufacturer at any quarter. This information is presented in P&L Table Q.

P&L Table Q – Cash flow, ROI, and overall profitability summary.

Quarters	**-2**	**-1**	**1**	**2**	**3**	**…**	**16**
Cost of Facility	$8,927.61	$9,199.50	$9,768.36	$10,065.85	$10,372.41	**…**	$15,319.84
Cost of Production	$0.00	$0.00	$2,214,180.37	$2,265,070.64	$2,333,022.76	**…**	$3,041,488.49
Cost of Equipment	$0.00	$87,687.96	$87,687.96	$88,107.36	$88,530.95	**…**	$48,691.04
Cost of Transportation	$ -	$ -	$ 121,461.75	$ 126,900.00	$ 131,306.25	**…**	$151,882.50
Revenue	$0.00	$0.00	$2,337,890.65	$2,392,197.05	$2,562,792.28	**…**	$3,600,596.65
Profit Margin	-$8,927.61	-$96,887.46	-$95,207.79	-$97,946.81	-$440.10	**…**	$343,214.78
Cash Flow	-$8,927.61	-$105,815.07	-$201,022.86	-$298,969.67	-$299,409.76	**…**	$872,904.57
ROI	-	-	-290%	-383%	-383%	**…**	5114%

After the table construction, we developed assumptions for the Profit and Loss analysis that build the framework's base. The overall analysis monitors the cost and revenue and does not include tax and inflation changes that can occur. Regarding the facility's operation, we developed the assumption that the facility will run for sixteen hours, seven days a week. The factory will also not use more than 5.5 kilowatts per hour (excluding the machine electricity usage) in comparison to traditional factories consuming 1095 kilowatts per hour. Our assumptions of the facility do not incorporate the changing energy levels of having a renewable source such as hydro, wind, and solar. The energy assumption is that the energy requirements will be relatively constant throughout each quarter unless cells are added or removed.

The machines are also operating under the assumption of module grouping. Each module can group machines to be moved around as necessary with ease. Each module will also house the development of one product, contain its heating and cooling system for the longevity of the module, and obtain a connection to the power source. Additionally, though not denoted in the Profit and Loss analysis, there are costs in the building and removal of the module, such as the product switch cost in P&L Table D.

The machines also have assumptions regarding kilowatts per hour utilization and usage. The machine energy utilization is developed through estimates considering the size, consumption, and heat output that they may have. An example is the energy usage of the Electric Arc Furnace (EAF), which is operating at the maximum capacity for the facility, which means higher energy usage. But while the EAF is operating at capacity, the throughput times of the output are not denoted. For the movements of parts from machines, handling equipment usage is assumed as well. Furthermore, cycle times for the usage of handling equipment are not considered for production.

There are also assumptions regarding materials, products, and demand. The raw materials purchase occurs weekly at a constant rate. This schedule is due to GenH's decision to opt out of mining raw materials in-house to avoid additional expenses. The theoretical products then utilized an estimated product composition to display different steel grades. Additionally, each product is designed for the manufacturer through the machine modules they pass through. Each product contains a constant defect rate to allow for the fluctuation of quality that the machines experience. Furthermore, we assume that the growth in the demand for each product is constant, which will portray the product's and facility's profitability over future quarters.

In summary, the profit margin and cash flow utilized the quarterly values derived from P&L Tables Q, R and S to evaluate the modular production system. The profit margin and cash flow were calculated from the parameters including units sold, cost of equipment, cost of goods, gross margin, cost of business, and sell-through. Below we summarize the equations and their parameters.

The **units sold equation** utilized the predicted demand and the sell-through coefficient, which shows product demand growth from the demand ratio. The **revenue equation** combined the quarterly revenue of each product and multiplied by the quarter's sell-through rate, representing the revenue from selling a proportion of units at full price. For simplicity, we then added the revenue from selling the remaining units at half price. The **cost of equipment equation** combines the quarterly production costs for each machine. The **cost of goods equation** combines production, material, and cycle time costs. The **gross margin equation** subtracted the cost of goods and equipment from the revenue. The **cost of business** evaluates two parts of the system, before and after the start of production. Before production starts, the equation summed the cost of product cells set up. After production starts, the equation combines the quarterly facility costs at a constant rate disregarding taxes and inflation. The profit margin equations subtracted the cost of business from the gross margin to present the quarterly revenue. The cash flow equation utilized the sum of the previous period's cash flow and the current cost of business for the quarter together. The quarterly values from the equations allow us to evaluate the return on investment and margins for the modular production system.

3.3.2 Monte Carlo Simulation

While an economic analysis like a P&L diagram is very helpful in analyzing the economic feasibility of a system or business, the discrete values of many variables and constants may be uncertain or forced to be averaged to fit into the equations. By conducting a Monte Carlo Simulation, a statistical simulation technique in stochastic modeling, we can represent single variables with probability distributions and account for uncertainties. A Monte Carlo Simulation uses random numbers to 'simulate' a scenario based on the defined probability distributions of uncertain variables. When running a Monte Carlo Simulation, the number of iterations is specified and the program uses statistics to calculate each variable's mean, mode, minimums, maximums, and confidence intervals. Then, the simulation defines the probability distribution for the output statistic based on the probability distributions of the uncertain variables. The simulation allowed us to better account for the uncertainties of various parameters and estimated data since much of the data is derived from various sources or created as mock data. Additionally, the simulation and the @Risk software allow us to examine the sensitivities of the different variables in the model and their effects on the objective. We used Palisade's Excel add-on software, @Risk, to conduct our Monte Carlo Simulation.

First, we modeled the simulation similar to the Profit and Loss analysis discussed in Section 3.3.1. P&L tables A through Q are very similar, but certain variables (as shown in table 12) are defined as probability distributions rather than a single value.

In the Facility Assumptions and Constants (Table A), the rent price, cost of kWh, and annual growth rates are each represented as probability distributions. The probability distributions for uncertainty variables are shown in Table 11.

Table F represents the sum of the manufacturing times (total value added time) per product type as a probability distribution. This variable is used to calculate the Full Capacity Production per quarter in the Product Production Quantities (P&L Table I).

P&L tables O and P are calculated based on the optimized quarterly production ratios (P&L Table J), or the output from the Linear Programming (Section 3.3.3) that maximizes profit in a recession, using data from the 2008 recession, by adjusting the production ratios for different products.

The Possible Revenue - Quarterly Table (P&L Table K) is the revenue by a quarter if every unit of each product is sold. In other words, P&L Table K shows the revenue assuming 100% sell-through.

The Actual Revenue - Quarterly (P&L Table P) is calculated from the Possible Revenue - Quarterly (P&L Table K) and the sell-through rate for each quarter. Since the sell-through rate is not always predictable, the sell-through of each quarter is defined as a probability distribution.

The data inputted for the following figures and tables are estimated from industry data and sources found online:

- P&L Table B - Cell module area required per product (estimated using machine type and size data)
- P&L Table C - Overhead (estimated using industry standard statistics) (Average industrial rent, 2021); Facility electricity cost is estimated from the cost of kWh per square foot per quarter (from P&L Table A) for a facility without considering machines and the area required for the facility. Since we incorporated electricity in the machine operations, the P&L Table C estimates are purely for rent and electricity requirements for non-machine related purposes (such as lighting or heat).
- P&L Table G - Maintenance costs (estimated from machine reviews and costs) (Jeon et al., 2019)

The estimated values for products A through E regarding product composition, process design, labor required, defect rates, and demand were created as mock data for the hypothetical scenario. These values were estimated from pessimistic assumptions and serve only as placeholders to conduct an analysis.

As in the P&L analysis, we made a list of assumptions (Table 11) for the Monte Carlo Simulation about the scenario and the information inputted into the model. The assumptions also describe some of the model configurations when running the simulation.

Table 11 – Assumptions for the Monte Carlo simulation.

1. All probabilities will be from 5,000 iterations of a simulation which is a large sample size.
2. All workers are paid a constant rate of $30/hour, and there are two shifts of workers per workday.
3. The facility functions on weekends but not on Federal holidays, meaning it is open 340 work days a year.
4. The MPS requires a two-quarter organization and start-up period to locate an adequate facility, hire the required workers, and obtain equipment.
5. The labor hours associated with establishing the MPS before the first production quarter is calculated from 15 workers working 12 weeks per quarter for $35/hour and the sum is added to the cost of production in P&L Table Q.
6. The cost of equipment is the cost of financing the machines at a financing rate of 3% and an expected price increase rate of 1% per quarter.
7. There is a production manufacturing overhead mark-up percentage on the production cost for ‘hidden fees’ in production, whether it is value-non-added time, increased defects, etc. It represents a probability distribution of a percentage and is multiplied by the sum of production costs (P&L Table H) to get the ‘true’ sum of production costs.
8. There is a facility manufacturing overhead markup percentage for ‘hidden’ facility costs (like P&L Table C) that are not accounted for in the cost of production for a given product. This markup does not impact any cost calculations since this would be double-counting. It only impacts the selling price of a product (P&L Table I).
9. The growth rate in production quantities (P&L Table I) used to calculate the revenue and production costs for each quarter is the same for all products and it follows ¼ the annual growth rate indicated in P&L Table A.

10. The following statistics are representative measures of the economic success of a manufacturing system and, therefore, will be used as output statistics of the model.
    a. Quarter in which the MPS breaks even
    b. Cash Flow for quarters after breaking even
    c. Average growth rate after the break-even point
    d. Return on investment (ROI) for quarters after the break-even point
11. The @Risk Simulation will use a random number generator (Mersenne Twister) and the sampling type is “Monte Carlo”, meaning the numbers are randomly generated and the variable’s value is determined from where the random number falls on a cumulative probability distribution. This sampling technique for Monte Carlo generally results in random numbers that are not forced to converge to a set distribution.
12. Defective units are scrapped and the materials are recycled. The potential money ‘saved’ from recycling a unit is not calculated. The scrapping cost represents the cost of time, movement, or other resources to ‘scrap’ that unit. (P&L Table H)
13. Quality control costs are the costs associated with the time required to check the units and conduct the required tests. (P&L Table H)
14. The possible revenue (assuming 100% sell through rate) and the cost of production (P&L Table K and P&L Table L), respectively, use an equation for continuous compounding ($P(t) = P_0 e^{r \cdot t}$) where P_0 is the calculated value for that quarter and each quarter is calculated independently.
15. The sell-through rate is the ratio the product being sold at full price. We used one sell-through rate for the proportion of goods sold at full price; the remaining goods were sold at half price.
16. Each simulation is run on a 16 quarter production period with a two-quarter start-up period. The quarters are labeled according to production, so quarter 1 is the quarter production started.

The outputs from each simulation iteration is the product of a random value for each uncertainty variable. This means that each iteration is an independent instance of the scenario and the output probability distributions are the statistical analysis for each variable and outcome. In other words, one iteration (or the results thereof) should not impact another iteration.

Fixed Numbers:

- Production ratio: Proportion of production of each product type for each quarter. This input is received from the linear programming explained in Section 3.3.3.
- Defective rate: Proportion of manufactured units that are defective and must be scrapped. There is a ‘learning curve’ component to the defective rate to account for the lack of

standardization and adjusting of facility practices. While the defect rate is not usually "fixed" or predictable, we assume it is fixed for consistency.

- Product data: Production composition, machines required, and defective rate, are all mock data numbers we assume to be constant. While these could be represented as distributions, varying them may create too much instability in the model.

Uncertainties:

- Annual rent price per square foot over the years, varies per area (P&L Table A)
- Cost of kWh, varies slightly over the years (P&L Table A)
- Value added time for each product in production. Our team had difficulty defining the nuance between the expected time a unit should be in production and the time needed to sit idle or wait for the next process. (P&L Table F)
- Variation to simulate a real process as well as uncertainty in mock data (P&L Table F). For example, determining how breakdowns or quality control could affect the overall process at the moment.
- Machine maintenance costs vary per wear and broken parts (P&L Table G)
- Hidden production (markup) fees can vary according to the practices of a manufacturing facility due to lack of standardization, bottlenecks, etc (P&L Table H)
- Facility 'tax' markup varies because electricity costs or material costs, etc may vary. (P&L Table I)
- Sell through rate cannot be predicted ahead of time–the rate follows the economic trends from quarter to quarter (P&L Table P)

We also had to define the probability distributions for the variables with uncertainty and the variables we knew might change over time. The tables of variables and their distributions are shown in Table 12.

Table 12 – Uncertainty variables and their probability distributions.

Table	Variable	Distribution type	Center or Mean	Lower	Upper	Type	Uncertainty function
Table A	Rent price	Normal	6.89	-10	10	%	yes
	kWh Rate	Triang	0.12	0.11	0.145	Actual limits	yes
Table F	Total Value-Added Time	Normal	Sum of Value Added time per product	-10	10	%	yes

Table G	Machine Maintenance Costs	Normal	Maintenance Cost per Machine	-10	10	%	yes
Table H	Hidden Fees MarkUp	Triang	0.1	-0.05	0.07	Actual +/-	yes
Table I	Facility 'tax' markup	Triang	0.14	-0.1	0.16	Actual +/-	yes
Table P	Sell Through Rate (per quarter)	Normal	0.775	-0.25	0.1	Actual +/-	yes

Once the uncertainty variables are defined as well as the relationships between variables, we can focus on the output of the simulation. Defining the output statistics in @Risk allows us to see the probability distribution and statistics of the output over the 5,000 iterations of the simulation. We chose to use multiple output statistics to better encompass the results and evaluate the success of the modular production system. The output statistics and the reasons, along with some metrics that add to the outputs, are shown in P&L Table R.

The numbered objectives in the table show the output statistics defined in the simulation software, meaning the simulation output will create probability distributions and sensitivity analysis for the statistics as a result of running the simulation with varying uncertainty variables. Two objectives in the table are shown in grey and are not numbered because they are not defined as output statistics. The First Positive Quarter Cash Flow and the Annual Return on Investment After 16 Quarters are the two metrics we considered in the outputs but are not defined as output statistics in the simulation. They are not descriptive enough or important enough to define them as output statistics, however, they help paint the big picture of the results of the model.

P&L Table R – Monte Carlo output simulation statistics.

Objective / Output Statistic	**Importance**
(1) Break-even point Quarter *First positive quarter in the row 'Cash Flow' in Table Q*	An important indicator of risk and return on investment in economics
First Positive Quarter Cash Flow*	Cash Flow from the quarter when the Cash Flow is first positive; lower values mean breaking even later in the quarter, higher values mean earlier
(2) Cash Flow Four Quarters After the Break Even Point *(Breaking even counts as the first quarter)*	Indicates the 'health' of the system one year after breaking even; how profitable the system is becoming at the early stages
(3) Average Growth Rate of the Profit Margin After the Break-Even Point	Shows how profitable the system can become and what we may be able to expect from the system in the future

(4) Annual Return on Investment One Year After Break-Even *(Including the quarter when the system breaks even)*	An economic indicator and motivator for businesses and investors; it shows how profitable the system is expected to be
(5) Annual Return on Investment After 12 Quarters, or 3 Years *(Including the quarter when the system breaks even)*	The ROI four years after starting production is a consistent metric for determining the ‘pace’ of profitability of a system.
Annual Return on Investment After 16 Quarters, or 4 Years*	The ROI in Quarter 16; return on investment four years after starting production, or four and a half years after starting to plan and deploy the system.

* Not an output statistic for the simulation. Only shown for reference.

The third output statistic, the average growth rate of profit margin after the break-even point is calculated from the change in profit margin each quarter. P&L Table S below is used in calculating the change on profit margin and calculating the average.

P&L Table S – Growth rate of the profit margin by quarter.

Break Even Quarter	7	
Break Even Quarter Cash Flow	$268,770.75	
Quarter after Break even	**Profit Margin**	**Rate of Growth**
1	$289,063.18	7.550%
2	$315,472.18	9.136%
3	$362,805.18	15.004%
…	…	…
Sum; Average	$3,452,745.01	6.03%

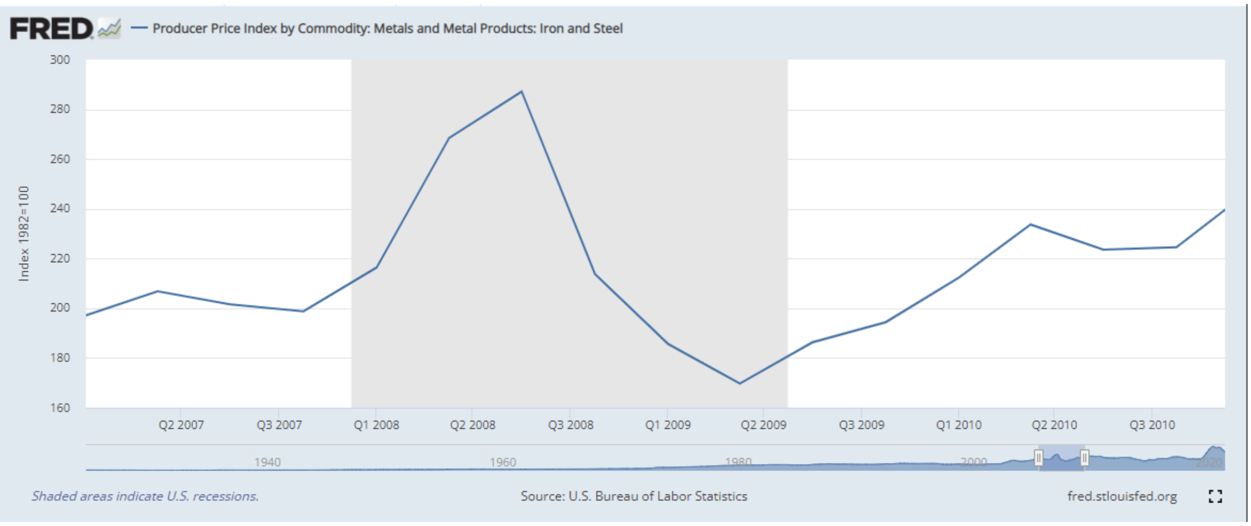
Note: The data shown in this table are of no significance– they are only sample data for demonstration purposes.

3.3.3 Linear Programming Model

A linear program is an optimization tool to find the best outcome given specific constraints. We developed a linear program to display how the steel modular production system will change during specific economic scenarios. The goal of the linear program is to optimize the production of each product to maximize revenue while staying within labor and electricity constraints. The economic scenario we chose to analyze was the recession between the years of 2008 and 2009 to show the benefits of cell switching and profitability.

Our first steps were to research steel demand and selling price data from the recession to develop our linear program. The data from the Producer Price Index, PPI, is utilized for production levels and changes in monetary necessities, such as selling price and labor cost. From there, we developed tables that predicted production levels, the count of cells per product, and electricity consumption. The tables outlined in the linear program are detailed to show the movement of production through each quarter for a continuous flow leading to the optimization of the maximum revenue.

The Selling Price Ratio (P&L Table T) calculated our selling price ratio from the full capacity production summed for all of the products, P&L Table I, and the producer price index (PPI). The producer price index measures the price change across the industry for a specific product, in this case, the iron and steel products as a whole (*Producer Price Index*) from 2007-2010 as shown in Figure 19. We captured this range to show how the system would change before, during, and after the recession. The PPI and the capacity production summed was used to set the standard of the first quarter to a value of 1 to set a range of how the prices will change over time.



Shaded areas indicate U.S. recessions.

Source: U.S. Bureau of Labor Statistics

Figure 19 – Producer price index (Producer Price Index).

P&L Table T – Selling price ratio.

Quarters	1	2	3	4	…	16
PPI (demand expectation)	197.133	206.767	201.533	198.8	…	224.53

Supply	1,288,673.587	1,288,673.587	1,288,673.587	1,288,673.587	…	1288673.587
Selling Price ratio since last quarter	1.00	1.01	1.00	1.00	…	1.02

The Profit per Unit (LP Table A) utilizes the selling price developed in the Profit and Loss analysis, Table I, and the selling price ratio. The selling price and the selling price ratio multiplied together calculate the sales per product per quarter, which shows the cost changes that occur throughout the year.

LP Table A – Profit per unit.

Original Selling Price	Product	1	2	3	4	…	16
$13.21	A	$13.21	$13.31	$13.26	$13.23	…	$13.49
$14.01	B	$14.01	$14.11	$14.06	$14.03	…	$14.31
$13.16	C	$13.16	$13.25	$13.20	$13.17	…	$13.44
$12.52	D1	$12.52	$12.62	$12.57	$12.54	…	$12.79
$12.76	D2	$12.76	$12.85	$12.80	$12.77	…	$13.03
$14.79	E	$14.79	$14.90	$14.84	$14.81	…	$15.10
$13.61	F	$13.61	$13.71	$13.65	$13.62	…	$13.89

*LP tables were developed using the linear programming model.

The Labor Cost (LP Table B) utilizes the labor costs developed in the Profit and Loss analysis, Table H, and the calculated rate of change from the selling price ratio. The rate of change is calculated by finding the difference between the current and previous quarters selling price ratios to show the rate of change between quarters. The labor cost and rate of change are multiplied to develop the labor costs per quarter as we enter the recession. The labor costs are calculated to display the expense of operating the facility and maintaining high production levels as the challenges of the facility's production change.

LP Table B – Labor costs.

		Quarter			
Labor Costs	Product	1	2	3	4
$5.75	A	$5.75	$5.79	$5.77	$5.76
$7.40	B	$7.40	$7.46	$7.43	$7.41
$8.63	C	$8.63	$8.69	$8.65	$8.64
$7.23	D1	$7.23	$7.28	$7.25	$7.23
$7.75	D2	$7.75	$7.81	$7.78	$7.76
$9.75	E	$9.75	$9.82	$9.78	$9.76
$8.50	F	$8.50	$8.56	$8.53	$8.51
55	Sum	$55.00	$55.41	$55.19	$55.07

The Production Ratio (LP Table C) includes the ratios developed from the linear program to optimize the system and find the maximum revenue. The total production level for each quarter is less than or equal to one to ensure production does not exceed 100%. Additionally, the production ratio for each product per quarter cannot fall below 5% and not exceed 30% (0.3). These constraints ensure that all products are produced to fulfill demand and production needs.

LP Table C – Production ratio per quarter.

Units Produced	Product	1	2	3	4	…	16
234338	A	0.24	0.23	0.21	0.22	…	0.24
202195	B	0.18	0.16	0.15	0.15	…	0.18
157572	C	0.07	0.06	0.06	0.06	…	0.12
195282	D1	0.13	0.12	0.11	0.12	…	0.17
228480	D2	0.19	0.08	0.12	0.08	…	0.05
136406	E	0.16	0.30	0.18	0.32	…	0.13
134400	F	0.05	0.05	0.17	0.05	…	0.11

1288673.587	Sum	1.00	1.00	1.00	1.00	…	1.00

The Number of Units Produced (LP Table D) utilizes the production ratio from the Production Ratio Table, full capacity units from the Profit and Loss analysis, and the inventory from LP Table F. The units produced is multiplied by the optimal production ratio to find the optimal number of units produced for each product. In the second quarter, we added inventory from the previous quarter to find the total amount of each product. The purpose of including inventory values for the next quarter is to ensure an optimal level of production and products sold.

LP Table D – Number of Units produced per quarter.

Product	1	2	3	4	…	16
A	55266	60402	57205	58010	…	66062
B	35746	36910	35856	36103	…	43567
C	10567	10920	10833	10858	…	20650
D1	25080	25056	24155	24350	…	35616
D2	42446	25760	32173	22657	…	13490
E	21294	42457	27271	46184	…	18801
F	6720	7560	23251	9579	…	17179
Sum	197119	209065	210743	207741	…	215366

The Products Sold (LP Table E) utilized the production values in the Number of Units Produced, the sell-through of each product, and the rate of change developed from the selling price ratio. The first step to creating an accurate sell-through rate is to incorporate the selling price ratio to model the changes from the recession. The sell-through percentage and the rate of change are averaged together to reflect changing sell-throughs throughout the recession. The average sell-through rate is multiplied by the products produced to develop the number of products sold.

LP Table E – Product sold.

Sell-Through	Product	1	2	3	4	…	16
0.75	A	48358	52626	50170	50820	…	58037
0.7	B	30384	31235	30550	30726	…	37185
0.8	C	9510	9787	9771	9784	…	18658
0.85	D1	23199	23083	22393	22550	…	33070
0.7	D2	36079	21800	27412	19282	…	11514
0.85	E	19697	39114	25281	42769	…	17457
0.75	F	5880	6587	20392	8392	…	15092
	Sum	173107	184232	185970	184323	…	191014

The Inventory (LP Table F) utilized the values from the Number of Units Produced and the Products Sold. The number of units produced is subtracted from the products sold to find the total inventory for each product at the start of each quarter.

LP Table F – Inventory.

	Quarters					
Product	1	2	3	4	…	16
A	6908	7776	7034	7190	…	8025
B	5362	5674	5306	5377	…	6382
C	1057	1133	1061	1074	…	1992
D1	1881	1973	1763	1800	…	2546
D2	6367	3960	4761	3374	…	1976
E	1597	3343	1990	3415	…	1344
F	840	973	2859	1187	…	2087

Sum	24012	24833	24773	23418	…	24352

The Average Electricity Consumption (LP Table G) utilizes a constant utilization rate and the electricity consumption of cells at capacity for the peak consumption per cell. The utilization rate is multiplied by the peak consumption for each product to develop the average electricity consumption. These values develop the number of kilowatts per hour the facility utilizes in production.

LP Table G – Average electricity consumption.

Utilization Rate	**Peak consumption per cell**	**Product**	**Average consumption per cell**
0.7	2.144	A	1.501
0.7	2.559	B	1.791
0.7	3.315	C	2.320
0.7	2.676	D1	1.873
0.7	2.333	D2	1.633
0.7	4.569	E	3.198
0.7	4.763	F	3.334
Sum	**122.971**		

The number of cells per product (LP Table H) considers understanding the production capacity of each cell, the total units produced, and the utilization percentage of each cell. Cell capacity is determined by finding the number of products that developed in one-hour multiplied by the operating number of hours of the facility and the percentage of capacity utilized. The number of cells was then developed by dividing the number of products produced by the cell capacity rounded up.

LP Table H – Number of cells per product.

Cell Capacity	**Product / Quarter**	**1**	**2**	**3**	**4**	**…**	**16**
8369	A	7	8	7	7	**…**	8
7221	B	5	6	5	5	**…**	7

5628	C	2	2	2	2	…	4
6974	D1	4	4	4	4	…	6
8160	D2	6	4	4	3	…	2
4872	E	5	9	6	10	…	4
4800	F	2	2	5	2	…	4

The Cell Change (LP Table I) utilized the Number of Cells per Product Table values. This table found the difference in the number of cells between each quarter to fulfill production. For example, Product A needed to add one cell in quarter 2 to fulfill production, represented by a value of 1. Then in quarter 3, one cell is removed not to overproduce, defined via a value of –1.

LP Table I – Cell Change.

Product /Quarter	**2**	**3**	**4**	**5**	**…**	**16**
A	1	-1	0	1	…	-1
B	1	-1	0	0	…	0
C	0	0	0	0	…	0
D1	0	0	0	0	…	1
D2	-2	0	-1	0	…	0
E	4	-3	4	0	…	-1
F	0	3	-3	0	…	0
Sum	4	-2	0	1	…	-1

The Cost of Cell Change (LP Table J) utilized the values in the Number of Cells per Product and the values in Table D from the Profit and Loss Analysis, and Product Switch Costs. The costs from Table D were input into the Cell Change Table. For example, in the Cell Change Table, the value of a positive number represents additions of a cell, meaning there is a setup cost attached and vice versa if negative.

LP Table J – Cost of cell change.

Product	2	3	4	5	…	16
A	$1400	$1200	0	$1400	…	$1200
B	$1900	$1350	0	0	…	0
C	0	0	0	0	…	0
D1	0	0	0	0	…	$800
D2	$1500	0	$750	0	…	0
E	$8200	$4200	$8200	0	…	$1400
F	0	$3000	$3600	0	…	0
Sum	$13000	$9750	$12550	$1400	…	$3400

The following two tables outline the constraints of the linear program utilizing the tables mentioned. The Electricity Consumption (LP Table K) utilizes the values in the Average Electricity Consumption Table and the values in the Number of Cells per Product Table. The average consumption of electricity values is multiplied by the number of cells associated with each product per cell. The constraint on electricity consumption is the peak consumption values summed to ensure that the electricity consumption summed per quarter does not exceed the values denoted by the peak consumption.

LP Table K – Electricity consumption per cell in kWh.

Product	1	2	3	4	…	16
A	10.504	12.005	10.504	10.504	…	12.005
B	8.957	10.749	8.957	8.957	…	12.540
C	4.640	4.640	4.640	4.640	…	9.281
D1	7.494	7.494	7.494	7.494	…	11.240
D2	9.800	6.533	6.533	4.900	…	3.267
E	15.991	28.783	19.189	31.981	…	12.793

F	6.668	6.668	16.669	6.668	…	13.335
Sum	64.054	76.871	73.986	75.144	…	74.460
Cap Electricity Usage	122.971	122.971	122.971	122.971	…	122.971

The Labor Cost of Production of Cells (LP Table L) utilizes the values in the Labor Cost Table, the values in the Number of Units Produced Table with Inventory, the values in the Inventory Table, and the values in the Number of Cells per Product Table. The number of units produced minus the inventory included is multiplied by the labor costs. From this, we developed the labor cost constraint. The sum of all labor costs for each cell in any quarter must always be less than the sum of the systems labor cost at full capacity.

LP Table L – Labor cost of cell production.

Labor of Full Capacity	Product	1	2	3	4	…	16
48123	A	$317,779.76	$343,001.41	$322,263.42	$326,942.17	…	$378,036.83
53437	B	$264,517.36	$269,812.91	$260,554.92	$262,195.15	…	$321,525.86
48538	C	$91,139.11	$93,831.87	$92,614.58	$92,707.69	…	$179,462.73
50390	D1	$181,202.55	$180,500.72	$173,140.71	$174,387.14	…	$259,419.72
63240	D2	$328,956.44	$194,764.02	$246,223.08	$171,049.73	…	$104,366.63
47499	E	$207,617.55	$415,456.30	$263,450.85	$448,865.56	…	$185,124.72
40800	F	$57,120.00	$63,900.40	$197,327.49	$78,665.78	…	$146,672.28
352026	Sum	$1,448,332.78	$1,561,267.64	$1,555,575.04	$1,554,813.23	…	$1,574,608.78
Full Labor Multiple	5	$1,760,132.14	$1,760,132.14	$1,760,132.14	$1,760,132.14	…	$1,760,132.14

The Quarterly Revenue (LP Table M) is the value maximized by the linear program. The quarterly revenues are calculated by multiplying the amount sold by the selling price, which is summed together for the total revenue.

LP Table M – Quarterly revenue.

	1	2	3	4	…	16
Quarter Revenue	**$2,311,626.54**	**$2,515,405.46**	**$2,509,235.96**	**$2,508,758.02**	**…**	**$2,611,969.52**

To simplify our linear program, we had to make some assumptions. First, we neglected some costs in the linear program, specifically inventory, electricity, and material costs. They are not in the program due to the size constraints of running the linear program in Microsoft Excel. The electricity utilization of the cells is an additional assumption. The utilization will not be at 100% in practice because of the time the machine is idle but high enough to account for production at capacity. The PPI values were another assumption. We believed that the demand for all the theoretical products would behave similarly in the recession. This might not actually be the case, but it was a simpler model to design.

3.3.4 Decision Tree

We decided to construct a decision tree to not only improve our understanding of the different sets of the decision GenH could make, but to better quantitate the potential risks and payoffs associated with each combination of chances or choices made. Decision trees are great risk management tools because they can predict the most profitable outcome when given a decision and set of chances. It should be noted that the decision tree we developed was illustrated for conceptual purposes and that the values for payoffs and risks were calculated using estimated figures. The tree can be revised as necessary when the decision maker obtains more accurate figures, or when price payoffs and risks change. Ultimately, these changes could affect the set of decisions determined to be the best decision.

It should also be noted that decision trees are only quantitative. While the probabilities of each chance are theorized, it does not capture the true extent of each risk, hence, the results should be taken with caution. It might be best to base a final decision on a multitude of factors. Quick decisions can be made using heuristics or mental shortcuts. They could rely on effect, anchoring, availability, or representation to make a choice. In cases such as deciding to build a modular steel production system, we do not anticipate heuristics to be used, but they should be something to consider.

The decision tree starts with one decision: whether to utilize a traditional, hybrid, or modular steel production system. Then, the decision maker has the option to use either grid energy (electricity originating from the power grid) or a renewable source of energy (such as hydropower, wind, or solar). The next decision is whether they want to utilize a current plan or to build their own infrastructure. Next, they have the option to purchase raw materials or to mine the materials themselves. Lastly, they will evaluate where they would like the production system to be and consider how far away it is from the average customer.

Associated with the process type decision (the green square that determines whether it is traditional, modular or hybrid) is an expected revenue payout. For example, we assumed the modular option could yield the greatest profit, considering how it would likely cut unnecessary markup chain pricing, partners, and channels and produce products quicker. This decision was assigned a profit of $15,000,000 annually. Next, estimates were carefully made regarding the series of chance branches (red circles) that followed. For example, if the modular process type was chosen, then we estimated there to be a 50% chance of it operating using energy from the grid and a 50% chance of the system operating from renewable energy that is self-produced. Associated with each probability is a different payoff. In other words, if grid energy were selected, then the decision maker could expect to pay $100,000 in electricity costs for the year. However, if the renewable energy option was selected, the expected payoff would be -$50,000. The probabilities and payoffs for subsequent branches would depend on the combination of outcomes that have already happened.

At the tail end (where the blue triangles are), after all the chances are made, are combination payouts that indicate how profitable the actions are. For example, when following the path of modular -> grid energy -> build energy infrastructure -> purchase raw materials -> close, we find the likelihood of following such a path is 3.6%, which is the product of all the preceding probabilities (0.5*0.4*0.6*0.3). The total payout, after considering all the expenses as outlined in the tree, is $12,000,000, or the sum of the decision payoff and each expense associated with the chance results taken along the path.

Also contained in adjacent to each chance node or circle is the chance payoff. Chance payoffs consider the average or expected payoff for each set of subsequent possibilities. For example, the chance node payoff immediately before the location classifier (close, mid, or far) along the path modular -> grid energy -> build energy infrastructure -> purchase raw materials is $11,967,000 as shown in Figure 20. It is determined by taking the $15,000,000 modular payoff, and subtracting $100,000 for grid energy, $2,500,000 for building infrastructure and $250,000 for purchasing raw materials. This would total $12,150,000. Then, it considers the expected payout of the close, mid and far options (30%*-$150,000 + 30%*-$180,000 + 40%*-$210,000 = $-183,000). This value is subtracted from $12,150,000 to generate $11,967,000.

A sample screenshot of the decision tree can be seen in Figure 20. Please consider that this is not the entire tree, but only a sample of branches as it will be too large to fit properly at this part of the report. The entire tree can be made available upon request. A full detailed analysis of the results of this tree will be explained in the findings section.

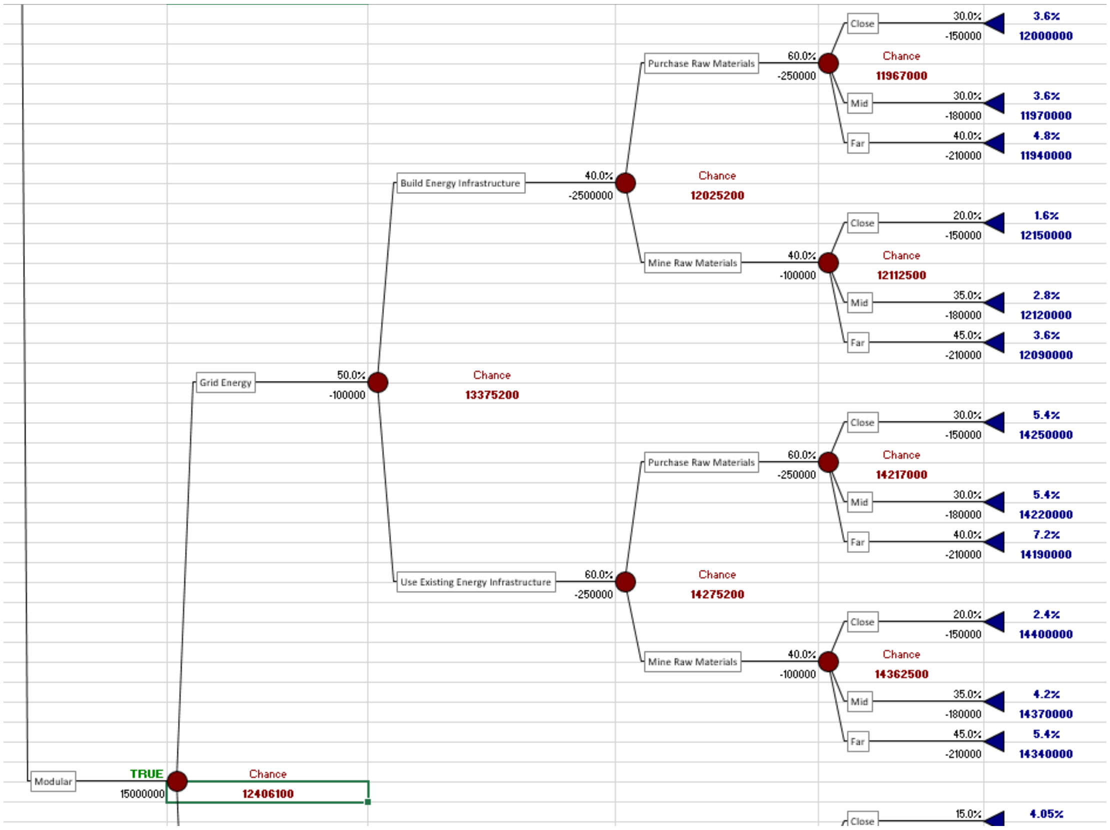


Figure 20 – A partial screenshot of the decision tree developed as part of our methodology. This image shows how the chance of each successive event depends on the prior decision or outcome.

For modeling purposes, the probabilities and payoffs in the tree were estimated, and may not necessarily be realistic. It should be reiterated that the decision tree serves as an elementary model to understand how decisions affect the possible courses of action and the consequences of those actions. That said, if more information becomes available or the decision maker has more accurate data, the decision tree can be updated to reflect these changes. Furthermore, suppose the decision maker is curious as to how changes to one variable affect the overall profit payout. In that case, they can make changes through the sensitivity analysis option in the software. This concept is similar to the sensitivity analysis performed in the @Risk model.

Similarly, this model fails to consider how the payoffs might change over time. There might be a change in the proportion of customers who live close by or far away from the production system. The amount of money spent on electricity could change depending on if additions are made to the facility or if modules or infrastructure are disassembled. If renewable energy sources are implemented, the energy produced might vary depending on the time of year. It can also be difficult to eliminate bias in the model depending on the variation of probabilities and payoffs.

3.3.5 Risks

After having spoken to our sponsor and other companies that we contacted, we have developed a set of risks worth considering upon constructing a modular steel plant. These risks (Table 13) should be thoroughly considered prior to make any decision and are difficult to quantify. These risks will be considered in conjunction with the outcomes determined in the models we developed. We found it difficult to incorporate all these risks into the P&L, @Risk Monte-Carlo Simulation, Linear Programming and Decision Tree Models.

Table 13 – A summary of the risks and considerations before deciding on the type of steel production system, energy type/source, material acquisition, transportation, and finance.

Risk Category	**Risk Explanation and Description**
Grid Reliance	- Operating fully on energy from the power grid implies that the manufacturer will need to pay standard electricity rates. There is no way to avoid paying if rates increase due to increased demand or natural disaster. - While traditional steel manufacturing requires a significant amount of energy that depends on the size of the facility, product throughput and machines, regardless of the specifics, will put a high demand on the system. This could lead to outages, especially considering the declining age and efficiency of the grid power. - Grid energy is produced typically in conjunction with coal or natural gas, neither of which are renewable resources. Burning coal produces emissions and creating power from natural gas is not as clean as renewable forms of energy. Ultimately, the materials used to produce grid energy have implications for the health and sustainability of Earth.
Use of Renewable Energy	- Currently, renewables are only capable of producing a portion of total energy required to power most buildings and infrastructure. There is currently no steel manufacturing facility completely powered by renewables. Unless the manufacturing process is completely redesigned, there will need to be some reliance from the grid or multiple energy sources. - Renewable energy sources provide energy as it is available. In other words, the total available energy will fluctuate depending on the amount and flow of water, hours and angle of sunshine, and speed and direction of the wind. - Storage, as an “energy inventory” will be required to hold excess energy when

	available. It may also lose capacity over time and will likely be expensive to maintain. - The type and amount of renewable generated will depend significantly on the climate of the location, geography, and terrain.
Purchasing Raw Materials	- Subject to paying at least what other companies charge (markup) as a selling price, and has a higher variable cost compared to mining or self-producing raw materials in the long run. Will also need to pay for shipping and handling. - Contributes an extra step to the supply chain that introduces longer lead and waiting times to receive material. - Lack of control over the quality of the product being provided.
Mining Raw Materials	- Eliminates supplier requirements of the supply chain and provides manufacturers more control over pricing. However, not all raw materials may be available at a particular mining location, which could require owning multiple mines or needing suppliers for less frequently used materials. - Manufacturers will have the ability to obtain as much raw material as available or desired. Could indicate reduced total production times (from raw material to finished product).
Transportation	- If mining raw materials, we will need to decide whether to hire a third party to transport materials back to the central manufacturing location, or to purchase transportation equipment and transport the material themselves. - Will also need to consider transporting finished product to customers, hire a third party to sell products to customers, or act as a product supplier to businesses. - Each transportation option has economic, control, and transportation time advantages and disadvantages.
Building Infrastructure	- Could either purchase an existing steel manufacturing facility or mini mill or build infrastructure from ground up. Purchasing is likely quicker, but may not have all the desired features of the facility design. Age and location are key drivers that could impact profitability. - If a renewable energy source is desired, infrastructure such as dams or turbines will need to be regularly maintained. Connecting the power source to the main processing facility will need to be considered.
Choosing a Modular or Hybrid Design	- Machines would operate effectively in a containerized shipping module, though it is unproven if current technologies are able to fit logistically inside such small volumes. - Likely will result in significant heat buildup, even with proper venting and air flow. - Risk of disconnection between modules. System could fail to provide cells with the correct amount of energy required.

	- Proper insulation and protection of modules from the environment and elements if not within a physical, closed-space facility. - Possesses the advantage of turning off modules and adjusting production to meet demand without producing inventory, but it might not be profitable if there is not enough or too much demand.
Choosing a Traditional Design	- Very costly due to the size of the facility, frequency of machine breakdowns, high throughput, and many sources of failure. - Difficulty adjusting output or reacting to consumer demand. - Requires significant amount of energy (typically from the grid), site of carbon emissions.
Financial Considerations (Modular Only)	- Failure to generate positive cash flows after the initial 1 to 2 year period of constructing modules could indicate that the modular system will not be profitable. Because the first few periods are crucial, it could take upwards of 10 years before the manufacturer begins to see net profit. - Building a modular facility 2-3 years prior to a recession also will likely be unprofitable, however waiting until after a recession is over will likely be more profitable. - There is a difference when it comes to rights and uses of equipment and property between financing, leasing, and owning. In terms of financing, it might be cheaper to finance or lease in the short run, especially if machines fail frequently or need to be upgraded. Owning requires more capital.

4.0 Findings and Metric Performance

We were able to determine conclusive effects and economic trends from the P&L and Monte Carlo Simulations. From the Linear Program, we were able to optimize production ratios for a worst-case scenario economic depression using data from the 2008 recession. Our analysis with the outputs from the linear program proves the flexibility and resilience of our abstract modular production system when steel production would usually suffer greatly.

4.1 Modular Production System Design and Implementation

Our final MPS design consisted of six different product types requiring six types of machines, several handling systems, a furnace, and rolling area. A completed process flow is shown in Figure 21. Common processors such as the EAF and rolling steps were omitted from this diagram since all products pass through in the same order. Handling and automation systems are also omitted for visual simplicity.

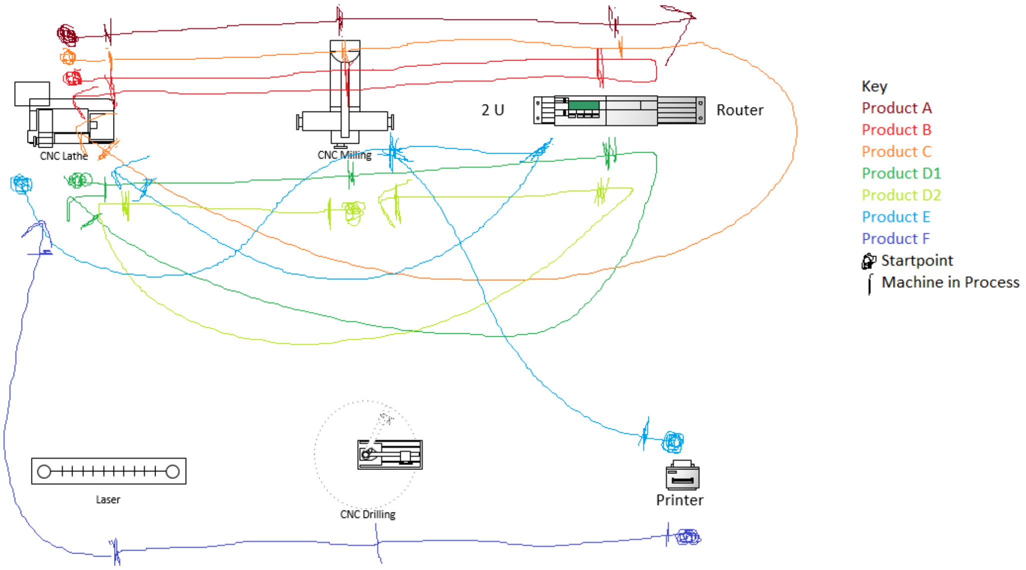


Figure 21 – Product flow map.

Upon presenting this design to our sponsor, we learned that this design resembled more of a hybrid design rather than being truly modular. Our sponsor's reasoning was that by definition to be modular, the machine types and technology would need to fit inside shipping containers or similar structures. Current and conventional machines can not fit inside these modules in most cases, but our team had made the assumption that if similar equipment existed, it would have similar costs, energy requirements, and process flow rates compared to their traditional counterparts. Our sponsor gave us the following suggestions (Table 14) to make the design ‘truly’ modular:

Table 14. Sponsor suggestions.

1. Substitute MOE in place of the electric arc furnace.
2. There is no need for a mini rolling mill. Instead, a polturing machine can be used.
3. Only include CNC milling machines if aerospace parts will be developed.
4. The laser is not necessarily required.
5. The MOE could also replace the printing technology, but comparing these two in parallel would yield different results.
6. Remove the printer outside of the manufacturing process and to a location closer to the market or consumer.

Our sponsor also suggested incorporating quality control, which was omitted from our process design but present in our P&L analysis. A laser integrated based system could allow the worker to check the part against the design file for its tolerance ratio. Products such as cladding, where the surface is the most important element, could be studied this way. Incorporating these changes, however, would limit the number of machine types required for each module. Because our team had developed cells, where we grouped together machines with similar attributes, replacing or omitting some of these machines would eliminate the need for having cells altogether.

Our team hoped to initially include cells, as it is a common method to produce standard work and to organize the process flow efficiently. While this is not always necessary, if our team had made all the changes desired by our sponsor, we would need to eliminate the cells, reorganize our modular production system design, and reformat the affiliated profit and loss model. Given these suggestions were offered out of good intentions, but with only a few weeks left until the final project deadline, our team decided to move forward with the changes we could. We then highlighted how these suggestions could greatly improve the profit and loss and other models we created, which could also indicate an improved profit margin and return on investment. It is significantly likely that fewer machines, electricity and labor would be required, suggesting lower equipment and cost of goods sold. Perhaps this new technology has the ability to develop or refine parts quicker, has more functionalities, or produces fewer emissions.

Regardless of these changes, our team felt that our design incorporated both our literature review and industrial engineering backgrounds on modular production systems. We believe our design certified our project understanding, and it paved the way for a productive conversation with our sponsor about the topic. Without developing a design, perhaps our team would have more difficulty in understanding how the different parts and pieces of this project are interrelated and fit together. Moreover, we were able to incorporate this design into not only the profit and loss analysis, but a Monte-Carlo simulation and linear programming model, which would inform us of how sensitive each quantitative variable is or how it impacts the overall profitability. Overall, this method was successful in achieving objective 1, even if we did not produce the ideal result.

4.2 MPS Analysis

4.2.1 Profit and Loss

As previously mentioned, the main purpose of the profit and loss model was to determine the overall profitability of investing in a modular production system for steel. Therefore, the key variables we were studying included the profit margin and cash flow for each period, and comparing how they changed over time.

The graph above (Figure 22) shows how it takes at least 4 quarters, or one year, to deploy the MPS. During this time, no profits are generated. The only realized expenses in this timeframe are the cost of business, equivalent to approximately $8500 per quarter. In quarter 5, MPS construction is complete and the manufacturing processes begin. During this quarter, the cost of equipment and goods sold is realized, hence the significant drop in overall profitability. There is also a learning curve for employees, and because the processes are new, we can expect there to be many production stoppages to ensure high-quality control and that equipment functions properly. Over the first few years, we expect the total demand to increase significantly. Production levels should be low, but as the manufacturer builds its reputation with lower prices, other companies will take notice and begin to place orders for a variety of steel products. Low pricing and reputation could attract power generation companies, such as GenH, or a variety of transportation or logistics partners who are also related to the steel supply chain.

Figure 22 illustrates that the MPS is never profitable or continues to become even more expensive to produce greater quantities of steel in time. This is not necessarily expected, given MPS are known to be initially very expensive before yielding great profits. Our team believes that our graph shows results contrary to our belief for a few reasons. First, we are assuming product growth rates are between 1 and 7 % each quarter but vary per product. We chose these values because it is more realistic to expect different levels of variability among different products. Second, because our design assumes that the current modules are performing at or near 100% utilization, additional modules must be installed to keep up with demand.

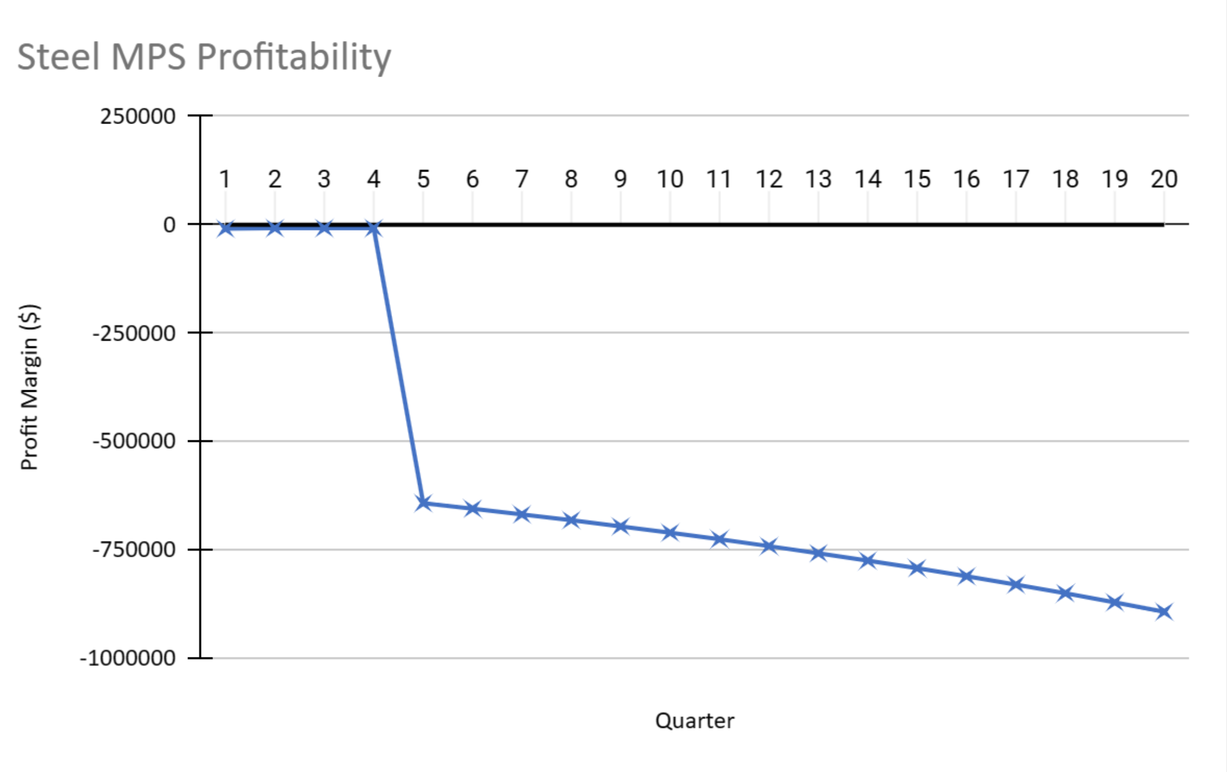


Figure 22 – Steel MPS profitability.

Perhaps both of our assumptions regarding growth and utilization rate are rather bold. Realistically, there will be expected periods of both high and reduced demand, and the growth or utilization rates should adjust accordingly. Third, the machines contained in the additional modules are also purchased at full price. These machines and equipment cost anywhere between $30,000 and $450,000, which has a far greater impact than the selling price or greater consumer demand. This observation endorses the suggestion our sponsor had regarding the machine types. For a true modular system to be economically feasible, the technology must be cheaper or more efficient than conventional machines. Since our team essentially put traditional machines into a modular design, the economics are not going to suggest the economic benefits.

Additionally, we should expect negative profitability for only the first year or so after deployment. The estimated profitability curve should approach greater, positive values, rather than continue the downward trend. Profitability also does not tend to follow a straight line either.

Upon noticing these trends, our team made several adjustments to the values entered in the spreadsheet to improve our projections and make them more realistic. Please note that the following screenshots are reflective of the edited P&L and do not necessarily line up with the previous screenshots we included in this report. A brief list of the changes and resulting profitability chart are shown in Table 15. Please see Appendix D for a thorough list of all the changes made, especially for points 1 through 6.

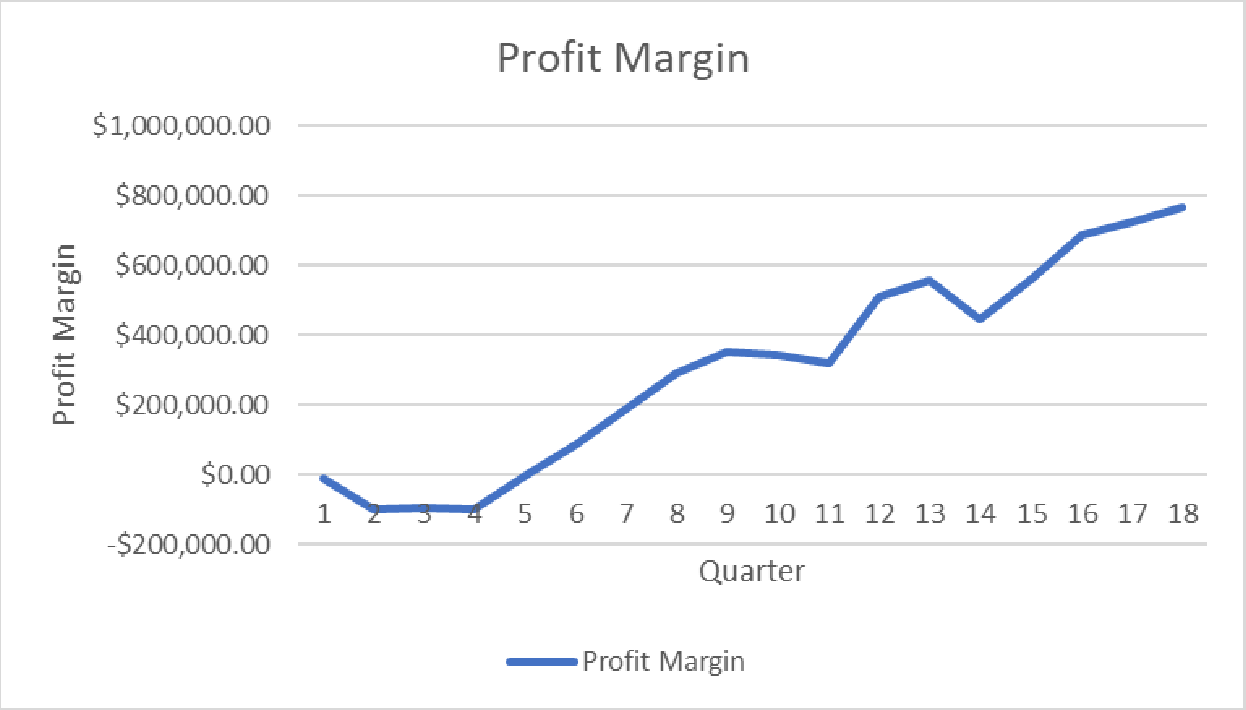


Figure 23 – Profit margin.

Figure 23 shows that how after our team made all the revisions, the profitability curve changes and therefore the design we recommended is somewhat profitable. Perhaps these changes are evidence that the optimal design can be achieved as improved estimates are inputted for the different product, equipment and process requirements. It should be noted that the true profitability will not necessarily follow this curve, given that changes in product or material availability, consumer demand, machine breakdowns, inventory selling price and other variables will impact this objective. Figure 23 follows the expected trends suggested by our research and sponsor. No revenue is generated in the first two quarters, since this is when the modules are being constructed. Production begins in period 3, although with an initially steep learning curve and training requirements, paired with a lower expected demand, the trend does not change until quarter 4. Starting in quarter 4, there should be a reduction in these issues and a positive gross margin.

Table 15 – Changes to P&L.

1. The number of most machine types was reduced.
2. The number of laborers was reduced by machine type. Also, we now assume laborers work 8-hour shifts, so the total number of laborers working at any one point does not change. The number of work hours was increased to reflect this change.
3. The machine leasing or financing price was reduced for the lathe, milling, printer and EAF.
4. Product starting and ending defective rates were reduced.
5. We ‘redefined’ one unit of a product to be something much smaller and more realistic. This should allow for greater throughput and utilize less electricity, time in inventory, labor and equipment costs.
6. The machine power requirements were revised to utilize less energy.
7. Inventory costs were separated from production costs, and are now $1.75 per lb per unit.
8. The cost of equipment and maintenance is now expected to rise 0.5% per quarter instead of 1% per quarter.
9. The growth rate per product type is slower.
10. Markup was redefined as 125% of the production price instead of 20%. This was a human error that previously contributed to the product selling price to be well below the cost of production.
11. The facility square footage was reduced from about 5200 square feet to 3500.
12. Improved sell-through rate to 75% from 70%.
13. The model was revised to include 2 quarters of set-up and 16 quarters of productivity.
14. Revise the equation for revenue. Originally, quarterly revenue was equal to the sum of revenues per product, multiplied by sell-through. However, this ignored the product that did not sell. We changed the equation to include that the leftover inventory sold half the normal price.
15. The rent price and facility electricity costs were lowered to $6.89 per square foot and 5.5 kWh per square feet per quarter.
16. Transportation costs were added since they were not previously in the model.

Due to the initial expenses associated with setting up the modules, it takes until quarter 5 when the net profit is 0. Starting after quarter 5, or 0.75 years after construction is complete, we predict the manufacturing system to be profitable.

Between periods 9 and 11, and between periods 13 and 14, the net profitability is still positive but declines slightly. This observation is due to the decrease in demand, significant change in selling price, and production ratios. To reiterate, switching between products and adjusting prices is one advantage of this modular production system. Had demand simply decreased, a regular steel manufacturing system would likely experience a more significant decline in profit. By the end of quarter 18, or 4 years after construction, the MPS yielded nearly $800,000 in net profit. We expect this trend to continue into future periods, although given the constraints of the linear program and greater uncertainty with forecasting many years in the future, we decided to not extrapolate our projections.

Our findings suggest that the manufacturer can expect profits close to a half-million dollars by the end of the fourth year. While this is a good sign, we can compare this figure to most traditional steel manufacturers, who generate profits between $500,000 and $1.5 billion dollars (*American Steel Institute*). This profit depends significantly on the size of the manufacturer, the items they are producing and the number of manufacturing locations. A better comparison may be to look at the overall return on investment, because modular production is not intended for mass production, but only when there is demand for certain, specialized product types. Furthermore, as we discussed in our literature review, traditional steel manufacturers produce 1.83 tons of CO2 per ton of steel produced. While our team was unable to calculate the total emissions in our design, we would expect the amount to be significantly lower due to the machine types and production processes.

Similarly, the cash flow represents the difference in money entering and leaving the company from one period to the next. Notice how in Figure 24, the cash flow is not net positive until quarter 7. Cash flow decreased in the first few quarters since the MPS is still being constructed. Starting in quarter 3, revenue is produced, however it does not offset the expenses of equipment or production. Until quarter 5, or 0.75 years after construction is complete, cash flow reaches its lowest value of nearly -$300,000. In other words, in quarter 5, $300,000 is flowing out of the company. Between quarters 5 and 7, the cash inflow starts to increase, but more cash and equivalents are still leaving the company.

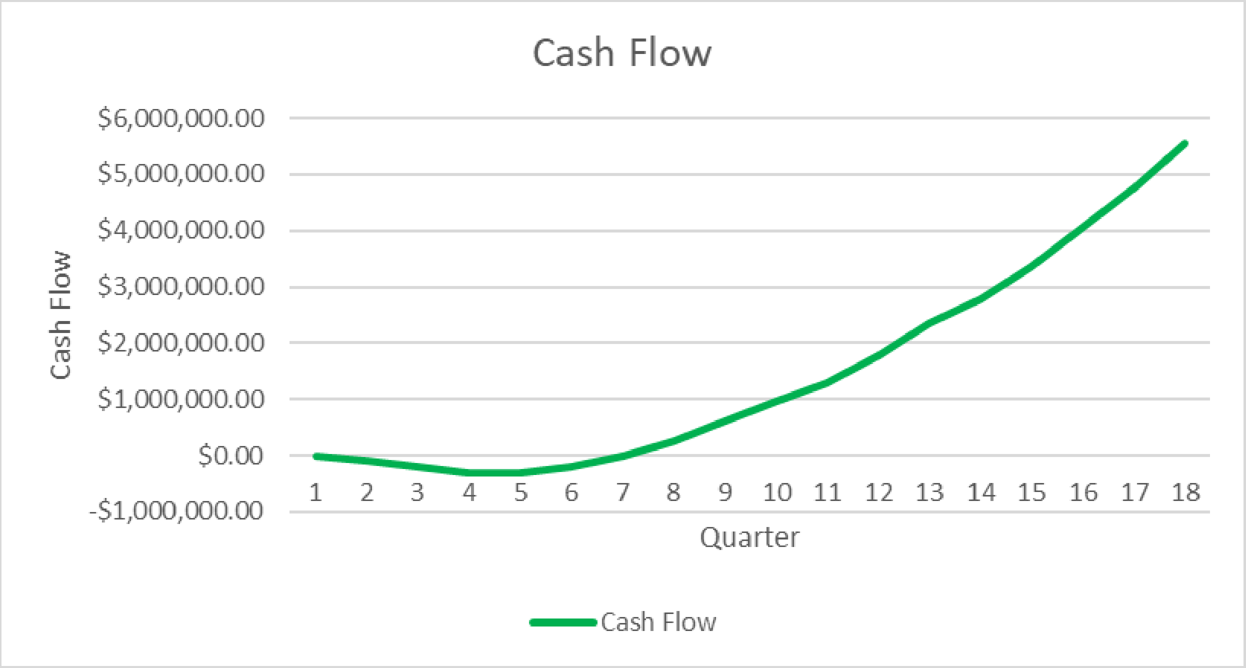


Figure 24 – Cash flow.

The total cash flowing into the manufacturing company does not surpass the total cash flowing out until quarter 7. Cash inflow then increases steadily in the next three quarters before projecting almost $6 million in quarter 18. If these projections continue, it should be expected that cash inflow will continue to outpace cash outflow for the next few quarters before eventually leveling closer to a constant amount. This finding indicates that the owner of the facility will earn high returns on their estimate.

Lastly, our team developed a third graph that illustrates the cost of financing over the same 18 quarter period. To reiterate, for the first two periods only the cost of the facility must be paid. Between quarters 3 and 5, the cost of production is slightly greater than the total revenue earned. Recall this observation is seen in both the cash flow and net profit charts. To be able to finance these first few quarters, loans will need to be borrowed, or funding should be acquired through other means. Starting in quarter 7, total revenue is greater than the four major expense categories (facility, production, equipment, and transportation). Beyond this quarter, the owner can expect to finance their operations through the revenue earned from selling the product. This finding indicates that our MPS will likely be profitable in at least 1.5 years. This is beneficial because the owner can project how much will need to be borrowed, and when they can expect to earn a return. It reduces the risk of taking out larger than necessary levels of debt, and prevents the risk of defaulting.

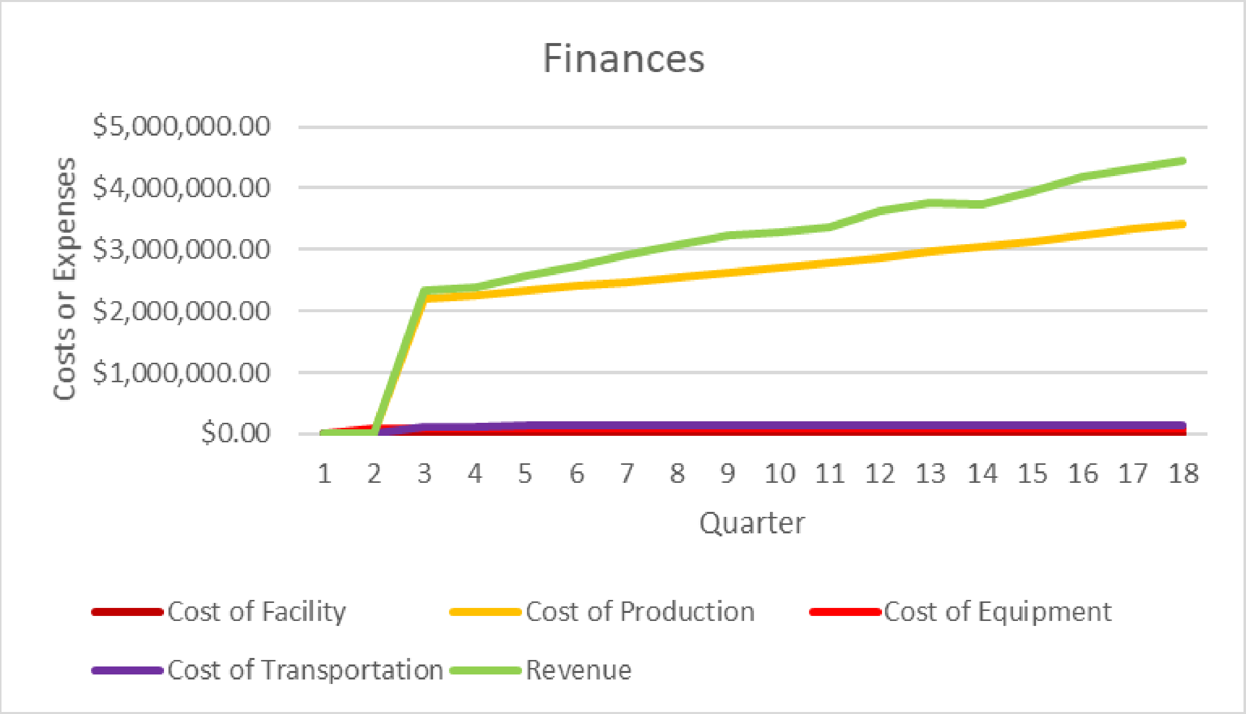


Figure 25 – Finances (costs and revenue).

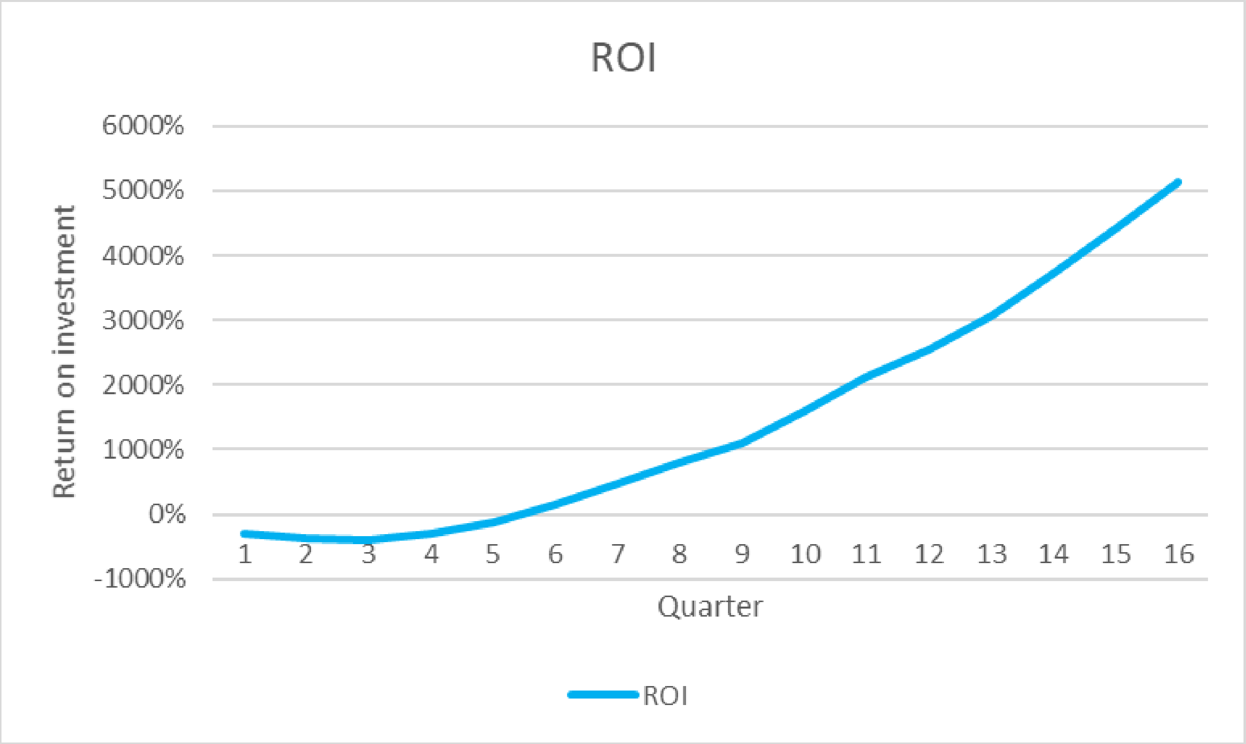


Figure 26 – ROI (quarterly)

Our team calculated return on investment in a few ways. First, we calculated ROI by period as shown in the figure above. It was determined by subtracting the successive quarter's cash flow from the previous quarter's cash flow. This result was then divided by the previous quarter cash flow and converted into a percentage. We found that the expected return on investment follows an exponential growth curve, although we do not believe this trend to continue if we forecasted multiple periods out. There are always periods of growth and decline. As expected, the first two periods have a negative ROI because production is relatively low and has a high learning curve/number of defective. It is not until period 5 where the sale of products has brought in enough revenue to offset the initial investment costs. The ending ROI after 4 years, or 16 quarters, suggests that the manufacturer has the ability to make over 5000% times the original investment. This value might seem large, but should be expected given the length of time and that this calculation is based on the original investment. Because it is from quarter to quarter and the revenue increases significantly between periods, we believe this is why the percentages are so great. We found that traditional ROI has fluctuated between -20% to 23% annually since December 2009. In December 2022, the industry ROI was at 12% and headed on a downward trend.

Because the industry ROI measures the difference from successive periods (typically years), we recalculated our ROI to make comparison easier. We used a similar formula, taking the difference in cash flow between quarters 4, 8 and 12, to find the new ROIs. For example, the ROI in quarter 8 was the difference in net profit between periods 4 and 8 (see Table 16). This amount was divided by the previous investment. The results of these calculations are listed below. Notice how in quarter 12, the ROI is finally positive. We expect it to remain positive for the coming quarters since revenue will stabilize and the profit margin is still greater than the initial investment expenses.

Table 16 – ROI by year.

Quarter (Year)	4 (1)	8 (2)	12 (3)	16 (4)
ROI	-303%	-547%	191%	98%

Our team believes that these findings may also be skewed because of the difficulty we faced obtaining legitimate data. We do not estimate our values to be too far off, however. It should also be noted that while our findings suggest the MPS design we developed to be profitable, we believe there are other, similar designs that are even more profitable. Furthermore, the profit and loss spreadsheet we developed is very detailed, as discussed in section 3.3.1. If anything, our sponsor could use this as a tool and input updated estimates, or change the machinery and equipment types to meet their needs, similar to the process we did upon studying the P&L. As we have discovered, even slight changes could have significant impacts on the overall return on investment, profitability, and impact the timescale of deploying the MPS. It is also worth reminding the reader that our second objective was to determine the economic feasibility of implementing a steel-producing MPS on the basis of a positive net profit margin and ROI. While we determined our design to be capable of achieving a positive net profit margin or ROI, we believe there are many opportunities to expand on this model through other research, as mentioned in section 5.2. The P&L is essentially a giant optimization problem in itself, and while it is difficult to pinpoint the best design, the user can consistently make changes to try to find a better, more profitable solution.

For reference, screenshots of our P&L tables are available in the appendix E. However, to truly encapsulate how the tables are interrelated, and if changes are desired to be made by the user, we recommend reaching out to our team.

4.2.2 Monte Carlo: Analysis of MPS Characteristics and Their Economic Effects

Using the @Risk software, we analyzed the sensitivities and probabilities of our economic metrics. Due to the project timeline and metal manufacturing company confidentialities, we were unable to obtain the relevant data on potential product manufacturing processes, costs, and profits. As described in Section 3.3.1 , we created a set of prophetic data based on research, steel industry characteristics, and assumptions to conduct a hypothetical analysis. Since the prophetic data on product manufacturing times, defect rates, inventory costs, etc. significantly affect the results of the Monte Carlo, we decided to analyze how unique characteristics of the modular production system influence the economic trends seen in the analysis. By exploring the characteristics and their impact on economic metrics, we can extract information independent of the prophetic data and could be generalized for any MPS in the steel industry.

Some of the characteristics that differentiate modular production systems from traditional manufacturing systems include the higher quality of products, versatile machine set(s), and production processes. The versatile machine set allows for a large variety of production processes which makes production very flexible. Since machines can be quickly configured for producing another product, an MPS can stop manufacturing a product if the product is deemed no longer profitable and the machines can be configured and start production for the next product in less than a day. Flexible production allows a system to stay competitive in the market, maximize high sell-through rates, keep up with product innovation, and minimize inventory and risk. The flexibility of MPS is portrayed in the economic analysis through cell-switching (P&L Table D), quarterly production ratios (explained and optimized in Section 4.2.3), and sell-through rates.

MPS offer higher-quality goods and cost-effective production for medium and low-demand products. Generally, in traditional metal manufacturing, the product is designed and then a production system is constructed for high-volume production, resulting in high initial costs to create the highly automated process, low per-unit costs once in production, and an inflexible production system. However, if the product is not profitable in such high volumes, creating a system for mass production is not cost-effective because the low cost of production does not offset the high initial cost of creating a production system for that product.

Since products in MPS are designed for manufacture, the cost of designing the product is higher and the cost of producing one unit is higher, however, the cost of starting production and risk for a product is much lower, making it more cost-effective for low-volume products. Additionally, the lower volume production requires more attention to product quality and defective rates since the unit costs are higher. Thus, the margin risk is lower if it is not adequately managed.

MPS-enabled production impacts construction time and costs, making production flexible and responsive and significantly decreasing waste (P&L Table D.1). The impacts of the modular characteristics are apparent in many economic trends. These trends hold true whether the data used is accurate because they result from the characteristics, not the data itself.

An MPS should have lower defective rates than those shown in P&L Table N due to more frequent quality inspections. However, higher starting defective rates are used for a more conservative analysis. Table 17 summarizes some of the mentioned characteristics and economic trends and other economic benefits that became apparent while analyzing the input sensitivities and output statistics’ probability distributions from the Monte Carlo Simulation (output statistics are shown in P&L Table R).

Table 17 – Modular production system characteristics, their effect on manufacturing, and the economic benefits.

MPS Characteristic	**Effect of Characteristic on MPS Manufacturing**	**Economic Effect / Trend**
Design for manufacture (DFM) and medium to low volume production	Lower defect rate, higher quality goods	More cost-effective and higher profits; good customer retention rates → higher sell-through
Versatile machine set	Quick and cheap production switching between products	Higher sell-through rate, quick market response/competitive market
Versatile machine utilities in cells and product switching	Less overproduction	Lower inventory costs and lower proportion of discounted selling price (higher sell-through; higher average profit per unit)
Modular, transportable manufacturing design in a non-permanent location	Lower initial investment for establishing the facility	Higher return on investment (ROI)
Standardized MPS design for deploying a facility (in an existing facility)	Quick start-up time	Higher return on investment (ROI)
Versatile machine utilities in cells and product switching	Lower product investment cost, lower risk pursuing a product	Higher profits or lower loss on products with a short success-lifespan or that flop
Versatile machine utilities in cells and flexible production process	Quick, low cost adjustments to product design and production	Higher market retention on high rates of product design changes and innovation
Design for manufacture (DFM) and medium to low volume production	Lower product investment cost and flexible product configurations	Targeting an underserved market for medium to low demand semi-specialized goods

4.2.3 Monte Carlo: Analysis of Simulation Outputs

As mentioned in previous Sections, due to the lack of access to steel companies' data, much of the data pertaining to the products and labor requirements are prophetic or mock data. Assumptions surrounding these prophetic data about the MPS design, scenario, and data tables can be found in Sections 3.1, 3.3.1, and 3.3.2. We recognize that the results of the Monte Carlo Simulation hinge on the data and the assumptions we made, and could be very different from an economic analysis with a company’s real data. However, we have laid a framework and produced a model for analyzing the economic success of a modular production system that someone with industry data could use by substituting the prophetic data with their industry data.

The first output statistic is the quarter the MPS breaks even. This statistic is important because it shows how quickly the business will become profitable, or if it will ever become profitable. The probability distribution of the break-even point is unimodal about a mean of 11.36 with 74.9% of samples yielding an output of three years or less. The distribution can be seen in Figure 27.

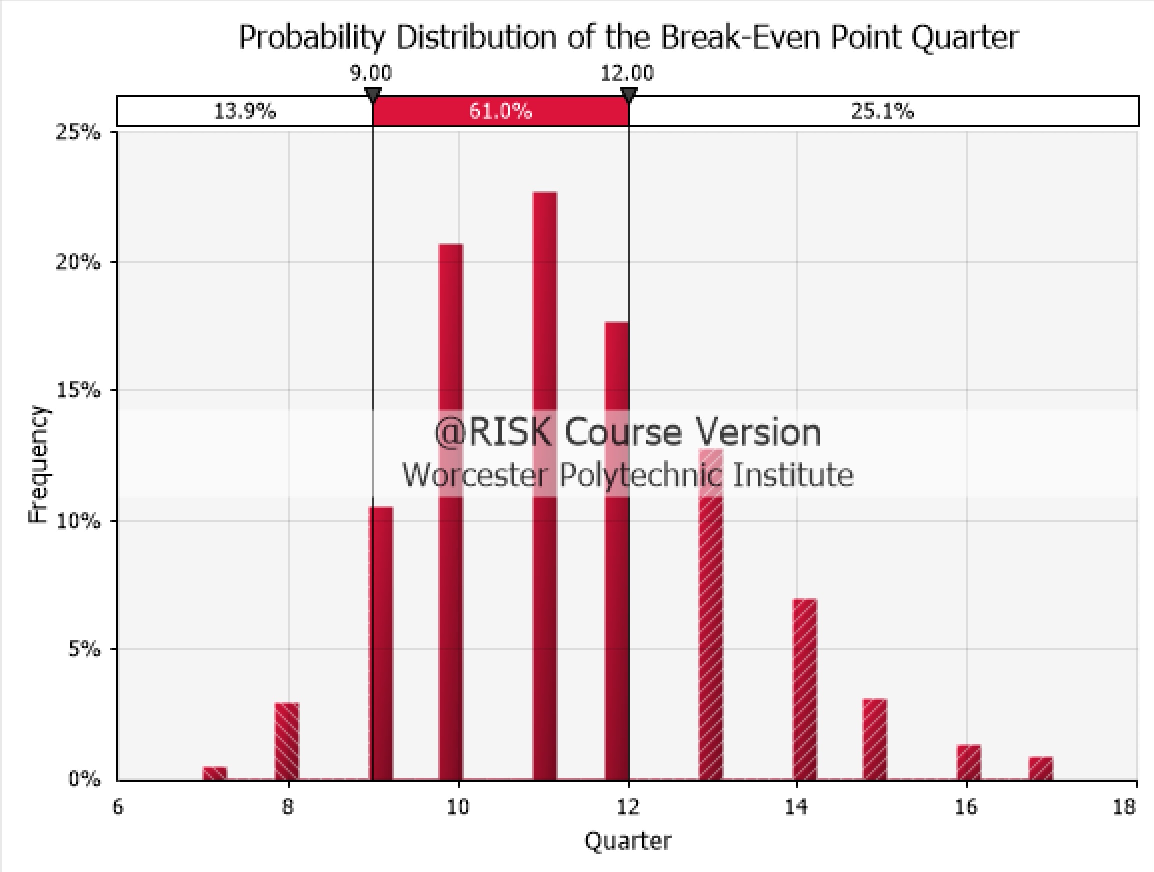


Figure 27 – Probability distribution of the break-even point by quarter after production starts.

The second output statistic is the cash flow one year after the break-even point. This statistic is meant to help better understand the growth of the process and the magnitude of its economic success. Like the first output statistic, the cash flow after four quarters has a unimodal, symmetrical distribution, and 90% of samples fall between $555,044 and $1,272,638 (Figure 28). This figure shows that the start-up period and the time until positive cash flow in a properly deployed modular system is certain to be positive and could start increasing very quickly. Additionally, in 81.4% of the iterations, the cash flow is at least $714,000 which is double the initial investment before starting production, meaning there is a high probability of breaking even within a few years of starting deploying such a system.

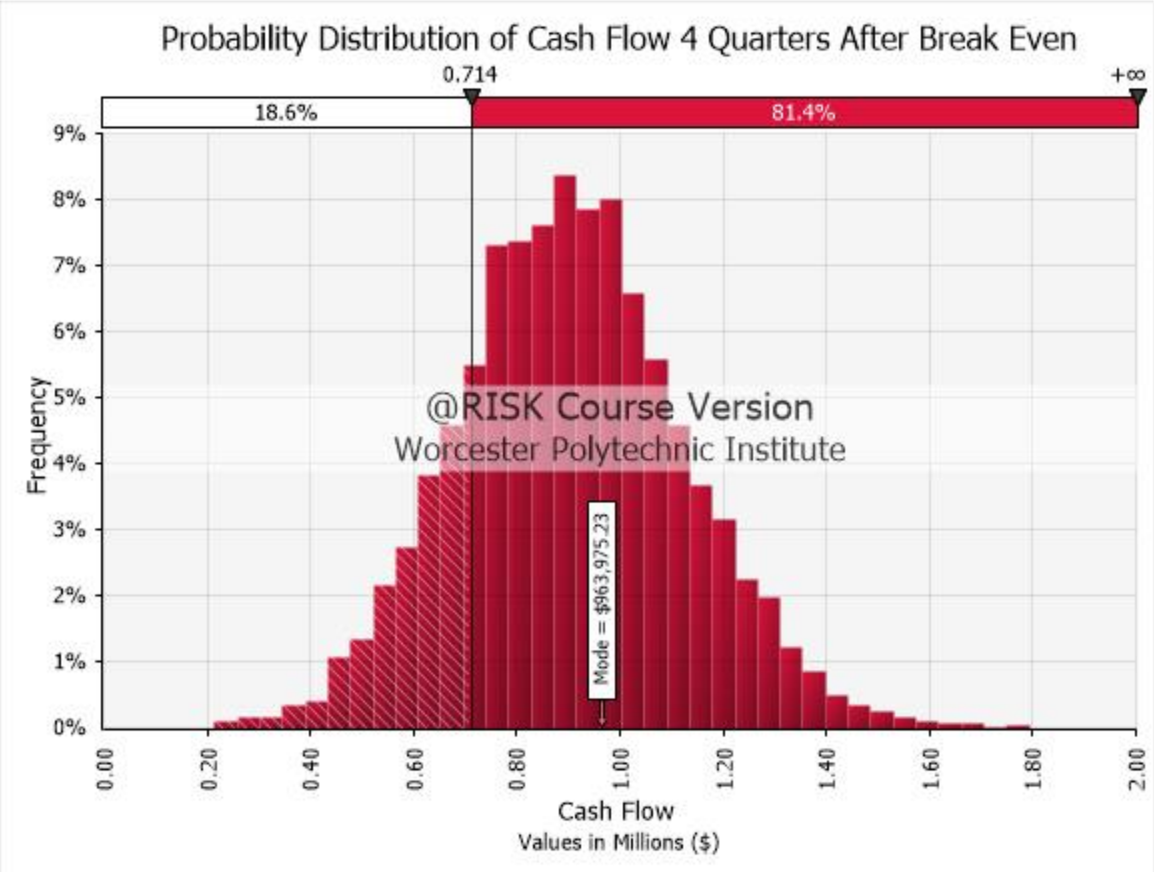


Figure 28 – Probability distribution of the cash flow four years after breaking even (including the quarter in which the MPS broke even) .

The third output statistic is the growth rate of the profit margin after breaking even. This is an interesting statistic because it shows the growth of profit margin from quarter to quarter which is a result of the annual expected growth rate, quarterly sell-through rate, and the decrease in defects due to the learning curve. 90% of the iterations yielded an average growth rate between -18.4% and +100.1%, meaning that despite having positive cash flow, the profit margin is not ensured to increase (Figure 29). However, over 80% of samples did have a positive average growth rate.

A tornado diagram of the effect of uncertainty variables on the average growth rate shows that the main impacts of changes in profit margin are the sell-through rate, certain maintenance costs, rent price, and costs of production by product (Figure 30). For each bar, the left side shows the magnitude of the variable’s negative impact on the output statistic when the variable is more pessimistic than expected and the right side shows the magnitude of the variable's positive impact on the output. The tornado chart summarizes the effects of all 5,000 of the iterations run.

Almost all of the bars are red, or represent ‘input low’. This means that which collecting data at each iteration, the input was considered low, or having a negative impact on the average growth of the profit margin. In fact, the only variable that is shown as a 'high input' was the sell through rate in Quarter 16. However, this positive result is likely not specific to Quarter 16 because all sell through rates are uncertain and have the same probability distributions.

Since the sell-through rate in quarter 15 is listed first, it had the most influence on the average growth rate. It makes sense that the sell-through rates are ranked highly for influencing the growth rate of the profit margin because they directly impact the revenue as a 'scaling' coefficient. A few 'total value added' variables make the list of 16 most important variables. These represent the labor time required to manufacture a unit of that product type, which impacts the labor costs, and increased electricity required to operate the machines when producing it.

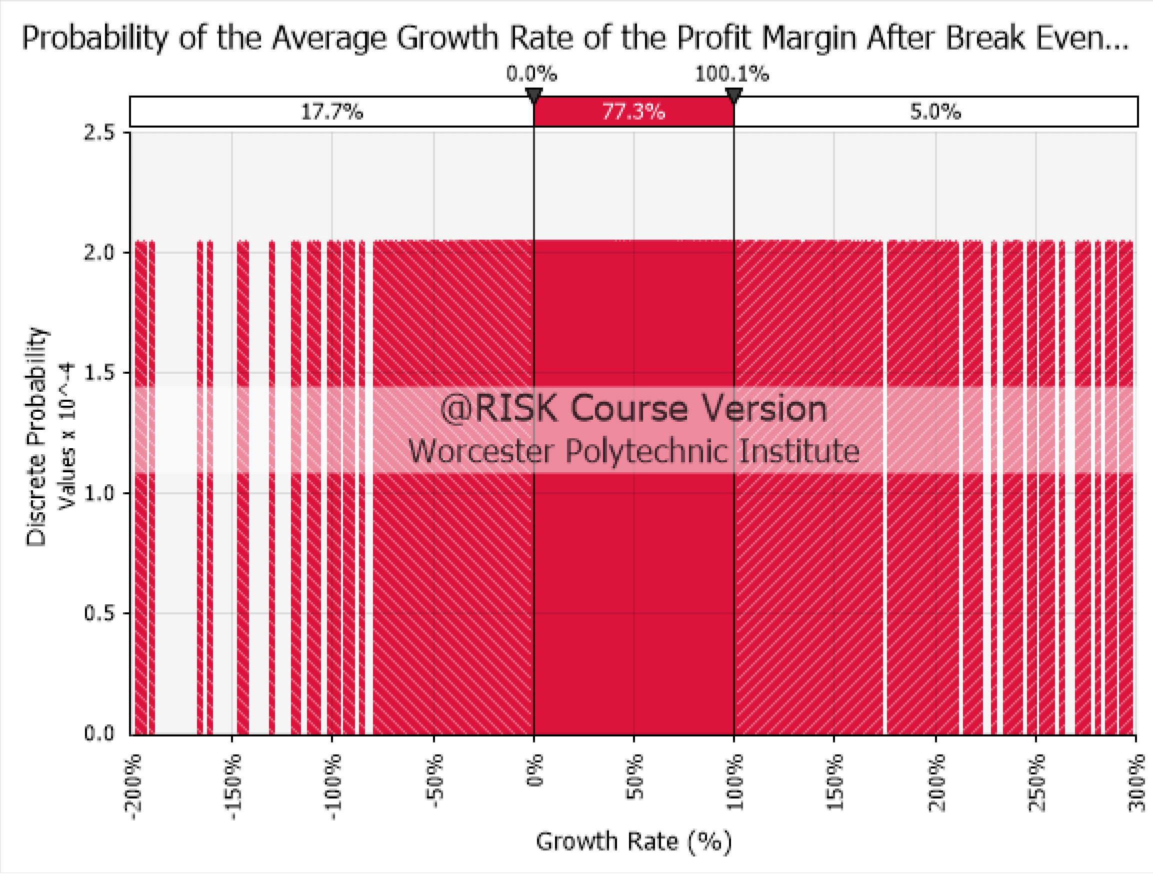


Figure 29 – Probability distribution of the average growth rate of the profit margin after the break-even point for a Monte Carlo simulation with 5,000 iterations.

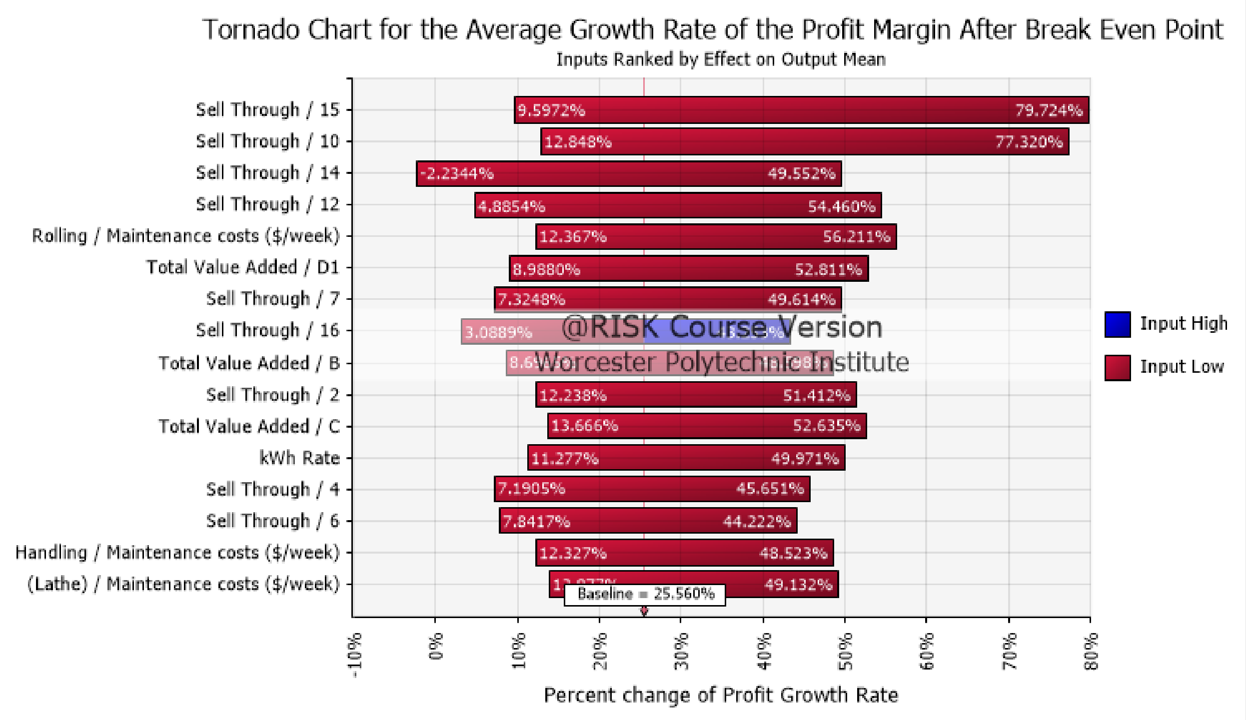


Figure 30 – Tornado chart with the impacts of variables on the average growth rate of the profit margin after the break-even point.

The last two output statistics are the return on investment (ROI) four quarters after the break-even point and the ROI in quarter 12. Figure 31 shows the unimodal, symmetrical distribution of the annual ROI one year after breaking even. Similarly, Figure 32 shows the probability distribution of the annual ROI three years after production, while Figure 33 shows the cumulative probability distribution of the annual ROI after three years. Of the 5,000 iterations, 82.50% of them had an annual ROI of 178% or larger.

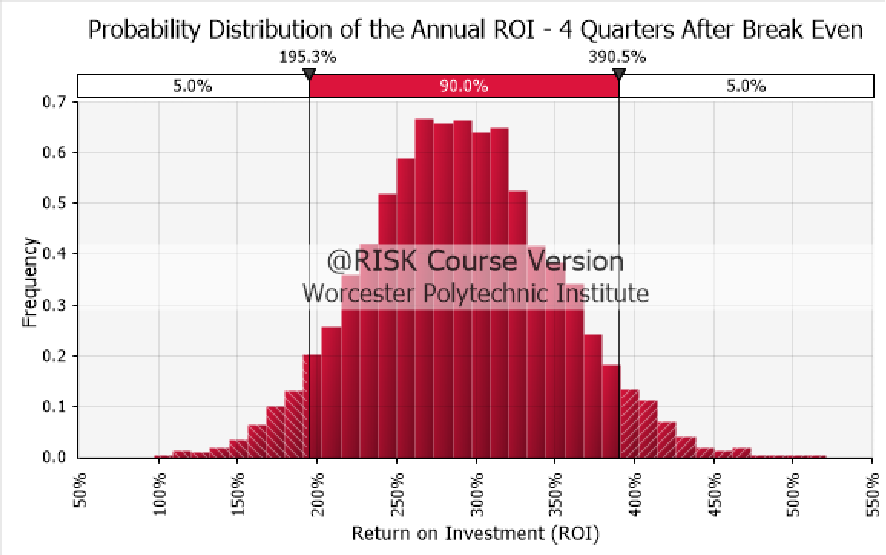


Figure 31 – Profitability distribution of the annual return on investment less than one year after the break-even point.

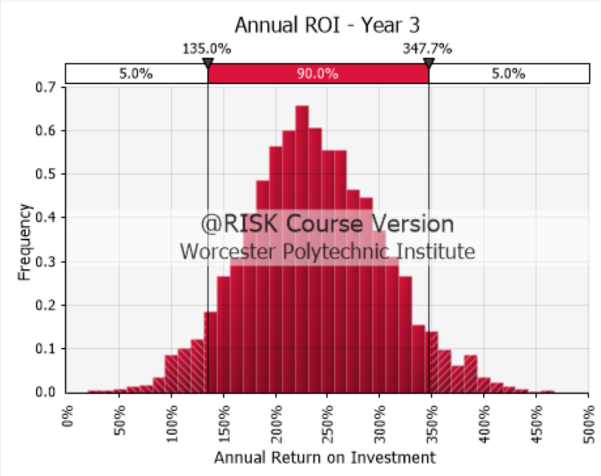


Figure 32 – Profitability distribution of the annual return on investment after three years of production.

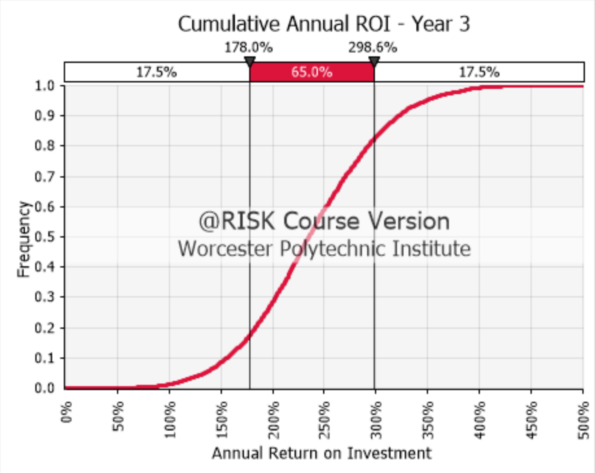


Figure 33 – Cumulative annual return on investment after three years of production.

Considering each of these output statistics and their distributions, we can be confident that the modular production system will break even before the third year of production and that the annual ROI will be greater than 178%.

4.2.4 Linear Programming

The purpose of the linear program is to model the modular production system's functionalities for production efficiency through product switching to adapt to a recession. As previously mentioned, the Producer Price Index models the demand for steel products during the economic scenario. The linear program utilized the Producer Price Index to optimize the production ratio and find the maximum revenue. The fluctuations in production ratios are seen in Figure 34.

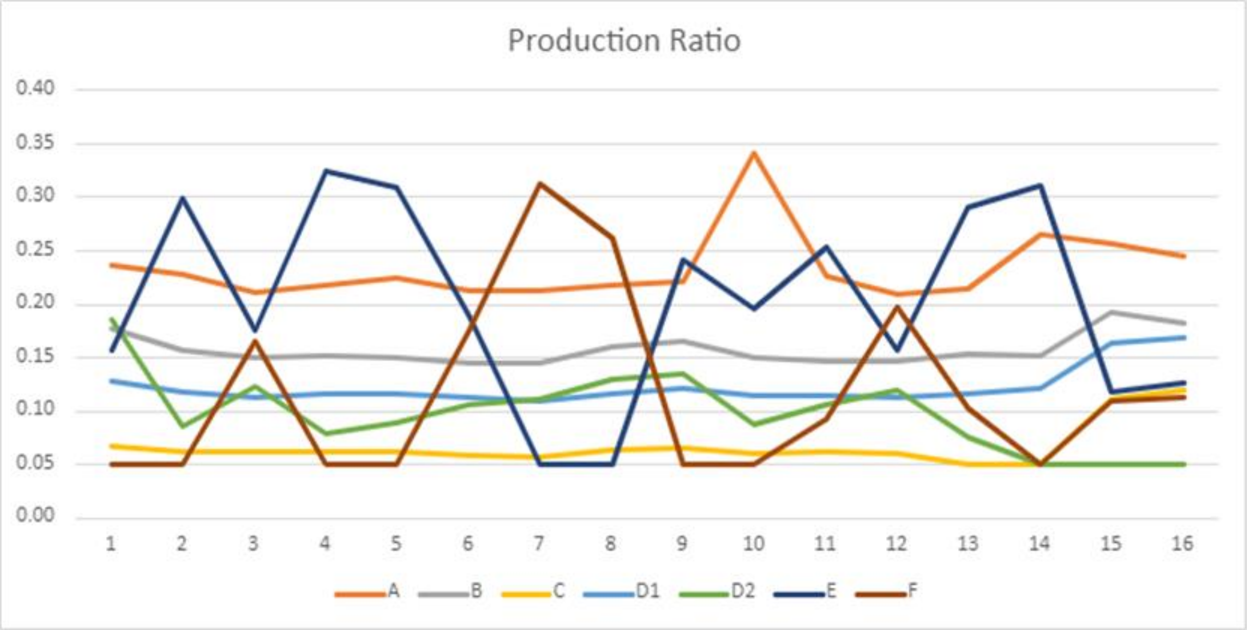


Figure 34 – Production ratio over time.

The graph above shows the changes in the production ratio for each product over time. The timeframes to focus on are from Quarter 1 in 2007 to Quarter 4 in 2009, which is when the economic scenario, recession, occurs. From this graph, we notice that Products B, C, and D1 maintain fairly consistent ratios throughout the time frame. These products hold low production rates, indicating that these products are not as profitable as others. Products E and F have the largest fluctuations throughout the four years and with heavier changes during the recession. Additionally, these products have the highest selling price, possible electricity consumption, and labor costs indicating they will have higher demand. Figure 34 shows the capacities of the linear program to detect profitable products decreasing waste of production.

The recession started in the last quarter of 2007 (Quarter 3 in the linear program) and ran until the second quarter of 2009 (Quarter 10 in the linear program). Here is the period that we expect to see knowledgeable fluctuations of cell switching and changes to ensure that the production of each product creates the maximum revenue. The number of cells is developed through the production ratio to account for the demand and sell-through during the recession; Figure 35 shows these fluctuations.

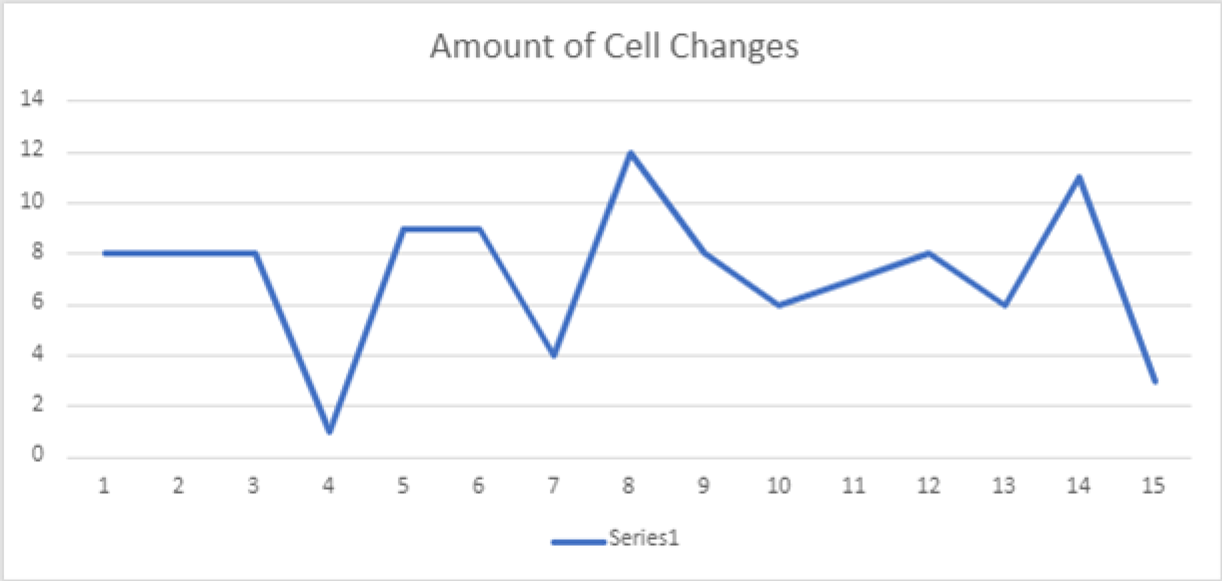


Figure 35 – Cell change fluctuations over time.

Note that X-axis denotes the present quarter we are in minus 1. If we are evaluating Quarter 4 in the graph, we are evaluating Quarter 5 in the linear program.

The linear program focused on the goal of maximum revenue allows our Modular Production System to present the benefit of cell switching. In Figure 35, the amount of cell switches drops when the recession starts, indicating that product production is being optimized. In the next quarter, we see a rise in cell switching to create a more profitable production ratio combination. This figure also shows the functionality of the modular production system to adapt to production changes by a standard setup and disassembly cost.

We have seen the recessions' effects on the change of production ratios and cell switching. Throughout the analysis of the steel modular production system we have seen the ability of adaptation to react to demand changes, now we look into the profitability of the system, the quarterly revenue.

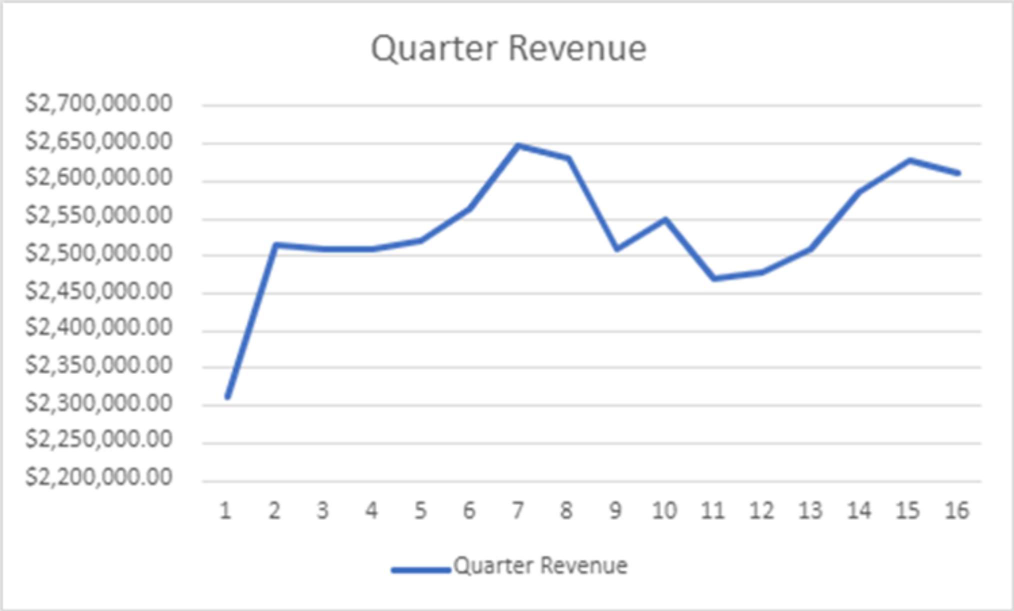


Figure 36 – Quarterly revenue (linear program).

Figure 36 shows the quarterly revenue over the four-year period. At first glance, the trough is in the first quarter, $2,311,626.54, and the amplitude is in the seventh quarter, $2,646,789.41, height of the recession. The objective that the linear program maximized was the sum of all the quarterly revenue, $40,545,286.56. The maximized revenue means that the system has the opportunity to be profitable and that cell switching is essential to adapting to unpredictable demand because of the accessibility in change. The linear program models what key production limits of the facility are, labor and electricity consumption, and provides a tool to develop an outline of how a steel modular facility will behave.

4.2.5 Decision Tree

According to the constructed decision tree, the most profitable decision in the long-term appears to be constructing a modular production system for steel. The expected payoff varied between $10.5 and $14.5 million for all its branches, though it was at its greatest at $14,400,000 over an expected lifespan of about 20 years and has a probability of 2.4% that a modular design is chosen. This payoff is associated with subsequent decision branches. It would still utilize energy from the grid, perhaps using existing energy infrastructure, mining raw materials, and locating the facility close to the target customer market. This result is not all that surprising, given that current research has suggested module designs have the potential to save significantly on annual expenses. It should be noted that the most likely scenario if a modular design is chosen, however, would be to build energy infrastructure for a non-grid or renewable energy operation. Raw materials would need to be purchased, and the distance to customers would likely be much farther away than desired. Still, this payoff is around $11 million, and has an occurrence likelihood of 14.85%.

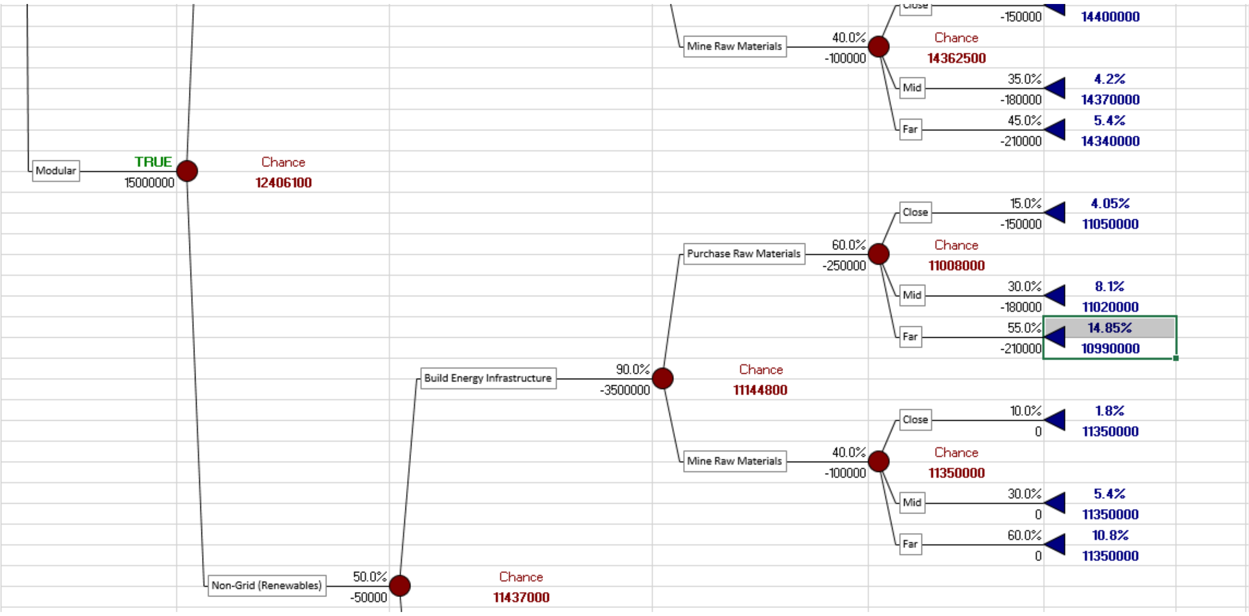


Figure 37 – Decision tree results.

Similarly, the traditional production system design is profitable, but yields lower margins between $4 and $8 million. They might be the safest bet financially, given the technology and materials to develop steel are well-established and there is little risk of failure. Interestingly enough, the branches associated with the hybrid design do not seem to be very profitable, yielding a net loss between $0 and $3 million. Our team reasons this might be the case, in reality, because not only would manufacturers need to acquire the traditional equipment and materials to build their operations, but will slowly need to change processes over, which could be costly. Furthermore, a portion of the operations will need to stop production to allow for new process construction. Recall that the new processes and equipment are also initially very expensive, and it takes a few years before earning back on the investment. It was difficult to model the element of time in this model too, which does not help as there was no way for our team to show this constraint. We found it interesting that this hybrid option was the least profitable because it also matched our findings from the profit and loss analysis, and the feedback we heard from our sponsor.

Given the way our team built this model, we would expect the decision and set of nodes with the highest payoff to be dependent on maximizing payouts and minimizing expenses. For example, we would expect it to be cheaper to use a renewable energy source eventually since it would be almost free, outside of maintenance. Using the current infrastructure would be cheaper than building it on our own. We would also expect it to be cheaper to mine our own materials over purchasing from suppliers, however, the probability of succeeding would be slim because of the limited locations of natural resources. Ideally, the manufacturing facility would be located closer to the customer, but the likelihood of this is low, given most customers will be coming from other places. Our model confirms that the most profitable outcome would follow the path of modular -> grid energy -> use existing energy infrastructure -> mine raw materials -> close customers.

Similar to what we described with the profit and loss analysis and results of the Monte-Carlo simulation, this decision tree serves as a tool that our sponsor can use to explore payoff scenarios. Given we do not anticipate any sort of MPS for steel to be produced for at least five years, the associated payoffs, costs, and probability occurrences will likely change. Because this tool is Excel-spreadsheet based, the decision-maker can simply input updated figures or add new chances or options as they see fit. Our team believes this method was successful and partially helped us achieve our third objective. We identified some risks and modeled how the different options could impact MPS deployment profitability and where the current supply chain could be interrupted.

4.2.6 Modularization Drivers

From the design and Monte Carlo analysis, we were able to explore the impacts of the modularization drivers list we had constructed in Section 3.2.5.

Our design approach and assumptions will most likely not be the same as MPS companies in the future, which will result in differing assessments of sensitivities within modular production systems. However, we believe our analysis can provide insight on the importance of some modularization drivers and general tendencies in the steel and metals industry.

Using the @Risk software in our Monte Carlo Simulation, we were able to construct sensitivity charts such as spider diagrams and tornado charts, as described in Section 4.2.3. Tornado charts show how variables impact the output statistic when variables are 10% to 25% less than expected and when they are 10% to 25% higher than expected, resulting in a greater or smaller impact on the output statistic, depending on the importance of that variable. The impact these variables have on the output is also referred to as the sensitivities of the inputs in the model.

As we saw in Section 4.2.3, the variables with the most impact on the model are sell through rate, cost of production, and manufacturing overhead mark ups, where the importance of these variables changes on the focus of the output statistic. However, it is difficult to predict the sell through rates accurately and the cost of production is prophetic data so the exact importance of the cost of production will likely change relative to other variables. Lastly, the facility manufacturing overhead rate is a coefficient that has direct impact on the revenues. While we cannot definitively rank the importance of various modularization drivers, we can suggest that production variables such as time and defective rate are very important. However, many of the modularization drivers discussed in Section 3.1.1 were not in the scope or not possible to analyze in our prophetic model and we cannot give conclusive comparisons between these drivers.

4.2.6 Risks

We believe that the summary of additional risks mentioned in section 3.3.5 is fairly robust and illustrates many potential decisions and points of failure that our sponsor or anyone deciding to build a modular production system for steel will need to determine. A significant underlying theme shared among most of these risks is their impact on the supply chain. There have been numerous supply chain crises in the world in the past two to three years specifically. Recall that the modular design is known for allowing the manufacturing company to have the option of relying on fewer parties. For example, the manufacturer could decide to mine the raw materials, use renewable energy sources to power the facility, and manage its own freight and logistics system to essentially oversee all the steps required to create a product for customers. The models we developed do not capture all of these risks but perhaps could be included if this project were to be revamped in the future.

Perhaps some other key takeaways from outlining these risks include the power of the decision-maker in times of economic uncertainty. In periods of inflation or recession, this modular manufacturing production system is advantageous in that the manufacturer has options to minimize potential losses. Financing, leasing and owning equipment all have their own benefits and drawbacks at different points along the construction and production timelines. Despite our best attempts to characterize and define risks relating to the implemented energy source, the decision to purchase or mine raw materials, transportation and logistics, and type of building infrastructure is still very difficult to quantify how these options could impact profitability. Nonetheless, we believe they were necessary to allow for some discussion and consideration for the decision-maker prior to constructing a steel MPS.

The main advantage of this production type is that it can incorporate many environmentally friendly technologies that have yet to be implemented in most manufacturing facilities. As with most new or “green” options and technologies, it will likely remain very expensive to initially switch to using “off-grid” power, moving to a remote location, and managing their own transportation and logistics program. However, even implementing one notable change or eliminating one or more unnecessary partners from the supply chain could allow for a manufacturer to lead innovative change in the industry. Perhaps making these changes are necessary steps to work towards gaining a greater portion of the steel manufacturing industry. Overall, we feel that developing this ‘risk analysis’ has been helpful in achieving our third objective because it provides our sponsor with other considerations that are not captured by our quantitative models necessarily.

5.0 Conclusion - A Word of Caution

Prior to exploring any recommendations, our team would like to reiterate that our findings should be taken on the side of caution. As mentioned in previous sections, we had to estimate our data points to the best of our ability. The true values for costs or expenses, demand or revenue will likely depend on the manufacturer's interests and needs. Many of the external risks as explored in the decision tree, Monte-Carlo simulation, and risk analysis will likely have an impact on the overall profitability. Our team was unsuccessful at determining how to implement these risks, although an analysis for future considerations is explored in section 5.2. In essence, we developed a series of tools that can be used as a template. The profit and loss analysis is an editable spreadsheet, where our sponsor, or anyone reading this report and wishing to recreate their own results, can input their own estimates. Since profitability is influenced significantly by the value of time, this provides a decision-maker with the option to manually adjust the results as necessary.

Our team believes that the greatest uncertainty lies in the machine maintenance, operational, and financing estimates. We adjusted these estimates several times to observe how overall profitability responded. We decided to omit most of our analysis on these observations since there are an infinite number of ways the input data could be adjusted and results compared. However, we suggest those interested in applying our framework to do the same if there is a particular variable worth studying. It could be worth verifying the production process estimates to determine that our team's estimates are in the range of most probable likelihood. Additionally, this could impact findings through the linear program or Monte-Carlo simulation. While our team found these tools interesting and insightful, we did find the results to be somewhat surprising. This suggests three possibilities. First, there were errors in how we developed these models. Second, our estimated data points were far off what they should have been, leading our team to make false conclusions. Third, the models and data estimates were realistic. However, our interpretation and analysis of the findings were incorrect.

Despite these challenges and possible nuances in our findings, our team believes we achieved the three objectives we set out to accomplish at the beginning of the project. ***First, we hoped to improve our team and sponsor's understanding of what modular production systems would look like in the steel industry.*** We set out to research possible machine types and technologies that could be incorporated into such a system. While our sponsor had pointed out the limitations of our design, we acknowledge that there is limited data available to have included accurately. We developed a full MPS design concept that illustrated product flow and gave suggestions to consider when implementing this system.

The second objective we set was to determine the economic feasibility of implementing a steel-producing MPS on the basis of a positive net profit margin and return on investment. The profit and loss analysis suggests that developing a system is theoretically profitable over time, generating just under $800k at the end of four years. The system is cash flow positive nearly one year after implementation, and the total revenue outweighs the four main cost categories (facility, transportation, production, and equipment) in quarter 3 and thereafter. The annual return on investment is also positive between 2 and 3 years after implementation is complete. While these findings may be unimpressive, recall that MPS are not designed for mass production. The system we designed should only generate approximately as much product as is in demand. Furthermore, the Monte-Carlo analysis informs us that there is significant variability in what the expected outcomes can be. Given such a system has not been implemented, and given that demand could theoretically be very different than our expectations, the results are difficult to trust completely. The results from this model suggest that the MPS system leans slightly more profitable. However, our more conservative estimates suggest it will likely take two years after deployment or implementation to achieve break-even. Similarly, the linear program suggests how external events, such as economic recessions can impact profitability. It provides the decision-maker with a tool to decide how to adjust operations to maximize revenue. For example, it recommends what product type(s) to prioritize during manufacturing, what cell modules develop additional or collapse, and how to adjust the selling price.

The third objective we aimed to achieve was to find a way to categorize risks and minimize potential points of failure in the system. First, our team identified several risks based on the assumptions we made in the different models we developed. Next, we explored each risk. We researched these risks through our literature review, talking through interviews with our sponsor and other key stakeholders, and compiling any limitations we sought not having been explained in other methods. We designated sections 3.3.5 and 4.2.6 to communicate these risks to the reader to aid in the decision-making process when deciding to deploy an MPS.

The following sections include our recommendations to our sponsor and decision-makers considering MPS deployment in the steel industry as well as future project applications.

5.1 Recommendations

Based on our findings, our team hopes to provide our sponsor with a few thorough recommendations. First, we recommend building a steel MPS. Perhaps such a system should not be constructed immediately, but our analysis revealed that the financial benefits will be realized within two years after construction is complete. The profit margin, statement of cash flows, ROI and major cost comparisons all indicate that such a system will continue to be profitable, at least through the first four years after implementation. Perhaps the first few quarters the manufacturer will accumulate upwards of $300,000 in debt, but the expected demand and revenue will greatly improve the overall profitability in under a year's time. Our design suggests using most current technologies and machine types in a modular format. While this design might be more "hybrid" in appearance, it does allow the manufacturer to wait until newer, more 'modular-friendly' technologies, such as MOE, are developed and become more commercially affordable and available. It also reduces the risks associated with using technologies not necessarily proven to operate well in a rapid manufacturing layout.

We also recommend against using renewable energy to solely power the facility. Doing so will not only require the manufacturer to determine the source and location of energy, but determine back up plans for storage or alternatives in case not enough energy is generated. Similarly, we do not recommend trying to mine raw materials. While these two options likely could have great impacts on the environment and emission levels and reduce the number of partners in the supply chain, they do carry significantly greater risk than simply relying on the grid energy and purchasing the raw material. Furthermore, we do not know how much funding our sponsor currently has or is willing to spend. Setting up manufacturing operations to resemble more of a 'hybrid' traditional-modular design could allow for our sponsor to generate revenue and profit in the first few years before trying to switch over and to incorporate these other concepts. Similarly, the same could be said about trying to manage a transportation system. It will likely be easier to work with a freight company, at least initially, to bring the finished products directly to the customers. Moreover, since the system is modular, it could eventually be moved to a remote location and implement a different power source. The concept of mini production systems could be set up throughout the United States. Regardless of these nuances, constructing a steel MPS would put GenH well ahead of its peers. Immediately, they would become a leader of change in the metal and steel-making industries. GenH or any company that will create an MPS and uses GenH technology for generating renewable energy could take advantage of the limitations of the traditional steel manufacturing systems and earn greater revenue.

Secondly, we recommend focusing on continuing to minimize the risks or most sensitive factors, as we discussed in our profit and loss analysis and Monte-Carlo simulation. Minimizing unnecessary equipment costs, wasted production hours or products, and electricity usage should improve the quality of our financial projections. As we have mentioned before, the data points we entered into our spreadsheet models can easily be manipulated. If new costs are realized, machine types or products change, the data sheet should be edited to allow for a more accurate representation of current conditions. Perhaps in a few years' time there will be many changes in the industry. It may no longer be financially intelligent to begin modular production of steel due to a recession or other technological advancements. More research may need to be done, either through an extension of our project deliverables, as will be mentioned in section 5.2, or through research in other industries.

5.2 Recommended Applications

Though our team has learned a lot through researching modular production systems, the steel industry and developing several quantitative models, we believe our project does not need to stop here. In addition to other recommendations we have suggested, we would be interested to learn if future projects could be developed on the basis of our project findings. Perhaps the machine, handling and quality suggestions mentioned by our sponsor could be better implemented in the model we developed.

First, we recommend building an interactive simulation model that incorporates a well throughout design and accurate data. This process would be similar to what our team originally intended to perform, though it would likely show a thorough and robust process design, paired with animation and record statistics. Perhaps it could be modeled in Arena or Python, but doing so would likely better encapsulate an understanding of the entire modular production system process in design. This simulation could be run through several iterations, and similar to the Monte-Carlo simulation our team performed, sensitivity analysis could measure the effects of each variable defined in the system.

Second, an analytical hierarchy process, or AHP model, could be considered. Our team was originally planning to develop an AHP of our own, however, the modularization and process drivers we selected, and the limited machine options prevented us from being able to differentiate among the most important aspects in the process design. The AHP would ideally demonstrate how tradeoffs in the modularization drivers, or the reason for making the production system modular, would rank and allow the decision-maker to develop a design based on those drivers.

They would be ranked and weighted against the strategic objectives. A formula for developing the weights would need to be determined by the designer. Additionally, it should be noted that ideally, fewer than ten drivers be selected, because incorporating additional drivers would make the design and ranking much more complex and possibly defeat the purpose. Our team believes considering the risk of the location of modular production to be one of the objectives, as well as product quality and price.

Our third recommendation for a future possibility would be to continue to expand on the profit and loss analysis we created. While our analysis was built from our sponsor's research, it was somewhat challenging to build the P&L because of all the unknowns in our estimates for expenses and revenue. Moreover, our P&L differed from traditional P&L models because of how we modeled the expenses and revenues. They were broken up into separate tables that incorporate the ability to change in cost or selling price annually and are a function of different process attributes, rather than being assigned one value or number. Examples include the cost of electricity, scrapping, amount of labor, etc. A future version of this profit and loss analysis could be more dynamic, where in a workbook, expenses are categorized by type and explored into more detail on different pages.

For example, our P&L analysis did not thoroughly consider the difference in costs associated with manufacturing or mining raw materials versus purchasing from one supplier over another. Furthermore, the distance traveled by the freight from the site of mineral extraction or purchase to the site of the modular facility will likely have a significant impact on transportation costs. Similarly, the distance of the manufacturing and production site to the customer was not explored in detail. Perhaps GenH or another company looking to build a MPS for steel could upcharge customers who are farther away. This could be part of their business strategy. Additionally, our P&L did not consider elements such as taxes, the learning curve of workers or managers, and module utilization. While these aspects were considered somewhat in our Monte-Carlo simulations, they could signal other expenses that our team has failed to identify.

While much of our project focused on the economics and production process, our team did not explore in detail the concept of renewables and how to power a modular facility. Below are some questions our team developed that we still do not know how to answer. Perhaps these questions could lead to new projects and innovations.

- Since MPS can be placed anywhere, how would the power source be connected if using electricity and is not located near a power grid?

- If powered by a renewable energy source, how is energy storage implemented and maintained?
- Since MPS are inside containers with minimal walking space, where would the finished product be stored? How could it be protected from the external environment or from building up heat inside?
- Since MPS are intended for low demand products and can incorporate products, how often would plants sit idle, be disassembled, or maintained?
- Is it realistic to have an MPS be completely automated? What types of tasks would laborers do other than supervising or observing the process?

Another consideration involves the process of forecasting. Because MPS is not intended for mass production, our team theorized that developing a forecasting equation would be necessary to prevent overspending on orders, either through too frequent or infrequent purchasing or through purchasing too much or not enough material. Specifically, we believe it could be interesting if the economic order quantity or similar method was used. We admit utilizing such an equation might require an understanding of previous demand and production requirements, which could be a challenge for a new production system type. Secondly, such a method would require understanding supplier options and rates, periods of expected inventory delay and the cost of holding inventory. This might require adjusting the number of modules in the process as necessary. While we do not recommend relying on a forecasting technique such as the EOQ alone, it could be helpful when it comes to decision-making.

Additionally, our team failed to deliver a levelization equation that would consider the difference between the amount of energy, renewable or nonrenewable, available with the concept of storage. Ideally, the modular steel plant would minimize its use of energy to produce as few emissions as possible. The amount of energy available depends on the energy type and source and the total demand on that source (if other companies are tapping into the same limited source). If the source is renewable, that amount might change depending on the season, climate, location, or geography. Perhaps a linear program or some type of prescriptive analytics software could be used to model this mathematical equation. The best solution would be the one that meets the requirements of the plant or mill.

One additional constraint is that the concept of emissions was largely ignored in this project. Perhaps this could be part of a well-detailed simulation model, in addition to other difficult-to-measure characteristics such as energy consumption, facility heat and humidity, and the scenario when one or more machines break down. We could conduct an analysis in Microsoft

Excel to determine how machine degradation impacts profit. This extension could be like the learning curve application we incorporated with the number of ‘good quality’ parts.

Likewise, we should study how changing the machine types would impact results to reflect a model that is truly modular. While our team felt it would interfere with the cell design, perhaps different results would be generated. The machines we chose were ‘technically’ still traditional, though we assumed they would fit in modular containers. The number of modules might also decrease, assuming they have greater functionalities. This could reduce the amount of square footage and electricity required to operate the system, and therefore has a significant impact on margin and ROI.

It might also be worthwhile to study the difference between financing and leasing. Leasing does not involve taking debt on the bottom line. In other words, leasing would be better if machines or modules were removed ever so often rather than paying full price upfront, then to not use for the full lifetime. Our model ignored the difference and assumed financing would work better.

Lastly, we recommend developing a detailed layout with machine and workspace sizes. Our team made many assumptions about the size requirements, but this would be beneficial if we ensure ergonomic policies are followed, and that the process flow is efficient. This could also contain an optimizing model for product switching where margin or revenue are maximized while demand and various environmental factors change. Perhaps this may not add significant value to our sponsor, but we would be interested nonetheless.

5.3 Other Considerations

Although our analyses considered the financial benefits and risks associated with operating an MPS for steel, launching a successful MPS will require a start-up to consider other responsible business measures. For example, an information or data management system will be needed to keep track of production and process data. Market research may be required if the company wants to keep up with trends and ensure they capture the intended market. Perhaps the modular design of the facility will become very advantageous and the start-up will need to consider licensing or patenting its intellectual property. Given one of the purposes of MPS is to reduce emissions, perhaps it is a good idea to partner with government or environmental agencies to determine other methods to improve manufacturing and to frame new emissions laws and requirements. Hiring key leaders and personnel will manage the company through difficult times and could prove to be an asset in growing the business. The purpose of this section is to suggest to our sponsor that there are other intangible assets worth considering prior to deciding to build an MPS. A detailed business strategy should be developed to better articulate the business model, goals, mission, projected timeline, and funding measures.

6.0 Project Reflections

Our team overcame many challenges throughout this project. Initially, we all had different interpretations of the project goal and objectives, where they changed from week-to-week, especially in the first term. Upon dividing research among ourselves and sharing it with our sponsor, we would frequently be instructed to focus in a different direction. For example, it was the team's understanding that this was a supply chain research project, where the team would look at ways to minimize the process inefficiencies of producing steel. While this understanding was on the right track, it was only one component of the project. There were many aspects our sponsor hoped for us to consider, but our team was unsure how to incorporate them. Our communication with our sponsor was not always very clear, until later in the first term where the team explained our research process and the steps we had to follow in this project. Initially, our sponsor desired our team to build a financial or economic model immediately, but given we found much of the terminology, purpose, and components of the project difficult to conceptualize, we decided to delay these tasks for the time being.

Our team also struggled with communicating among ourselves, particularly in the first term as well. Sometimes, one team member would ask many open-ended questions, which would prevent the team from making progress. Other times members of the team would not respond to team chats and group messages. We struggled to effectively share our research and findings with one another. When the project scope kept changing, many of us felt that the work or research we performed became useless and put us behind schedule. We also wanted to meet our advisor and sponsor's expectations. These problems, combined with the stress and workload associated with other courses and personal commitments, had caused the team to feel overwhelmed and anxious for much of A-term.

While some members of the team shared their frustrations with the professor, it was not until we collectively met as a team to discuss these problems did we realize many of us felt the same way. We planned to finish our background research and methodology sections for the rest of the term, dividing the work amongst the four of us. We met with our sponsor one final time in A-term to determine what our process would look like for B-term, and what models we would be developing. At the time, we were thinking of constructing a leveling equation that would consider the changes in energy demand throughout a day at a steel mill. Ideally, if a plant was powered by a renewable energy source, we would need to consider storing this energy for times when energy was not available. Our team also considered developing a factory simulation model in software, such as Arena, to determine factory throughput and to identify any potential bottlenecks in a modular production system.

To develop these models in B-term, we planned to collect process data from a variety of traditional and mini mill steel manufacturers. This data would include information such as composition and type of steel product being produced, machine(s) used, processes, amount of time in each process, energy source (hourly supply), pricing and other indicators. We developed a list of companies to contact through searching on the internet and asking our sponsor for suggestions. This list consisted of the company name (or the name of an employee name), their email, phone, or other contact information. Our team then split up the list, where each person attempted to contact multiple companies, following up as necessary. While most steel manufacturers did not respond, some informed our team that they were unable to provide us with the data we were asking for, or provided us with a company report that, while interesting to read, was not particularly helpful for determining estimates for our models. We also developed an online form that described the data we were looking to acquire, and it asked the intended participant to answer a series of basic questions about the company. Furthermore, we created a promotional flyer and email script that would help communicate to the participant who we are, the purpose of our study, and why we are contacting them. These graphics can also be found in Appendices A through C.

Midway through B-term, we only received one spreadsheet of data from a hydropower dam company that outlined the energy demand for a three day span broken into half-hour intervals. We were assisted by two other companies, however, they only provided our team with a short document outlining annual steel production or energy used, which was not helpful in building our models. Upon sharing this energy demand data with our sponsor, we were informed that it would not be adequate to use in our leveling equation model, because it did not fluctuate enough as most renewable energy sources do. Furthermore, our sponsor had previously suggested that if we struggled to obtain data from companies, that they would be willing to use a Gaussian equation to provide us with sample numbers. Upon requesting our sponsor to perform this action, they had mentioned feeling overwhelmed and not having the time to be able to do that. Therefore, our team decided to scrap the leveling equation idea, and instead of developing a simulation that used process data, we would research a list of sample machines to be used as part of our profit and loss analysis.

Upon sharing these machine types with our sponsor, we began the discussion of what makes something truly modular. Because limited information was available about modular manufacturing and production system processes and technologies available, we decided to incorporate the machine statistics on the conventional machines that are more readily available. We assumed these machines would go inside modules, or shipping containers, and that they would be located in some sort of facility. Our sponsor shared that what we were proposing was more of a hybrid-modular system, and that if it were to be truly modular, we would need to incorporate technologies such as molten-oxide electrolysis (MOE) instead of a furnace and substitute a polturing machine for a rolling mill. They also suggested that the printer should only be involved as part of the consumer process, separate from the manufacturing process we were studying. Furthermore, they recommended removing all of our conventional machines. These machines included lathes, milling, drilling and lasers.

While we understood and appreciated this feedback, we felt that it halted our progress once again. Making these changes would prevent our team from developing machine cells, as discussed in our methodology section, which would essentially put us back a few weeks. We also felt that we would need to restart our methods from scratch, and given the term was almost over, we decided it was best to keep pushing forward with what we had already produced. With that said, we felt this meeting was beneficial and implemented some suggestions into our project. We had since added handling systems, reconsidered how to implement quality control, and considered the process by which real products, steel cladding, auto parts, and medical tools were made.

Following this meeting, we had received an email from our sponsor thanking us for our cooperation and confirming that they had understood our attempts in this project. They had mentioned that perhaps one point of difficulty in this project came from our perspective on the project. They highlighted the difference between how an engineer and business person thinks, and the importance of communicating between parties. Our team believes this is where our difficulties with understanding our sponsor came from. As students, we had more of an industrial engineer or operations management perspective. We were focused on processes and numbers and wanted to understand how each component fit together. Our sponsor was focused heavily on the economics and business side of the plant. If the numbers suggested the modular plant was operational, which according to our sponsor’s previous research was the case, then they were set on making it happen. They also admitted that they did not realize how much time we were spending on the design process. Granted, there is currently a lack of proven research indicating that it is possible to design modular production systems in metal-making industries. However, there have been advancements in additive manufacturing and other technologies that can be produced in ISO shipping containers.

Once again, our team decided to pivot at the start of C-term. In addition to the profit and loss analysis we developed, we developed a set of tools that we believed to be useful when considering the decision-making process. We were introduced to these tools in our industrial engineering courses and wanted to align this project more with our major. The first tool was a decision tree, which urges the decision-maker to consider the payoffs and probabilities of success or failure for each decision made. Secondly, we developed a Monte-Carlo simulation that could provide the decision-maker with insight as to expectations for product throughput, demand and revenue. This tool incorporated sensitivity analysis when changes were made to one variable, assuming the other variables were held constant. Third, we formulated a linear program that illustrated how changes in demand and switching products could impact the financial performance of the company. We then created a summarized table of risks to aid in the decision-making of our sponsor. These risks mostly covered topics that we were unable to incorporate into our models either due to time, complexity, or purpose.

Our teamwork had improved significantly over the course of the project. Each team member took the lead at different points throughout the project, especially if there was a part that piqued their interest. We were able to delegate the workload, so no one team member felt too overwhelmed. Although challenging, we managed to find times to meet consistently twice a week to keep ourselves on track. If a group member could not make a meeting or were unable to perform the task they had agreed upon previously, we alerted each other of the issue. If we had questions, we made sure to address them to the team and discuss them before making a decision. When necessary, we would split up into smaller groups to tackle a particular assignment for the project and address questions to individuals who may be quiet during a meeting to ensure everyone was onboard with our plans.

As a team, we also learned the importance of communication. Not just among ourselves, but with our sponsor and project advisor. It was very important to communicate effectively for us to receive feedback that could push us in the right direction. Unfortunately, there were times when our team had great ideas, but either because of lack of understanding, or ineffective communication, we were not able to fully implement them. This is partly why we have so many recommendations on how to build on this project.

Third, we learned the importance of creativity in applying our knowledge. Often, regular coursework requires us to implement a technique or process to determine an answer. We learned valuable tools that we use in the course, but likely may not use again. This project was very different. It was open-ended, and our sponsor seemed open to taking the project in different directions. With one term left to complete this project, our team realized that instead of waiting to be told what our next steps should be, we should make our own decisions. While they might not line up with what our sponsor or advisor preferred, they add originality and allow for this project to be viewed from a different perspective. We ended up incorporating tools from several courses: prescriptive analytics, stochastic models, engineering economics, operations and supply chain management, work systems and facilities planning. We enjoyed applying what we learned, rather than focusing solely on the economics of the project.

We also needed to apply soft skills, or skills learned from courses in organizational behavior courses. For example, we needed to coordinate with our sponsor and communicate effectively with the steel mills to acquire data as a team. We prepared to conduct interviews and spoke with a human subjects research expert to prepare us for our initial data collection methods. We realized the importance of asking for help, and did so at many points throughout the project.

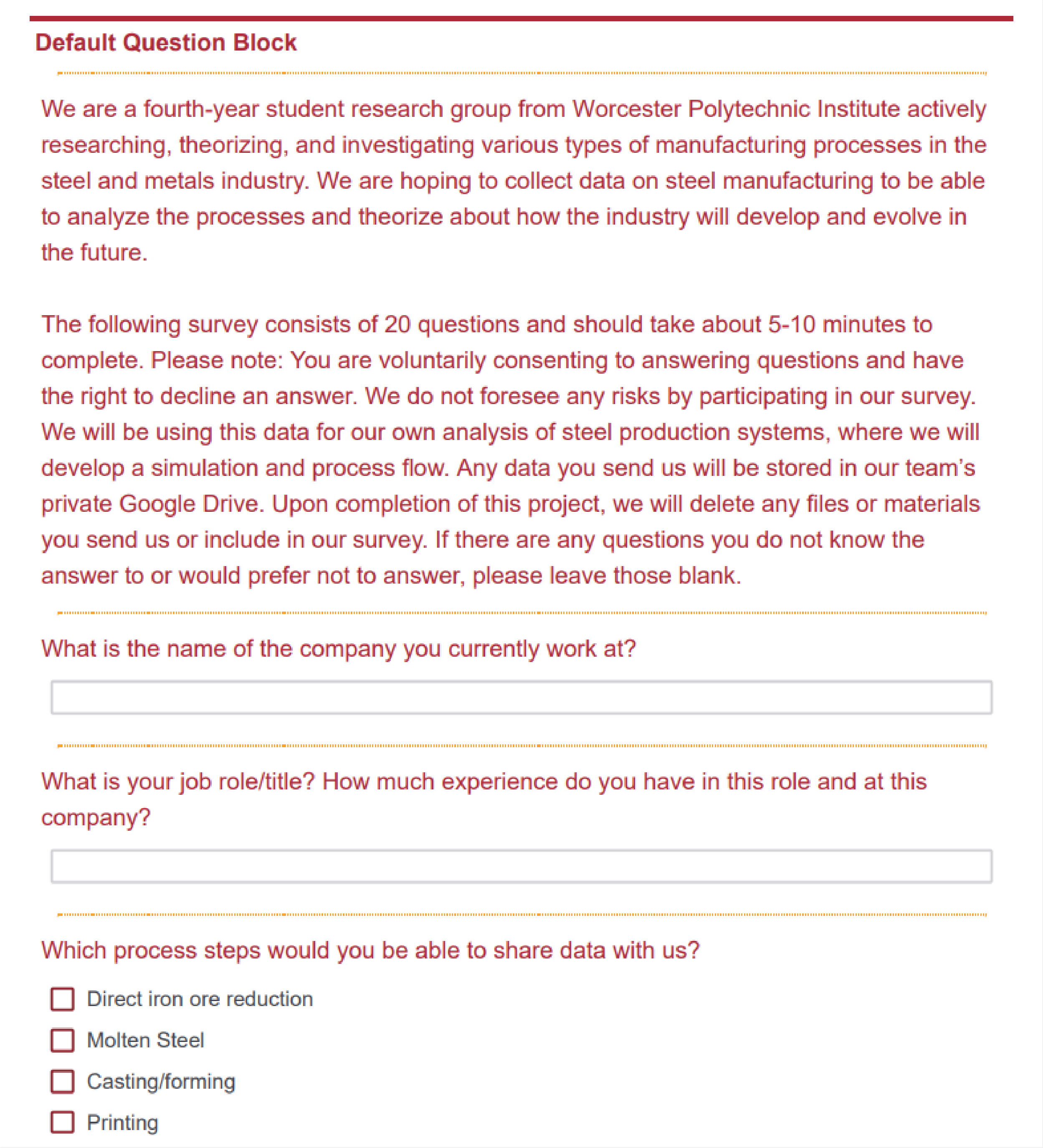
In the end, we ended up developing a profit and loss analysis that provided our sponsor with insights as to the profitability and return on investment of implementing a steel MPS. The linear program and Monte-Carlo simulations were adaptations of this analysis. All three of these tools, along with the decision tree and risk analysis, serve as a template, where our sponsor can input new data as desired. For example, they might have better estimates for machine or product costs. Perhaps they would like to include a topic we did not explore in detail, such as transportation or renewable energy. There are many options to incorporate these concepts into the models we have, however, our team did not have the time, nor knew the best method to do so. While our model had many constraints, as discussed in sections 5.1 and 5.2, we believe it is still rather robust, and are fascinated to see how the components we did incorporate fit together.

Lastly, we wanted to thank our project advisor, Professor Sara Saberi, for her commitment in keeping this team together, and for her advice along the way. She went above and beyond her role in assisting our team’s communications with our sponsor, addressing individual student concerns, and meeting with our team consistently to ensure we were on track. Without her, this project would have likely been much more difficult, and we likely would not have hit each of our objectives.

Appendix

Appendix A.

Screenshots of the survey our team sent to steel manufacturers.



Default Question Block

We are a fourth-year student research group from Worcester Polytechnic Institute actively researching, theorizing, and investigating various types of manufacturing processes in the steel and metals industry. We are hoping to collect data on steel manufacturing to be able to analyze the processes and theorize about how the industry will develop and evolve in the future.

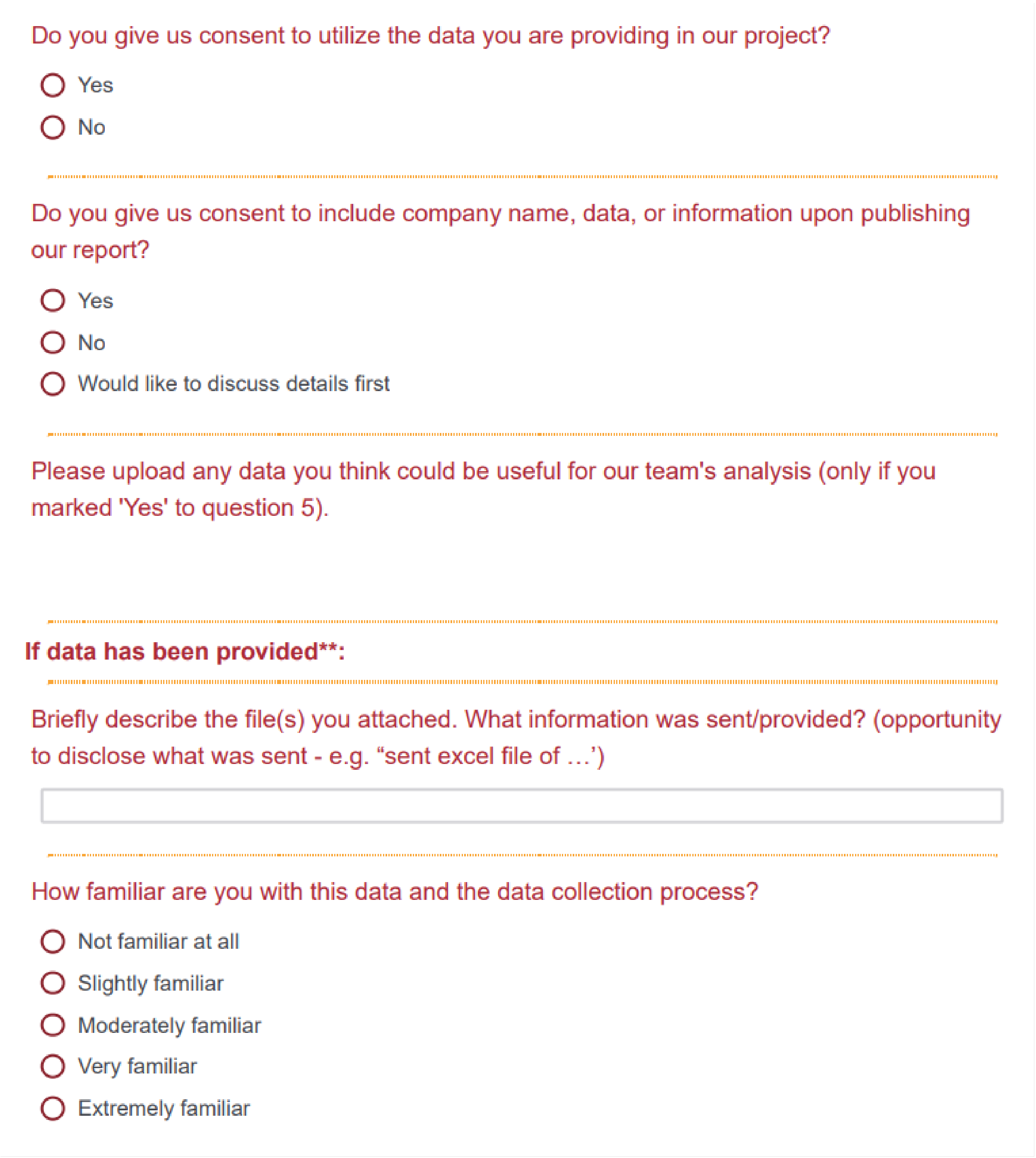
The following survey consists of 20 questions and should take about 5-10 minutes to complete. Please note: You are voluntarily consenting to answering questions and have the right to decline an answer. We do not foresee any risks by participating in our survey. We will be using this data for our own analysis of steel production systems, where we will develop a simulation and process flow. Any data you send us will be stored in our team's private Google Drive. Upon completion of this project, we will delete any files or materials you send us or include in our survey. If there are any questions you do not know the answer to or would prefer not to answer, please leave those blank.

What is the name of the company you currently work at?

What is your job role/title? How much experience do you have in this role and at this company?

Which process steps would you be able to share data with us?

- ☐ Direct iron ore reduction
- ☐ Molten Steel
- ☐ Casting/forming
- ☐ Printing



Do you give us consent to utilize the data you are providing in our project?

○ Yes
○ No

Do you give us consent to include company name, data, or information upon publishing our report?

○ Yes
○ No
○ Would like to discuss details first

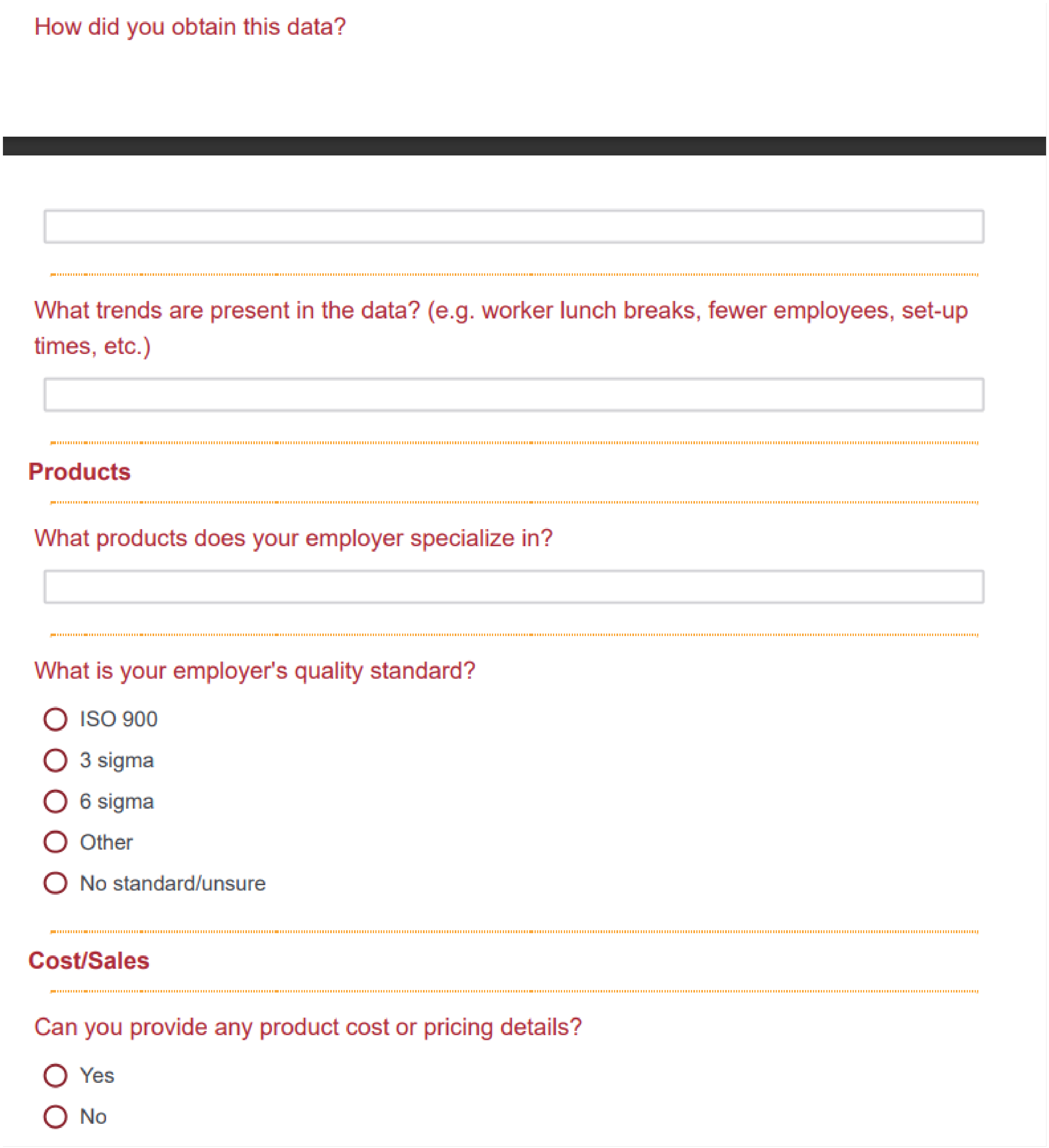
Please upload any data you think could be useful for our team's analysis (only if you marked 'Yes' to question 5).

If data has been provided:**

Briefly describe the file(s) you attached. What information was sent/provided? (opportunity to disclose what was sent - e.g. “sent excel file of …’)

How familiar are you with this data and the data collection process?

○ Not familiar at all
○ Slightly familiar
○ Moderately familiar
○ Very familiar
○ Extremely familiar



How did you obtain this data?

What trends are present in the data? (e.g. worker lunch breaks, fewer employees, set-up times, etc.)

Products

What products does your employer specialize in?

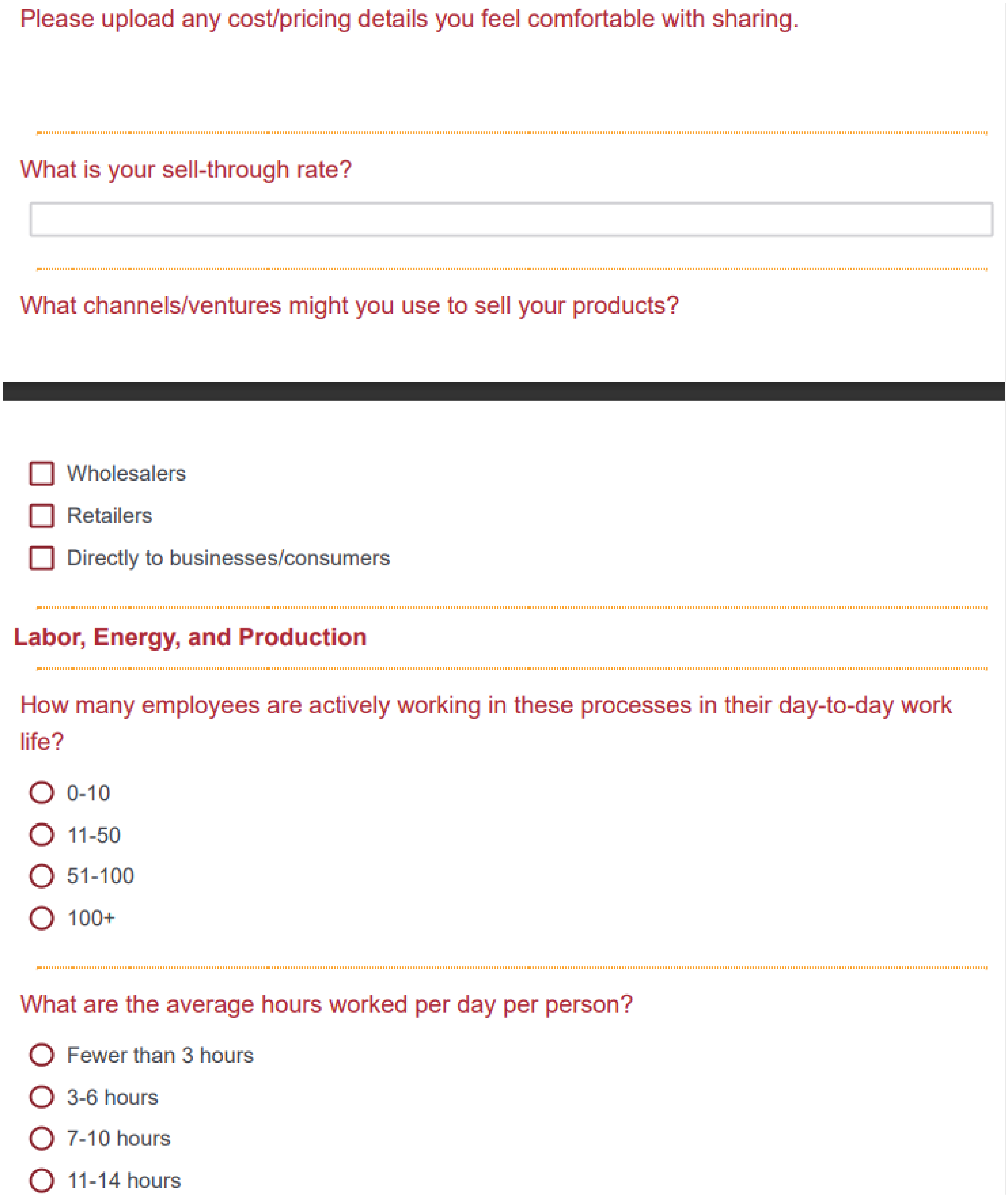
What is your employer's quality standard?

- ○ ISO 900
- ○ 3 sigma
- ○ 6 sigma
- ○ Other
- ○ No standard/unsure

Cost/Sales

Can you provide any product cost or pricing details?

- ○ Yes
- ○ No



Please upload any cost/pricing details you feel comfortable with sharing.

What is your sell-through rate?

What channels/ventures might you use to sell your products?

- ☐ Wholesalers
- ☐ Retailers
- ☐ Directly to businesses/consumers

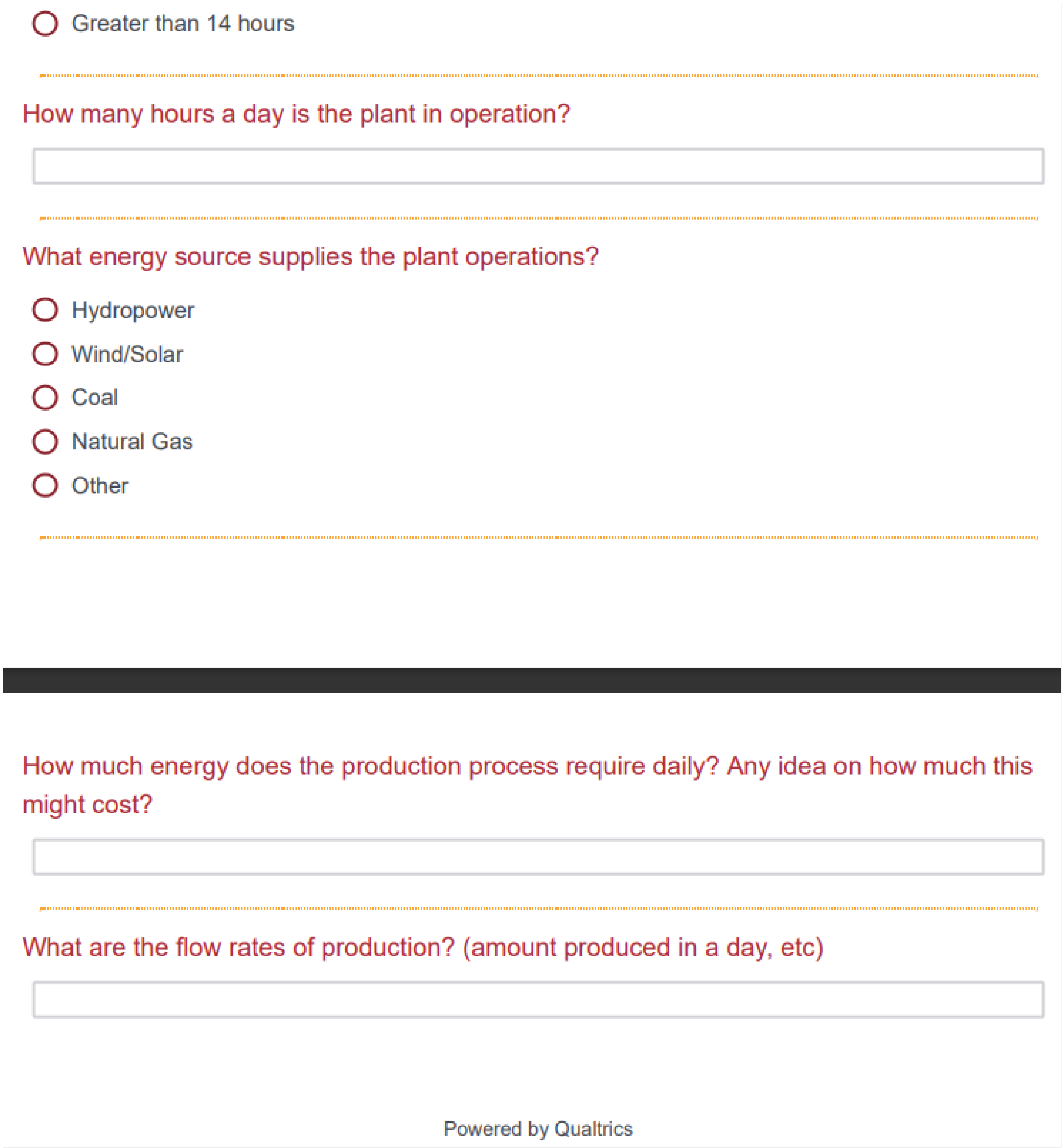
Labor, Energy, and Production

How many employees are actively working in these processes in their day-to-day work life?

- ○ 0-10
- ○ 11-50
- ○ 51-100
- ○ 100+

What are the average hours worked per day per person?

- ○ Fewer than 3 hours
- ○ 3-6 hours
- ○ 7-10 hours
- ○ 11-14 hours



○ Greater than 14 hours

How many hours a day is the plant in operation?

What energy source supplies the plant operations?

○ Hydropower
○ Wind/Solar
○ Coal
○ Natural Gas
○ Other

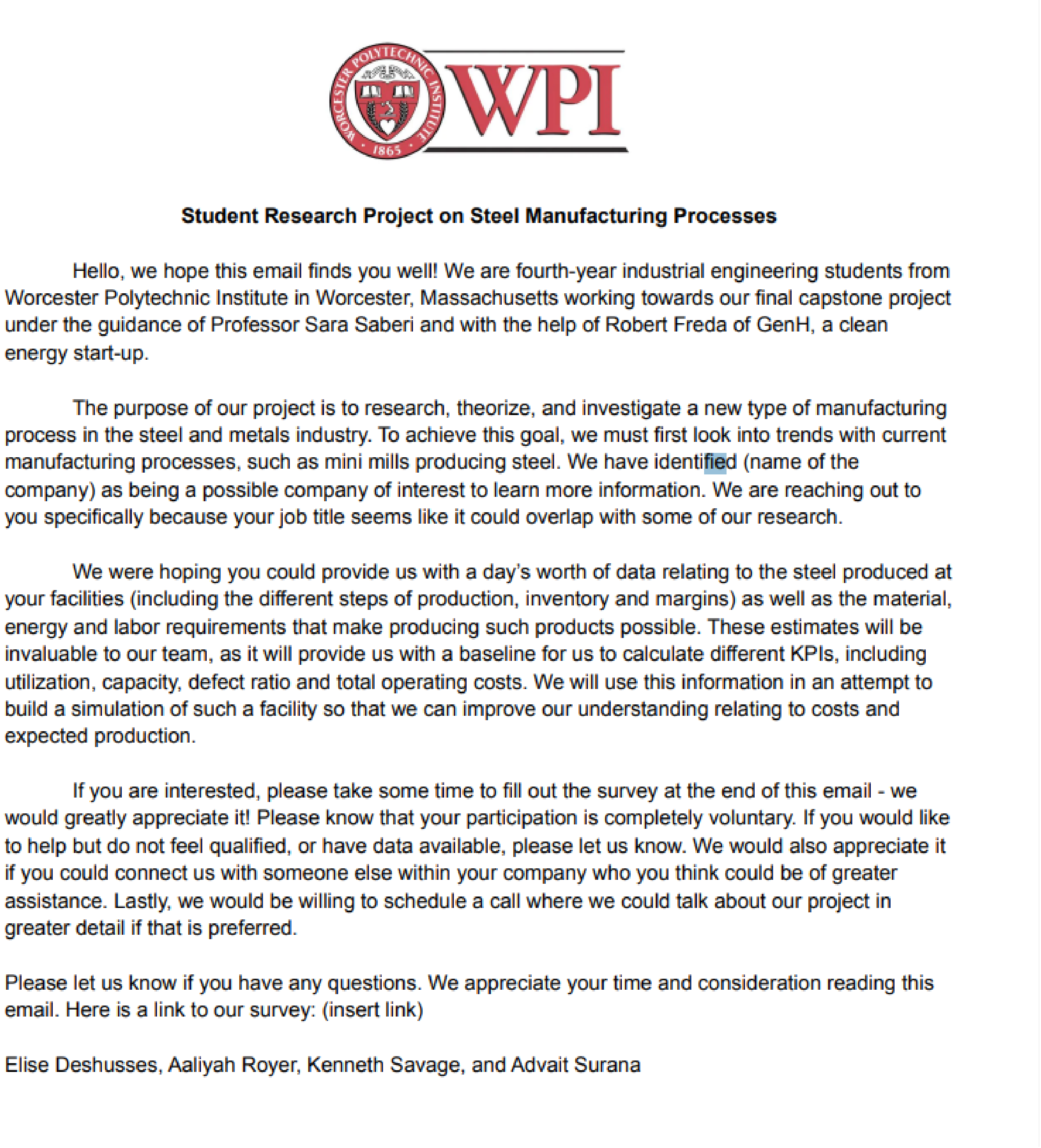
How much energy does the production process require daily? Any idea on how much this might cost?

What are the flow rates of production? (amount produced in a day, etc)

Powered by Qualtrics

Appendix B.

Student Research Project Email Contact



Student Research Project on Steel Manufacturing Processes

Hello, we hope this email finds you well! We are fourth-year industrial engineering students from Worcester Polytechnic Institute in Worcester, Massachusetts working towards our final capstone project under the guidance of Professor Sara Saberi and with the help of Robert Freda of GenH, a clean energy start-up.

The purpose of our project is to research, theorize, and investigate a new type of manufacturing process in the steel and metals industry. To achieve this goal, we must first look into trends with current manufacturing processes, such as mini mills producing steel. We have identified (name of the company) as being a possible company of interest to learn more information. We are reaching out to you specifically because your job title seems like it could overlap with some of our research.

We were hoping you could provide us with a day's worth of data relating to the steel produced at your facilities (including the different steps of production, inventory and margins) as well as the material, energy and labor requirements that make producing such products possible. These estimates will be invaluable to our team, as it will provide us with a baseline for us to calculate different KPIs, including utilization, capacity, defect ratio and total operating costs. We will use this information in an attempt to build a simulation of such a facility so that we can improve our understanding relating to costs and expected production.

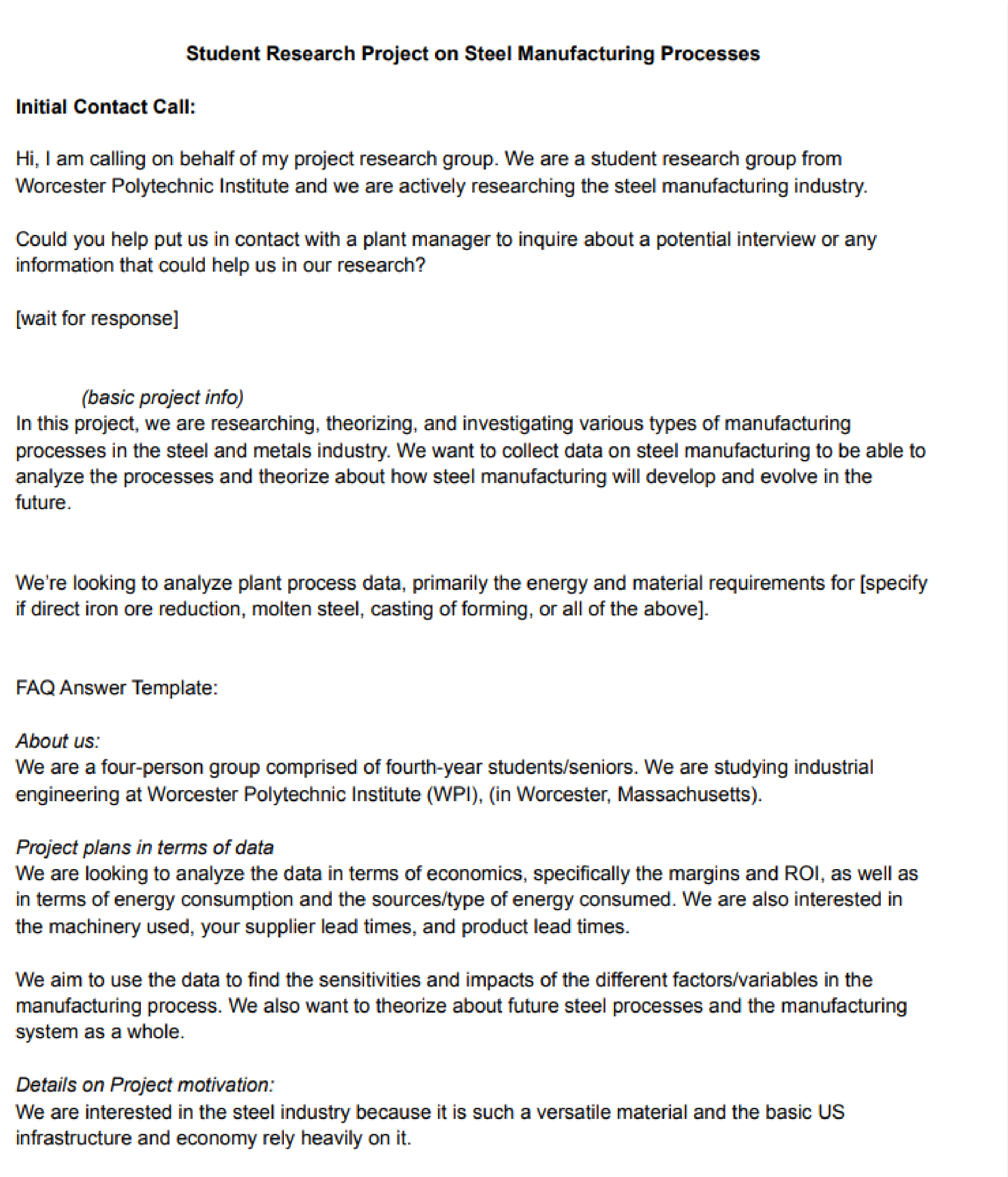
If you are interested, please take some time to fill out the survey at the end of this email - we would greatly appreciate it! Please know that your participation is completely voluntary. If you would like to help but do not feel qualified, or have data available, please let us know. We would also appreciate it if you could connect us with someone else within your company who you think could be of greater assistance. Lastly, we would be willing to schedule a call where we could talk about our project in greater detail if that is preferred.

Please let us know if you have any questions. We appreciate your time and consideration reading this email. Here is a link to our survey: (insert link)

Elise Deshusses, Aaliyah Royer, Kenneth Savage, and Advait Surana

Appendix C.

Student Research Project Script



Student Research Project on Steel Manufacturing Processes

Initial Contact Call:

Hi, I am calling on behalf of my project research group. We are a student research group from Worcester Polytechnic Institute and we are actively researching the steel manufacturing industry.

Could you help put us in contact with a plant manager to inquire about a potential interview or any information that could help us in our research?

[wait for response]

(basic project info)

In this project, we are researching, theorizing, and investigating various types of manufacturing processes in the steel and metals industry. We want to collect data on steel manufacturing to be able to analyze the processes and theorize about how steel manufacturing will develop and evolve in the future.

We're looking to analyze plant process data, primarily the energy and material requirements for [specify if direct iron ore reduction, molten steel, casting of forming, or all of the above].

FAQ Answer Template:

About us:

We are a four-person group comprised of fourth-year students/seniors. We are studying industrial engineering at Worcester Polytechnic Institute (WPI), (in Worcester, Massachusetts).

Project plans in terms of data

We are looking to analyze the data in terms of economics, specifically the margins and ROI, as well as in terms of energy consumption and the sources/type of energy consumed. We are also interested in the machinery used, your supplier lead times, and product lead times.

We aim to use the data to find the sensitivities and impacts of the different factors/variables in the manufacturing process. We also want to theorize about future steel processes and the manufacturing system as a whole.

Details on Project motivation:

We are interested in the steel industry because it is such a versatile material and the basic US infrastructure and economy rely heavily on it.

Appendix D.

Charts illustrating changes made to the Profit and Loss Analysis after first revision.

Change 1: Number of Machines

Machine Type	**Former Count**	**Revised Count**
Lathe	8	4
Milling	8	4
Router	6	3
Metal Printer	2	1
CNC Drill	6	3

Change 2: Number of Laborers (identical to machine count changes)

Machine Type	**Former Count**	**Revised Count**
Lathe	8	4
Milling	6	3
Router	6	3
Metal Printer	2	1
CNC Drill	6	3

Change 3: Machine Pricing

Machine Type	**Former Cost**	**Revised Cost**
Lathe	$413,000	$40,000
Milling	$400,000	$50,000
Metal Printer	$400,000	$80,000
EAF	$2,000,000	$500,000

Change 4: Starting Defective Rate

Product Type	**Previous Rate**	**New Rate**
Product A	25%	10%
Product B	18%	7%
Product C	10%	12%
Product D1:	14%	6%
Product D2:	17%	9%
Product E:	22%	13%
Product F:	20%	8%

Change 5: Ending Defective Rate

Product Type	**Previous Rate**	**New Rate**
Product A	3%	0.3%
Product B	1%	0.01%
Product C	5%	0.5%
Product D1:	1%	0.2%
Product D2:	2%	0.03%
Product E:	1%	0.5%
Product F:	0.5%	0.05%

Change 6: Redefine 'one unit' of product to smaller sizes

Product	**Machine**	**Previous Time**	**Revised Time**
A	Lathe	13.75	1.5
A	Milling	1.75	1
A	Router	3.5	3
A	Total	19	9
B	Lathe	27.5	2
B	Milling	3.5	2
B	Router	3.3	1.75
B	Toal	34.3	10.75
C	Lathe	29.5	4
C	Milling	2.75	1.75
C	Router	2.75	2.1
C	Total	35	11.8
D1	Lathe	29.5	2.75
D1	Milling	2.75	2.5
D1	Router	2.45	1.5
D1	Total	34.7	11.5
D2	Milling	21.25	5.5
D2	Total	25.75	18
E	Lathe	29.5	4
E	Total	45.25	19.75
F	Lathe	11	6
F	Printer	18.5	11
F	Total	35	22.5

Change 7: Reducing Machine Power Requirements

Machine	**Previous Energy (kWh)**	**Revised Energy (kWh)**
Lathe	4	2
Milling	5.5	3
Printer	11	5.5
Drilling	4.5	2.8
EAF	30	25
Rolling	20	15

Appendix E.

Summarized P&L Tables

1 Table Base Equations

1.1 Table A - Table of Constants

Rent Price, KWh rate, workers, workdays, workday hours and facility KWh per hour per sq ft. can be changed depending on user requirements

1. Hours in a quarter

$$Hours\ in\ a\ quarter = \frac{Workday\ Hours \times\ Workday}{4}.$$

2. Quarterly Worker hours

$$Quaterly\ Worker\ Hours = Hours\ in\ a\ Quarter \times Number\ of\ workers.$$

1.2 Table B - Area Requirements

Width and Length of product modules are based on real-life examples found online.

1. Area of Module

$$Area\ of\ Module = Length\ of\ module \times Width\ of\ module.$$

2. Extra Space required

$$Extra\ Space\ Required = Sum\ of\ Area\ of\ module \times 0.45.$$

1.3 Table C - Facility cost

- Facility square footage.

  From Table B, which calculates the land requirement for cells

- Land Rent price (Quarterly).

$$Cost\ of\ Land\ Rent\ (quarterly) = \frac{Average\ rent\ Annually \times Total\ Square\ footage}{4}.$$

- Electricity Cost (quarterly).

$$Cost\ of\ Electricity\ (quarterly) = Facility\ size \times Kwh\ cost\ per\ sq\ ft.(quaterly) \times kW\ per\ hour$$

1.

$$Sum\ of\ facility\ costs\ (quarterly) = Cost\ of\ rent + Electricity\ cost + Overhead\ cost.$$

1.4 Table D - Product switch cost for products

This table contains cell Disassembly and cell Assembly costs which are hypothetical and can be changed based on the scenario being simulated

1.5 Table D.1 - Cell Switch Cost Matrix

1. Cell Switch Cost

$$Cell\ Switch\ Cost = Cell\ Disassebly\ cost + Cell\ setup\ cost.$$

1.6 Table E - Product Composition

Product composition by percentage = ore + coal + scrap steel + other

1.7 Table F - Time for each product by machine

Time spent on each machine was hypothetical and different for different products to simulate what would happen in a real production unit that carries multiple products

1.8 Table G - Quarterly Cost for machines

1. Labor Cost ($ per hour)

$$Cost\ of\ Labor(Hourly) = Labor\ requierd\ per\ machine(Hourly) \times Average\ worker\ wage.$$

2. Energy Cost.

$$Cost\ of\ Energy = Number\ of\ Machines \times Kwh\ cost \times kW\ rate.$$

3. Maintenance Cost

   Estimated using data available

4. Total cost(weekly)

$$Total\ cost =$$

$$(Labour\ cost + Energy\ cost) \times weekly\ hours + maintenance\ cost.$$

5. Finance Cost

   Hypothetical number that can be changed based on user needs

6. Expected Price Increase

   Hypothetical number that can be changed based on user needs

1.9 Table H - Product Production Cost

Sample Products (A, B, C, D, E, F) each have their own production process entirely contained in one cell. Each product, n, and therefore process has its specific:

1. Labor Cost ($ per unit)

$$Cost\ of\ Labor(Hourly) =$$

$$\frac{Labor\ cost\ per\ machine(Hourly) \times Minutes\ spent\ on\ machine}{60}.$$

2. Inventory Cost

$$Inventory\ Cost = Weight\ of\ material(lbs) \times 1.75.$$

3. Material Cost

$$Material\ Cost(unit) =$$

$$market\ cost\ per\ material(lbs) \times Amount\ of\ material\ used\ (lbs).$$

4. Quality Control Cost

$$Quality\ Control\ Cost(non-defectiveunit) =$$

$$Defective\ rate \times LaborCost + ElectricityCost + MaterialCost + InventoryCost$$

5. Scrapping Cost

$$Scrapping\ Cost(Hourly) = \frac{MaterialCost}{8}.$$

6. Sum of Production cost per unit

$$Sum\ of\ Production\ cost\ per\ unit =$$

$$Labor{+}{+}Material+Inventory+Qualitycontrol+Scrapping)\times(1+HiddenFee)$$

1.10 Table I - Product Production Quantities

1. Full Capacity

$$Full\ Capacity = Number\ of\ hours \times (\frac{60 \times (1 - defective\ rate)}{time\ spent\ on\ each\ machine})$$

2. Units Produced

$$Units\ produced = Production\ Ration \times \ Full\ Capacity.$$

3. Quarterly Costs

$$Quarterly\ Cost = Production\ Cost\ per\ unit \times \ Units\ Produced.$$

4. Selling Price

$$SellingPrice = Production\ Cost\ per\ unit \times \ (1 + Markup).$$

1.11 Table J - Production Ratio

Production ratio was calculated by using optimization software that would maximize the revenue generated by taking factors such as labor availability and costs into account.

1.12 Table K - Possible Revenue Quarterly by product

1. Possible Revenue (Quarterly by Product)

$$Quarterly\ Revenue\ by\ Product =$$

$$Units\ Produced \times \ Selling\ Price \times e^{(Growth\ Rate \times (Quarter\ Numer - 1)}$$

1.13 Table L - Cost of Production Quarterly by product

1. Cost of Production (Quarterly by product)

$$Quarterly\ cost\ by\ Product = Production\ cost\ per\ unit \times Production\ Ratio \times Full\ Capacity$$

1.14 Table M - Cost of Equipment

1. Cost of Equipment

$$Cost\ of\ Equipment\ = Number\ of\ Machines \times Price \times Finance\ cost$$

1.15 Table N - Defective Rate by Product

The starting defective rate and defective rate are hypothetical and can be changed based on user requirements

1. Cost of Equipment

$$Defective\ Rate = Previous\ term\ defective\ rate \times 0.9^2$$

1.16 Table O - Production by Product type

1. Production by Product type

$$Production = Production\ Ratio \times Full\ Capacity \times (1 - Defective\ Rate)$$

1.17 Table P - Actual Quarterly Revenue

1. Actual Quarterly Revenue

$$Actual\ Revenue\ = \\ Possible\ Revenue \times Sell\ Through + (1 - Sell\ Through) \times \frac{Possible\ Revenue}{2}$$

1.18 Table Q - Summary by Quarter

1. Cost of Facility

$$Cost\ of\ Facility = Total\ Facility\ cost(Table\ C) \times e^{Annual\ Growth\ Rate \times Quarter\ Numeber - 1}$$

2. Cost of Production

   Cost of Production is taken from table L

3. Cost of Equipment

   Cost of Equipment is taken from table M

4. Cost of Transportation

$$Cost\ of\ Transportation\ = Products\ Produced\ in\ a\ Quarter \times 0.75$$

5. Revenue

   Revenue is taken from table P

6. Profit Margin

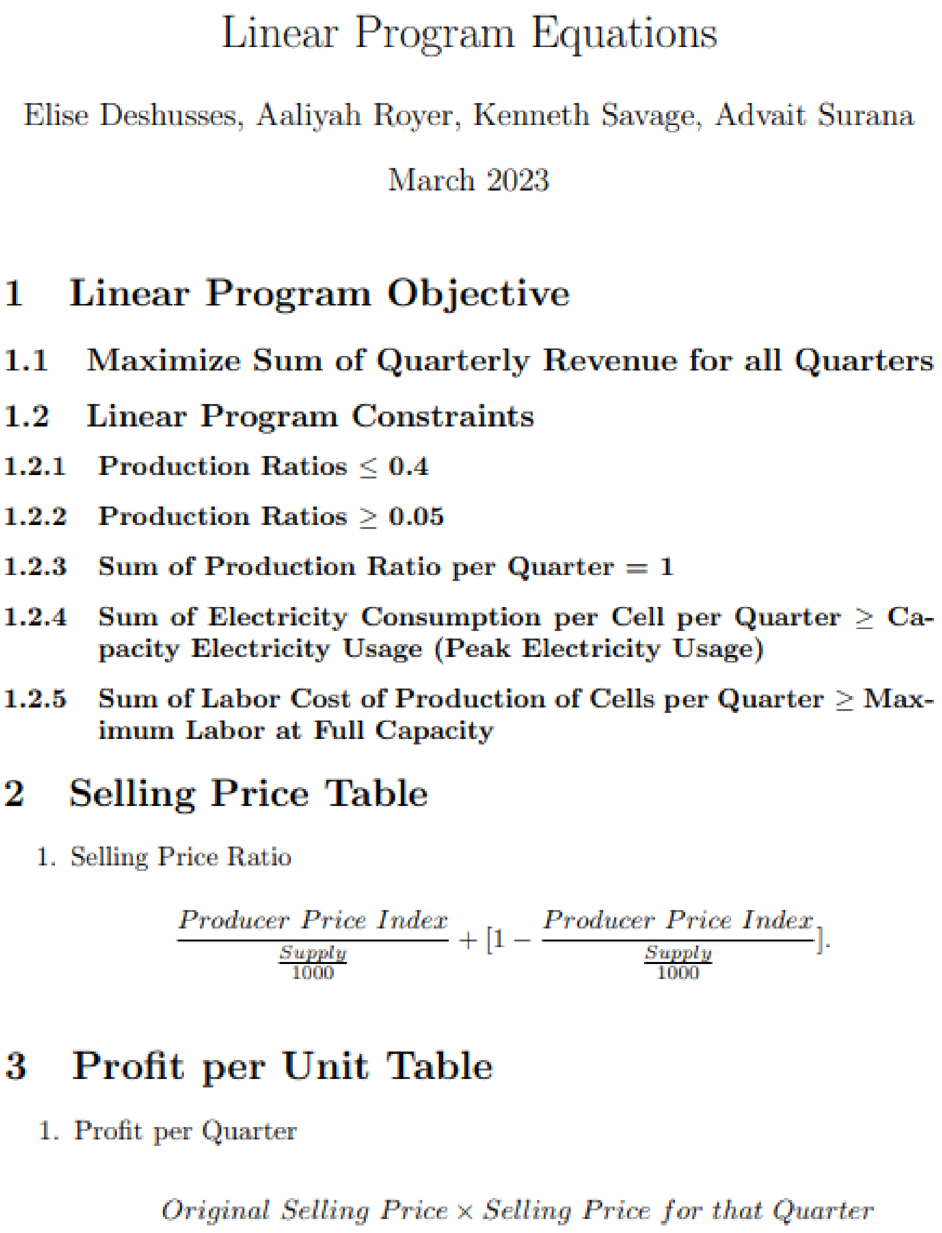
$$Profit\ Margin = Revenue - Costs\ of\ Facility,\ Production,\ Equipment,\ Transportation$$

7. Cash Flow

$$Cash\ Flow\ = Previous\ Cash\ Flow\ +\ Profit\ Margin$$

Appendix F.

Linear Program Equations



Linear Program Equations

Elise Deshusses, Aaliyah Royer, Kenneth Savage, Advait Surana

March 2023

1 Linear Program Objective

1.1 Maximize Sum of Quarterly Revenue for all Quarters

1.2 Linear Program Constraints

1.2.1 Production Ratios $\leq$ 0.4

1.2.2 Production Ratios $\geq$ 0.05

1.2.3 Sum of Production Ratio per Quarter = 1

1.2.4 Sum of Electricity Consumption per Cell per Quarter $\geq$ Capacity Electricity Usage (Peak Electricity Usage)

1.2.5 Sum of Labor Cost of Production of Cells per Quarter $\geq$ Maximum Labor at Full Capacity

2 Selling Price Table

1. Selling Price Ratio

$$\frac{Producer\ Price\ Index}{\frac{Supply}{1000}} + [1 - \frac{Producer\ Price\ Index}{\frac{Supply}{1000}}].$$

3 Profit per Unit Table

1. Profit per Quarter

$$Original\ Selling\ Price \times Selling\ Price\ for\ that\ Quarter$$

4 Labor Cost Table

1. Rate of Change

$$Selling\ Price\ from\ the\ previous\ Quarter - Selling\ Price\ from\ the\ current\ Quarter$$

2. Labor Cost per Quarter

$$Previous\ Quarter\ Labor\ Cost + (Previous\ Quarter\ Labor\ Cost \times Rate\ of\ Change)$$

5 Production Ratio Table

1. Ratio for each Product per Quarter
   Optimized by the Linear Program

6 Number of Units Produced (with Inventory)

1. First Quarter

$$Full\ Capacity\ Units \times Production\ Ratio\ Table$$

2. Following Quarters

$$Full\ Capacity\ Units \times Production\ Ratio\ Table + Inventory\ from\ previous\ Quarter$$

7 Products Sold Table

1. Updated Rate of Change

7.1 1 - Rate of Change

2. Sell-Through

$$Assumed\ Sell - Through\ Rates\ for\ each\ product$$

3. Products Sold in each Quarter

$$Number\ of\ Units\ Produced \times \frac{Sell - Through\ \times Rate\ of\ Change\ for\ the\ Quarter}{2}$$

8 Inventory Table

1. Inventory per Quarter

$$Number\ of\ Units\ Produced\ for\ that\ Quarter - Products\ Sold\ in\ that\ Quarter$$

9 Average Electricity Consumption Table

1. Utilization Rate

$$Assumed\ Rate\ of\ Utilization\ per\ Product\ Cell$$

2. Peak Consumption

$$\begin{aligned}
&(\frac{Time\ of\ the\ product\ in\ the\ Lathe}{60} \times kiloWatt\ per\ Hour\ for\ the\ Lathe)+\\
&(\frac{Time\ of\ the\ product\ in\ the\ Milling}{60} \times kiloWatt\ per\ Hour\ for\ the\ Milling)+\\
&(\frac{Time\ of\ the\ product\ in\ the\ Router}{60} \times kiloWatt\ per\ Hour\ for\ the\ Router)+\\
&(\frac{Time\ of\ the\ product\ in\ the\ Laser\ Cutter}{60} \times kiloWatt\ per\ Hour\ for\ the\ Laser\ Cutter)+\\
&(\frac{Time\ of\ the\ product\ in\ the\ Metal\ Printer}{60} \times kiloWatt\ per\ Hour\ for\ the\ Metal\ Printer)+\\
&(\frac{Time\ of\ the\ product\ in\ the\ CNC\ Drilling}{60} \times kiloWatt\ per\ Hour\ for\ the\ CNC\ Drilling).
\end{aligned}$$

3. Average Consumption

$$Utilization\ Rate \times Peak\ Consumption$$

10 Number of Cells per Product Table

1.

$$\frac{Number\ of\ Units\ Produced}{Cell\ Capacity}$$

11 Cell Change Table

1.

$$Number\ of\ Cells\ per\ Product\ in\ Previous\ Quarter - Number\ of\ Cells\ per\ Product\ in\ Current\ Quarter$$

12 Cost of Cell Change Table

1. If the Value in the Cell Change Table is Positive – Addition of a Cell (Cell Set-Up)
2. If the value in the Cell Change Table is Negative – Removal of a Cell (Cell Disassembly)

   Utilize the Product Switch Cost for Product Table (Table D) to find the cost associated with the cost for cell changes for each Product

13 Constraints

13.1 Electricity Consumption per Cell Table

1. Sum of all Electricity Consumption per Quarter $\leq$ Capacity Electricity

   Capacity Electricity

   Sum of the Peak Consumption of all Products

   Electricity Consumption per Product

$$Average\ Consumption\ per\ Cell\ per\ Product\ \times Number\ of\ Cells\ per\ Product\ in\ each\ quarter$$

13.2 Labor Cost of Production of Cells Table

1. Sum of all Labor Costs per Quarter $\leq$ Labor Cost of Full Capacity

$$Cell\ Capacity\ per\ Product\ \times Labor\ Cost\ per\ Product$$

2. Labor Cost per Product

$$Labor\ Cost\ in\ Current\ Quarter\ for\ each\ Product\ \times Number\ of\ Units\ Produced - Inventory\ from\ Previous\ Quarter$$

14 Quarterly Revenue Table

1. Quarterly Revenue per Quarter

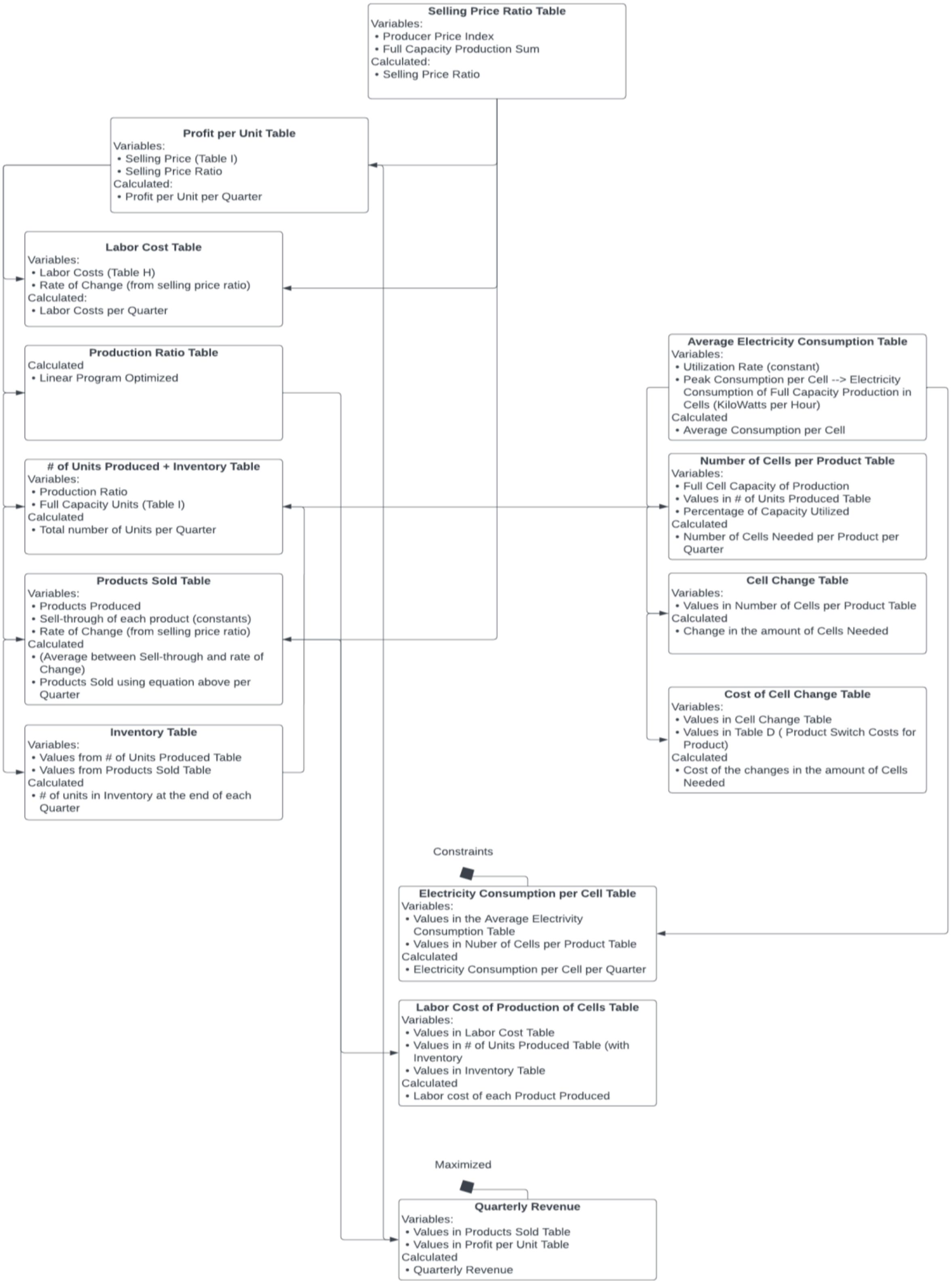
$$Sum\ of\ all\ of\ (Products\ Soldin\ the\ Quarter\ per\ Product\ \times Product\ per\ Unit\ in\ the\ Quarter\ per\ Product)$$

2. Maximize Revenue

$$Sum\ all\ of\ the\ Quarterly\ Revenues$$

Appendix G.

Summarized Linear Program Tables



Selling Price Ratio Table
Variables:
- Producer Price Index
- Full Capacity Production Sum

Calculated:
- Selling Price Ratio

Profit per Unit Table
Variables:
- Selling Price (Table I)
- Selling Price Ratio

Calculated:
- Profit per Unit per Quarter

Labor Cost Table
Variables:
- Labor Costs (Table H)
- Rate of Change (from selling price ratio)

Calculated:
- Labor Costs per Quarter

Production Ratio Table
Calculated
- Linear Program Optimized

# of Units Produced + Inventory Table
Variables:
- Production Ratio
- Full Capacity Units (Table I)

Calculated
- Total number of Units per Quarter

Products Sold Table
Variables:
- Products Produced
- Sell-through of each product (constants)
- Rate of Change (from selling price ratio)

Calculated
- (Average between Sell-through and rate of Change)
- Products Sold using equation above per Quarter

Inventory Table
Variables:
- Values from # of Units Produced Table
- Values from Products Sold Table

Calculated
- # of units in Inventory at the end of each Quarter

Average Electricity Consumption Table
Variables:
- Utilization Rate (constant)
- Peak Consumption per Cell --> Electricity Consumption of Full Capacity Production in Cells (KiloWatts per Hour)

Calculated
- Average Consumption per Cell

Number of Cells per Product Table
Variables:
- Full Cell Capacity of Production
- Values in # of Units Produced Table
- Percentage of Capacity Utilized

Calculated
- Number of Cells Needed per Product per Quarter

Cell Change Table
Variables:
- Values in Number of Cells per Product Table

Calculated
- Change in the amount of Cells Needed

Cost of Cell Change Table
Variables:
- Values in Cell Change Table
- Values in Table D (Product Switch Costs for Product)

Calculated
- Cost of the changes in the amount of Cells Needed

Constraints

Electricity Consumption per Cell Table
Variables:
- Values in the Average Electrivity Consumption Table
- Values in Nuber of Cells per Product Table

Calculated
- Electricity Consumption per Cell per Quarter

Labor Cost of Production of Cells Table
Variables:
- Values in Labor Cost Table
- Values in # of Units Produced Table (with Inventory
- Values in Inventory Table

Calculated
- Labor cost of each Product Produced

Maximized

Quarterly Revenue
Variables:
- Values in Products Sold Table
- Values in Profit per Unit Table

Calculated
- Quarterly Revenue

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