Minimizing Total Delivered Cost of Stamped Assemblies Through Sourcing Optimization

By

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ABSTRACT

This thesis presents an optimization model for identifying alternate and cost-competitive assembly sourcing strategies in the automotive industry, focusing on the "Make vs. Buy" decision-making process for a multinational automotive OEM. A “Make vs. Buy” process evaluates the strategic benefits and cost advantages derived from in-sourcing or out-sourcing a production process. Typically, one in-source scenario is evaluated, but capacity constraints may limit the opportunity to in-source. To combat capacity constraints, the optimization model was developed to evaluate sourcing production processes from other plants within the OEM’s manufacturing network. The sourcing strategy evaluates production scenarios for multi-process stamped assemblies undergo. Utilizing a mixed integer programming framework derived from the knapsack problem, the model evaluates all production scenarios to minimize total costs while adhering to capacity and capability constraints. Results demonstrate the model's effectiveness in identifying cost-saving and alternate sourcing strategies. Future work may explore extending the model to encompass broader geographical and operational complexities within the automotive sector.

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Key Terms and Definitions

COCA	Carry Over, Carry Across
Entry Ticket	Capital costs needed to start production of a part or assembly
MHU	Man Hour Unit
OEM	Original Equipment Manufacturer
SOP	Start of Production
EOP	End of Production
BOM	Bill of Materials
MOB	Make or Buy
TDC	Total Delivered Cost
CPU	Cost Per Unit
LCPU	Logistics Cost Per Unit
RFQ	Request for Quotation
UIO	Units in Operation
SPH	Strokes Per Hour
OEE	Overall Equipment Effectiveness
JPH	Jobs Per Hour

1 Introduction

1.1 Problem Statement

Over the past five years, the automotive industry has faced significant headwinds. As the industry navigated through the COVID-19 pandemic, many original equipment manufacturers (OEMs) encountered disruptions in their supply chains, notably in the procurement of chips and semiconductors. In parallel, the industry has contended with costly labor issues, including United Auto Workers strikes and an aging workforce. These challenges have been further compounded as the industry accelerates its transition towards electric vehicles (EV), which require significant investment to retool or standup plants to support EV production. Coupled with inflation, these issues resulted in increased production and distribution costs across the industry, and the industry's response signals a transformation in its operational landscape.

To remain competitive, OEMs must engage in cost-reduction activities by either increasing the efficiency of their production lines, streamlining and simplifying the design of their vehicles, or improving their sourcing strategies. Given the level of coordination between engineering, manufacturing, and supply chain required to support these activities, many of these projects require multi-year and capital-intensive efforts to carry out and are not reversible without going through another multi-year cycle to refine or rectify the implemented project. For example, a vehicle launching in 2023 would have had any major design, manufacturing, and sourcing decisions made in the 2019 timeframe. Decision-making this far upstream inherently grapples with significant levels of uncertainty as the vehicle design remains unfinalized and projected production volumes may not align with sales volumes once a vehicle enters production. Furthermore, economies of scale can work for or against an OEM as even small perturbances in volume, demand, or cost can give way to fluctuations worth millions of dollars in total production costs.

One way to minimize costs is by identifying the lowest-cost sourcing strategy for a part or assembly. When a vehicle is allocated to a plant, some parts, mostly large metal or plastic parts and parts that are visible to the customer, are always produced at the plant where the vehicle undergoes final assembly. Other parts, usually those that the OEM cannot produce themselves, are outsourced and multiple suppliers submit bids to produce these parts – these parts include electronic assemblies, windshields/windows, wiring harnesses, etc. Even when parts are outsourced, the supplier may be near or on-site, this strategy allows the OEM to benefit from short, low-cost shipping routes and improved lead times. Thousands of parts need to be sourced, creating a significant load on the procurement organization. Due to the complexity of managing and evaluating costs for thousands of parts from just as many suppliers, simple evaluation methods were put in place to simplify this workflow. Recent work (Queiros, 2021) made strides to create a more comprehensive evaluation of supplier cost nearly instantly, allowing procurement to be more efficient and handle more cost complexity.

Some parts and assemblies lie between the “always-insource” and “always-outsource” categories. These parts and assemblies fall into the scope of the “Make Vs. Buy” workstream. These are assemblies that the OEM can produce using internal production capabilities but aren’t critical to the external quality of the vehicle. Historically, very few assemblies fell into this category, and, when considering “Make Vs. Buy” for a particular set of assemblies for a vehicle, bids were between producing the assembly at the vehicle’s final assembly plant or producing the assembly at a single supplier. This comparison is simple. However, it doesn’t evaluate production scenarios that leverage internal manufacturing networks or evaluate bids from more than one supplier. This simplification makes the workflow manageable for the supporting groups since developing in-house sourcing costs for a single assembly requires inputs from design, manufacturing, finance, procurement, and supply chain. These studies often include multiple assemblies, further amplifying the work. Given the complexity, which is the number of unique vehicles/models produced in a plant or on a line, of the production lines at the OEM, all forms of sourcing for multiple vehicles may overlap in any given period.

This overlapping of sourcing activities for the supporting functions, on top of their other duties, can create long lead times for getting information to complete the in-house sourcing studies for the make case, and after weeks or months of gathering inputs, the study may show that internal sourcing is not cost-competitive or that internal capacity cannot support the required production volume. Despite this, the Make Vs. Buy workstream has become more prevalent and will continue to increase in scope as OEMs look to improve asset utilization, make more strategic Make Vs. Buy. decisions, and to remain competitive as they face increasing costs from suppliers.

To prevent the issues described in this section from proliferating, this project aims to proactively address some of the shortcomings of the current Make Vs. Buy study workstream. The goal is to develop an optimization model that minimizes the total delivered cost of assemblies, with a focus on stamped assemblies, which make up the largest group of in-scope parts for Make Vs. Buy. The project's objective can be summarized into the 2 objectives below:

1. Efficiently identify cost-competitive studies for further analysis by modeling cost inputs and capacity constraints
2. Uncover cost-saving opportunities by evaluating total delivered cost (TdC) for all internal production scenarios

This optimization model can be utilized by the OEM to determine the most cost-effective approach to producing an assembly, whether that be insourcing or out-sourcing, before committing to a full study. This is achieved by modeling the calculations and inputs from groups that support Make Vs. Buy studies. By modeling the cost, capability, and capacity of the OEM's internal manufacturing network, the model can provide the OEM with an optimal and feasible sourcing strategy for all the assemblies under study by comparing the optimal in-house total delivered cost with the outsourcing cost.

1.2 Thesis Outline

The thesis is divided into 5 sections. It begins with the background, the approach, the methodology, the methodology applied to case studies, and ends with a discussion. Section 2 defines key terms, provides a high-level overview of the OEM's operations, and finishes with a literature review of make-or-buy and the optimization approach. Section 3 goes into a detailed description of the cost and capacity data for the plants, characterizes the part data for the case studies, highlights the differences between the future model and past model parts, and formulates the optimization model. Section 4 provides the output of the model under different scenarios to develop use cases for the model. Section 5 concludes the thesis with a discussion of limitations and improvements for this work. Given the strategic and potentially sensitive nature of the work, the firm will be referred to as the "OEM" to maintain a sense of anonymity and allow the thesis to focus on methodologies and outcomes rather than the identity of the firm.

1.3 Thesis Contributions

The thesis introduces an integer program that integrates cost, capacity, and logistics data to guide decision-making in the "Make vs. Buy" process. Typically, a linear program (LP) following manufacturing network framework can be applied to this type of problem. The LP framework can satisfy demand from multiple sources, going from the lowest cost to the highest, but the OEM must allocate all volume to a single source. Thus, multi-sourcing is not option. To facilitate a single source approach, the researcher developed and formulated an approach using an integer program derived from the knapsack problem. The knapsack problem is commonly used to allocate resources to optimize for a given parameter. As such, it is well suited for the OEM's problem. In addition, this approach allowed the model to generate make or buy decisions itself, abiding by the logic used by the OEM. By building the decision-making entirely within the model, it is able to more effectively utilize resources in the complex and variable planning horizon automotive manufacturers face.

2 Background

2.1 Company Overview

The OEM is a multinational automotive manufacturer with operations in Asia, Europe, and the Americas and ranks in the top 25 automotive companies by sales volume. This work was performed for the North American subsidiary, consisting of the United States, Mexico, and Canada. The OEM's North American Operations are in the United States and Mexico, this is commonly referred to as the "Region." The Region is a concept introduced in the 2010s, along with the coalescing of leadership across the Region, and is meant to convey unity across the OEM's North American Operations. While the name took root quickly, standardizing processes, aligning culture, and encouraging increased cooperation amongst the Region's plants was an ongoing endeavor.

The manufacturing strategy team, for whom this work was performed, was created in the same decade. The office's scope of work was closely aligned with its name, and for the office to carry out this work, it has several teams each with its own set of responsibilities. Chiefly, these teams coordinate activities around the future of the OEM's manufacturing plan. Their work includes dealing with vehicle volume allocations, in-site and on-site supplier strategy, digital transformation, investments in enhancing manufacturing capability or capacity, and make vs. buy studies for plants within the Region. From an organizational perspective, it also serves as an ad-hoc analysis group for the manufacturing leadership team and often liaisons with the global headquarters' strategy team.

The researcher was embedded with the industrial strategy team while undertaking the research. The industrial strategy team focuses on vehicle volume allocations, investments in new manufacturing capabilities and capacity, and co-coordinates make-or-buy studies.

At the onset, the focus of the research was to help determine a cost-optimal approach to develop a facility or set of facilities that would allow the OEM to supply past model aftersales parts. "Aftersales" refers to the services, support, and products offered to customers after they have purchased a vehicle. Aftersales services typically include maintenance and repair services, parts and accessories, and warranty services. Aftersales service is critical as it not only contributes to customer satisfaction and retention but also represents a significant portion of an OEM's profits. "Past model" refers to vehicle models that have ended production but still require replacement parts for any repair, maintenance, or warranty claims. Section 2.7 provides more information on aftersales.

Past model parts in the US are either outsourced to a single supplier or are slate for a "lifetime buy", in which a final run of the part is performed and the tooling disposed of. The sourcing decision is typically made by the aftersales team at or near the end of production (EOP) date of the vehicle. When a model EOPs, it is "replaced" by a new model. The tooling and equipment to support the production of the past model is sent to the supplier and, in its stead, tooling and equipment for the new model is brought in.

However, with the relationship with the aftersales supplier souring and the costs of outsourcing past model parts rising, the focus swiftly shifted to developing an optimization model that would enable the industrial strategy team to evaluate make-or-buy decisions for both new model and past model parts. While past model parts encompass a broad range of part categories, the focus of this work is on metal assemblies for past models and new models. An overview of the manufacturing process for a vehicle is outlined in the remainder of section 2.

2.2 Operations

A vehicle begins as a coiled sheet of metal in the material storage area of the OEM's blanking area. Coils are turned into square sheets of metal and primed for stamping. Once parts are stamped, they go through a series of welding and assembly operations in the body shop. The assembled body is known as a "body-in-white" (BIW), which is then painted. The painted body then enters the trim and chassis stage. At this stage, the electronics, harnesses, powertrain, engine, tires, glass, seats, and plastics are installed. Figure 2-1 outlines the steps required for producing a vehicle along with the production processes that are the focus of this thesis.

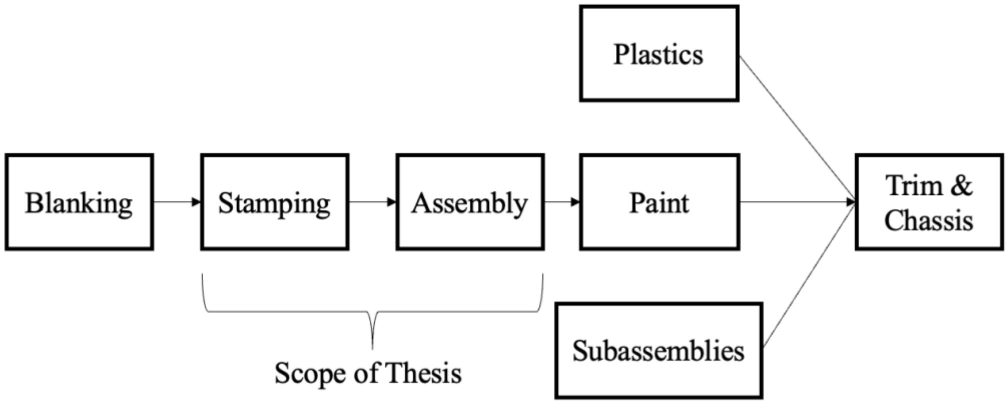

Figure 2-1: Process Flow Overview for Vehicle Production

2.3 Stamping

Stamping is a straightforward process. Metal blanks enter the stamping press and exit the stamping press as a formed part, ready for assembly. A stamped part is formed by progressively pressing and cutting the blank into a variety of shapes using several dies. The design of a die can be highly precise and complex, and the machine in which the dies are placed produces hundreds of parts per hour. Figure 2-2 depicts the inside of a stamping die.

Figure 2-2: Image of Stamping Die for a Hood
(*Enhancing Durability of Automotive Stamping Dies with Plasma Nitriding*, n.d.)

The downside of the stamping process is that housing the machinery, tooling, and dies requires large amounts of floor space. In addition, space for material storage, material handling, and safety areas add to the footprint of a stamping press. Figure 2-3 provides a hypothetical layout of a stamping plant.

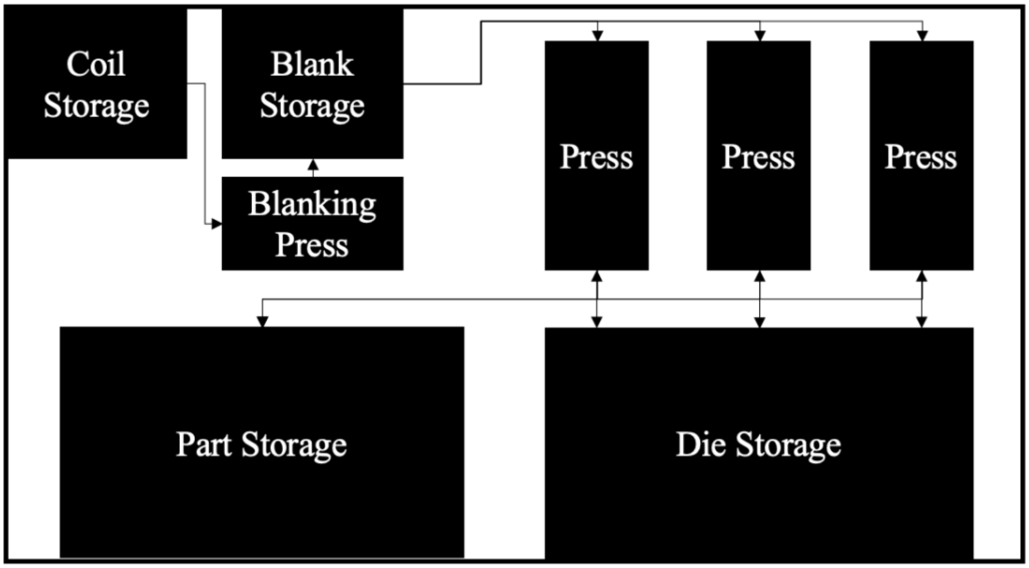

Figure 2-3: Layout of a stamping shop

When thinking about capacity for parts, not only does the OEM have to consider process hours but also storage for tooling, equipment, and the parts themselves. For production parts, a part is run every run for 2 to 3 days depending on downstream demand. Past model parts are run as needed – with no specific cadence. Once a part is stamped and racked, it moves to its designated storage area, and depending on the dimensions of the part, several racks may be needed to store enough inventory until the part is run again. Figure 2-4 represents the process flow of a part.

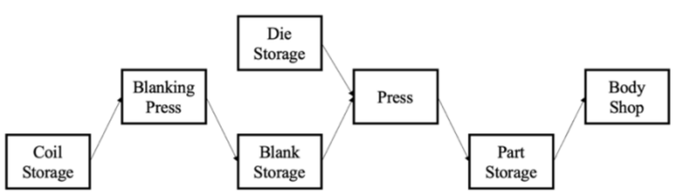

Figure 2-4: Process Flow within Stamping Shop

2.4 Body Shop

The Body Shop is made up of multiple assembly lines, one for each model the OEM produces in a plant. An assembly line is made up of several feeder lines and a main line. An assembly line can be thought of as a tree, with the leaves being assembly cells, the branches being the feeder lines, and the trunk being the main line. The feeder lines are where parts begin assembly and consist of multiple assembly cells. Each assembly cell performs a joining process on the parts that are fed into it – an operator is usually stationed at the assembly cells to assist in prepping and loading parts. The number of parts needed for an assembly can be between the low single digits to the high teens. Automation takes over after the first stage of a feeder line, and robots move and load parts onto the secondary stage of the feeder line or onto the main line. A production part will go through the entire assembly process whereas an aftersales part may only require assembly within the scope of the feeder line operations. The throughput of these stages is near the overall rate of production, or JPH, of the plant. The throughput of the press lines is many times that of the Body Shop, allowing the OEM to store several days of inventory for stamped parts while only using a few hours of production time of a press. Figure 2-5 provides an outline of the process.

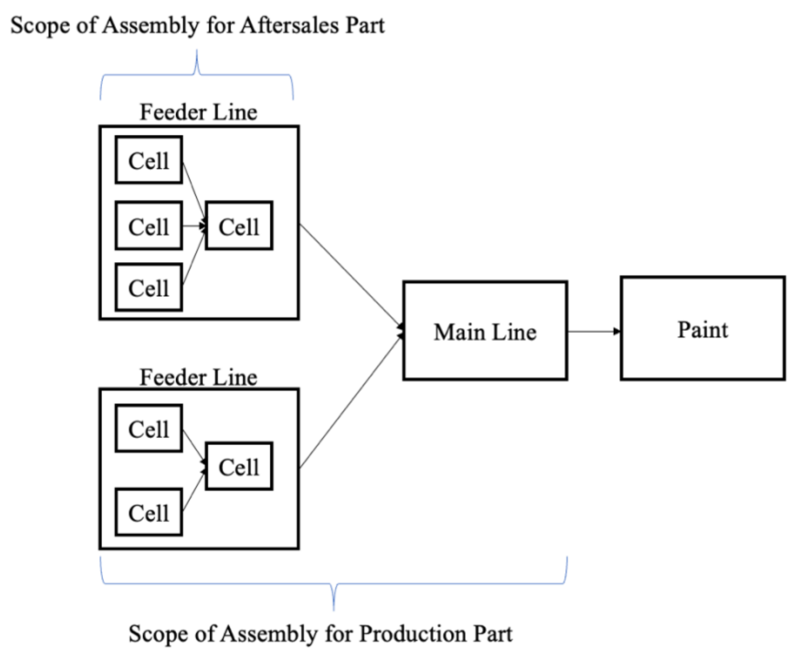

Figure 2-5: Layout of Body Shop

This thesis focused on sourcing parts as they enter the feeder line or in the first stage. At the earlier stages of assembly, the only requirement for inventory is that it is available at the time it's required, no matter the source. However, parts of the BIW that are critical to the appearance and quality of the vehicle are always sourced in-house. Fortunately, these parts are often cost-competitive to produce in-house due to their size since they are larger and less logistically efficient than smaller parts. Figure 2-6 represents the frame of a vehicle after exiting the Body Shop – note the bumpers are not present at this stage in the vehicle's life.

Figure 2-6: Body-in-White (Source, 3M)

2.5 Vehicle Launch Timeline

The development and sourcing of a vehicle's parts begin 4 to 5 years before the vehicle enters production. At this point, the vehicle's expected volume, location of manufacturing, and majority of the detailed design are known. A vehicle, across all its trims, requires anywhere from 2,000 to 3,000 parts. A trim is a version of a vehicle that is equipped with a specific set of features, options, and performance capabilities. Different trims allow the OEM to serve different segments of customers with the same platform. Sourcing these parts requires tremendous effort from the manufacturing, procurement, and supply chain teams. Most parts are sourced from suppliers. These suppliers can be on-site, near-site, in the Americas, or overseas. High-volume parts, which are those that are used for every trim, are typically sourced as close as possible to the plant. To limit the amount of change-over work required when sourcing parts for new vehicles, the OEM relies on carry-over, carry-across (COCA) parts. These are parts that can be carried over from older models or carried across from in-production models. Designing new models with COCA parts reduces the workload on all parties that support the development of a model. Sourcing decisions are not easily changed and require a commitment for the model's entire production lifecycle, which is usually 7 years.

As touched on in the prior section, a subset of the thousands of unique parts required to build a vehicle are always sourced in-house. The parts always produced in-house are constrained to a subset of parts that are critical to the quality of the vehicle, parts that confer a competitive or technological advantage, or parts that require unique production processes within the OEM's manufacturing capability. Between the always-outsourced parts and the always-insourced parts, lie even a smaller subset of parts that are candidates for make vs. buy. The candidate parts are stamped or assembled metal parts, plastic parts, commonly known as fascia parts, and subassemblies for trim and chassis. In terms of capacity, or investment to develop capacity, to make parts within this scope, stamped or assembled metal parts are the costliest. Producing an assembly may require multiple stamped parts, which themselves require unique die sets, to be in-sourced and the assembly process itself requires shop floor space to accommodate production. The cost of the die sets and a cell doesn't vary greatly between the OEM and a supplier, but the footprint of the tooling takes up significant floor space. Floor space is quickly consumed as complexity increases. A fascia part requires a single mold – some assembly of the fascia is required to install harnesses and electronics. The maximum throughput of the injection molding machines, which produce fascia parts, is near the maximum throughput of the production line. Fascia parts for high-volume models may require investment in additional injection molding machine(s) to adequately support demand. Producing trim and chassis subassemblies requires an area to store parts and an area to assemble parts.

Stamped and assembled parts have the largest number of candidate parts in make-or-buy, as such, a case study is analyzed for these categories of parts in parallel with past model stamped and assembled parts. The following sections offer and overview and a timeline of the make-or-buy process at the OEM.

2.6 Make Vs. Buy at the OEM

Manufacturing companies achieve long-term cost reduction and maintain cost competitiveness through strategic insourcing and outsourcing different components of their product. This decision-making process, typically referred to as Make Vs. Buy, is critical for several reasons: maintaining cost efficiency, leveraging core competencies, managing capacity and resource utilization, and developing strategic partnerships and relationships.

Developing a make vs. buy analysis can be an intensive process and involves alignment across several functions and groups to reach the point where a decision on whether to outsource or insource a part or assembly can be properly vetted. However, often these analyses are not exhaustive of all potential production scenarios, and the production scenario that is analyzed may not be the least costly option. A production scenario details the allocations of process of an assembly. For example, an assembly and its subassemblies can all be produced in-house, or they can be outsourced. If made in-house, the parts could be sourced from any of the facilities the OEM has in service. How does an OEM, at the onset of an analysis, determine the right production scenario to fully develop? Consider Figure 2-7, assembly A is made of component B and component C. All elements of this part can be outsourced or manufactured by any plant the OEM owns.

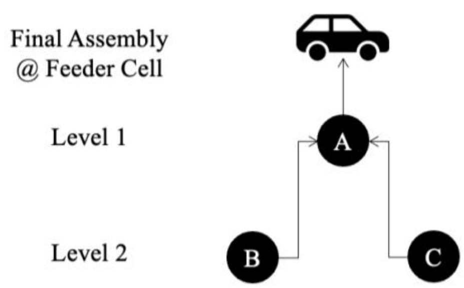

Figure 2-7: Assembly Structure of a Part

Each component must arrive at assembly A's location, and the assembly must then arrive at the final assembly location. If there are 3 production options, 2 factories and 1 supplier, for each component and the assembly, there are 9 total production scenarios. How can an OEM identify and select the most cost-effective scenario for analysis, ensuring that the identification process does not adversely impact the schedule or create excess work for supporting functions? Furthermore, how does the organization address situations where multiple assemblies require sourcing? Or when there are capacity constraints in each factory? Lastly, how can the organization address these conditions and still identify optimal sourcing strategies? In response to these challenges, the proposed solution is an optimization model that can determine the optimal sourcing strategy given the cost, capabilities, and capacities of the factories.

2.7 Make Vs. Buy Timeline

A "Make vs. Buy" study is the process by which the OEM determines how to source a part or assembly for a new model. Overall, there are four tiers of studies. Each tier is studied in sequence and is allocated approximately 16 weeks to reach a decision. Each tier can contain several parts or assemblies. For example, parts that utilize new technologies or processes are studied in the first tier, which is farthest upstream from the start of production (SOP) of the model. Each subsequent tier contains parts or assemblies that use increasingly familiar technologies or processes. Figure 2-7 represents the make-or-buy timeline for the OEM.

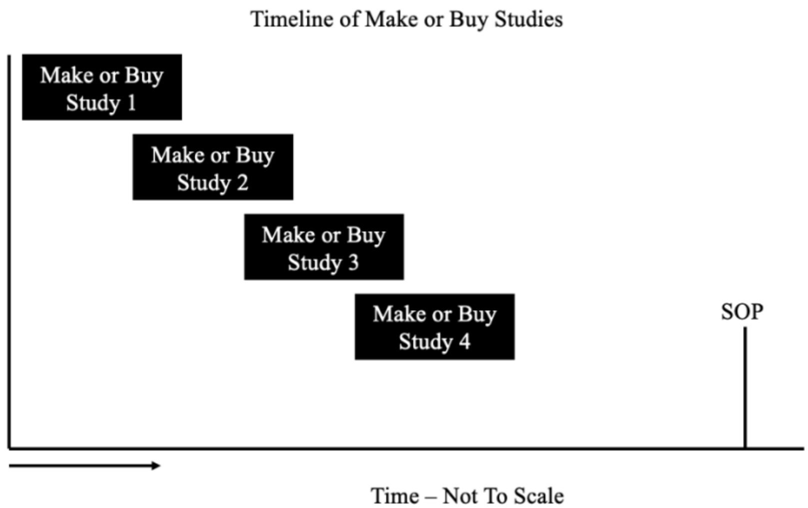

Figure 2-8: Timeline of Make or Buy Studies for a New Model

Given the cadences of the OEM's vehicle launch strategy, studies for multiple models may overlap at any given time. In contrast, the make vs. buy study for past model service occurs closer to a given model's EOP date and does not employ a tiered evaluation methodology. The tiered methodology is a sound strategy when a part may require the development or sourcing of a new manufacturing process and therefore may require more time to prepare the plant for the introduction of the process. Past model parts do not require as much runway. At this point, each past model part has a "lifetime buy" or continued production – this study is carried out by the aftersales team. Figure 2-8 highlights the make-or-buy study cadence and its timeline for a past model part.

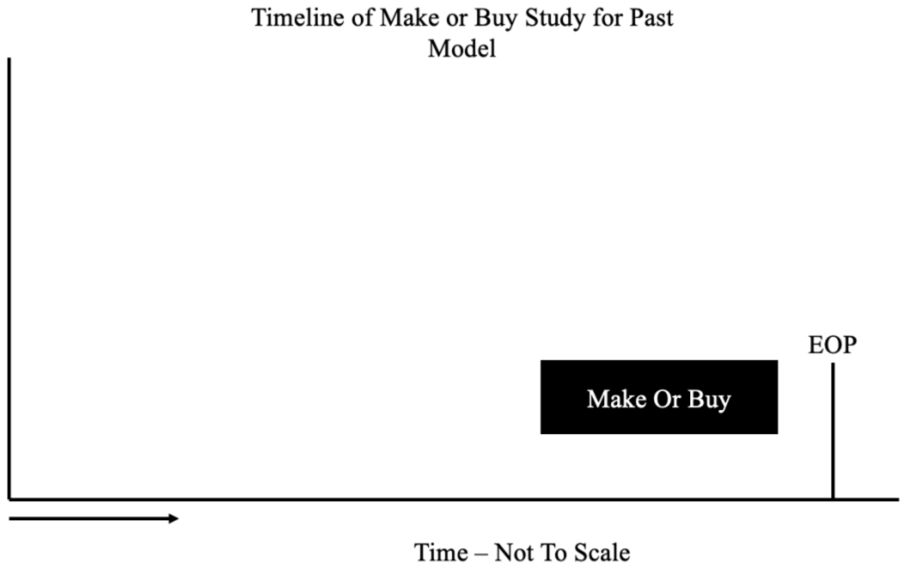

Figure 2-9: Timeline of Make or Buy Study for Past Model

Note that the make-or-buy decision for a past model occurs relatively close to its EOP date in comparison to a future model. This is a benefit of having the tooling, design, and equipment finalized for several years. Continuing to make a past model part incurs little capital investment while outsourcing the part requires the transfer of the tooling and processes to a supplier. The challenge arises when a model that is starting production requires the capacity that a model that is ending production occupies. Figure 2-10 highlights the gap in decision-making that could lead to the costly outsourcing of a past model part.

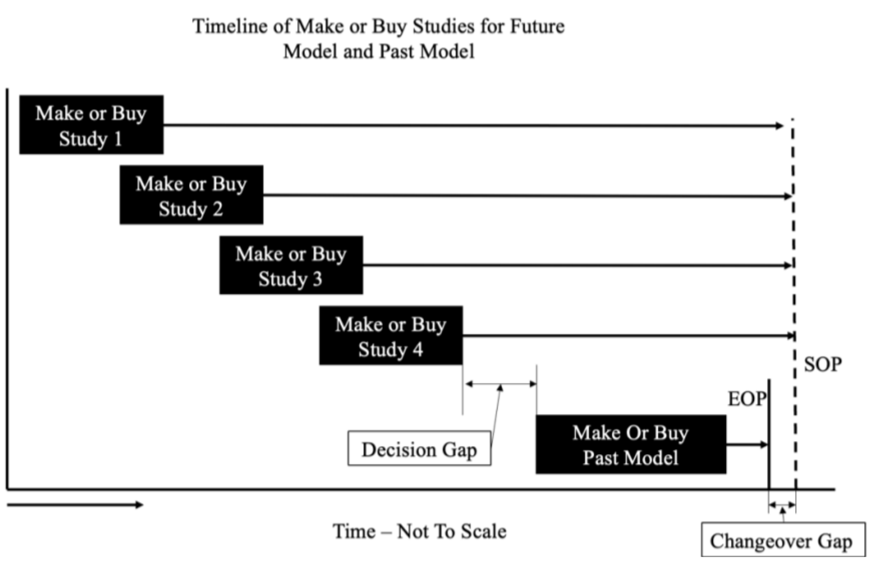

Figure 2-10: Timeline of Make or Buy Studies for New and Past Models

The “Decision Gap”, while not shown to scale, highlights the lag between sourcing activities. Closing this gap allows the OEM to evaluate the opportunity cost of outsourcing a past model part to insource a future model. Historically, this gap was not an issue. The OEM could reliably and profitably source past model production to their supplier- albeit at a higher cost. When trading off capacity between future model and past model parts, future model parts were given priority if cost advantages could be gained by insourcing the future model part. Operational and financial metrics could be improved through this strategy as well – better overall equipment effectiveness (OEE) and lower overhead by moving a higher volume of parts through the plant. However, the disadvantages of having a sole supplier for past model parts began to manifest. The supplier began to raise the prices of quotes and, in some cases, declined to quote a part at all. Thus, a once extremely profitable vertical for the OEM began to succumb to the challenges that arise when a customer has limited bargaining power. Leverage became limited, terms were not as favorable, and parts they expected to outsource, but no longer could, may have already had their capacity allocated to a future model part. For upcoming make vs. buy decisions, the OEM wants to consider future model parts and past model parts holistically. Figure 2-11 represents the “want-to-be” condition for subsequent sourcing decisions.

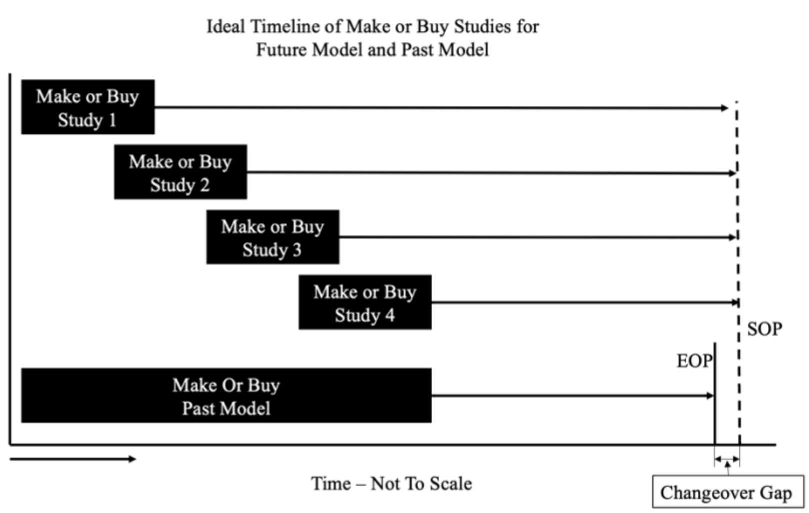

Figure 2-11: Proposed Timeline for Make or Buy Studies for New and Past Model

Ideally, sourcing decisions are made with information on all known future production scenarios.

2.8 Aftersales & Past Model Service at the OEM

The purpose of this thesis is to examine optimization methods that can be used during the Make vs. Buy workstream to minimize the cost of producing and delivering a car part or assembly with respect to the capacity constraints of the company's asset base.

However, the project from which the thesis is derived was originally aimed at designing a cost-optimized facility that would exclusively produce aftersales parts and assemblies. Aftersales is a term used to describe all items of a vehicle that are purchased after a vehicle is sold. As such, aftersales parts include electronics, accessories, and, most importantly, replacement parts, which are also commonly referred to as service parts. An aftersales part can be produced for a vehicle that is in current production or for a vehicle that has ended production, this category of vehicle is typically referred to as a "Past Model". The rule of thumb states replacement parts must be available for at minimum 10 years past the model's end of life.

There are debates as to whether this is state or federal regulation (Strohl, 2020); as OEMs are only required to supply parts within a vehicle's warranty period under the Magnusson-Moss Warranty Act, colloquially known as the "Lemon Law", which is a regulation enacted to curb automakers from shipping a new vehicle that is defective or fails to meet advertised quality standards. Nonetheless, the average lifetime of a vehicle in the United States is 12.2 years (United States. Department of Transportation. Bureau of Transportation Statistics, 2019). Providing past model service parts as long as possible can only reinforce the positive externalities mentioned.

As such, there is a precedence that OEMs must supply service parts for 10 years after the vehicle ends production or else the OEM must buy back, at market rate, the vehicle from its owner. It follows that past model service parts are a critical channel to serve from both a regulatory and customer service standpoint. In theory, past model service parts are parts integral to the function or structure of a car. For example, an engine, a door, a transmission, etc. However, in practice, past model service parts are parts that can be damaged in an accident but do not result in a totaled vehicle. A vehicle is considered totaled when the insurance provider considers the vehicle a "total loss", which occurs when the cost to repair the vehicle is higher than its actual value. One key point to note is that demand for past model service parts comes largely from vehicle collisions, which are largely unpredictable and entirely dependent on "Units-In-Operation" or UIO. UIO represents an estimated number of vehicles on the road of a particular model. Throughout the 10-year past model service period, UIO follows an exponential decay distribution, with a higher number of vehicles in operation in the earlier years and then tapering off as time passes. It follows that demand for past model service parts is largely predicated on the number of units sold and the expected rate of non-totaled accidents within that population. This unpredictability in demand produces challenges when forecasting expected demand and when planning for long-term capacity. Over the lifetime of a past model, the number of service parts produced for it will number in the tens of thousands, which, when compared to the production capacity of the assets used to produce the parts, is a small load factor. However, the equipment used to produce these parts requires floor space for 10 years, and floor space is a premium for the OEM. The OEM faces trade-offs when deciding whether to continue making a past model service part or contracting the production out to a supplier. Allocating floor space for a single past model doesn't pose too much of an issue. However, given the 10-year production requirement, the equipment needed to continue to produce service parts can begin to take up more and more floor space as models end production. Many OEMs avoid the slow creep of past model service by building a plant dedicated to the production of these parts. In contrast to other OEMs, this OEMs business model focuses on maintaining and investing in a set of longstanding production facilities – shuttering a plant comes with much deliberation. Other OEMs often open, close, and retool plants at will. Given the OEM's adherence to its business model, opening a factory also comes after much deliberation, especially if it is in a market that is already being served by a factory. However, this requires that the company make the best use of its plant's production capacity and square footage. As such, past model service parts have typically been outsourced. Outsourcing comes at an increased cost, but past model service parts maintain robust profit margins. The decision to outsource or insource these assemblies is made the year a model ends production. In the past, past model service was always outsourced in the US, allowing the company to reserve space for production parts. Due to the unpredictability in demand and the unbalanced load past model service places on a factory, only one supplier in the US quotes past model service parts. Recently, this supplier has been raising prices by hundreds of percent, cutting into, or nearly eliminating, profits of past model service parts. In response, the aftersales team proposed the development of a past model service plant. The investment in the plant was deemed too capital-intensive, especially at the time when OEMs were investing billions in the production of EVs (Lienert, 2022).

2.9 Literature Review

2.9.1 MIP Modeling

This section outlines the methodology employed to address the project's problem, focusing on an optimization approach inspired by the knapsack problem, a well-established problem in combinatorial optimization. The core of the methodology is a Mixed Integer Programming (MIP) model and is an adaptation of the knapsack problem ("Knapsack Problems," n.d.). Development of the model was guided by the application and synthesis of several logical constraints found in (Williams, 1999)

The knapsack problem, traditionally, involves selecting a subset of items, each with a given weight and value, to maximize the total value without exceeding a specified weight limit. In this context, the 'items' represent assemblies or parts, the "weight" is a part's load factor, and the 'weight limit' corresponds to a production asset's capacity. Value, in this case, is equivalent to cost, we want the lowest-cost items in the knapsack and that is driven by whether a part is made or bought. The adaptation of the knapsack problem in this project involves minimizing the cost of items placed in the "knapsack" and adding continuity constraints, such that a part's assembly is made entirely in-house and a time-series capacity constraint. This approach and methodology may be atypical for this type of problem. However, as the goals of the project changed, the knapsack model evolved along with it. This problem can be solved using a network flow approach (LP) as well by applying appropriate logic constraints where necessary.

2.9.2 Make Vs. Buy

Evaluating sourcing goes beyond developing an economic analysis. The approach developed by the OEM follows closely with the make vs. buy framework proposed by (Ordoobadi, n.d.). This approach not only develops an economic analysis but also evaluates the OEM's core competencies and concludes with an evaluation of ROI. The dataset for this research contains parts that have passed the core competency check and have moved into the economic analysis, which is supported by determining the parameters that impact cost.

There are many benefits to outsourcing elements of a product. A firm can: avoid increasing its headcount, take advantage of the supplier's economies of scale for lower costs, and focus on developing capability in high-value work (James A. Welch & P. Ranganath Nayak, 1992). The risks of outsourcing are many, too. As we've seen with the OEM, the supplier of a critical vertical has gone rogue, putting a profitable segment of the OEM’s business at risk. Other risks include the inability to react to fluctuations in volume, the lack of quality control, and the inability to develop additional core skills (Aron et al., 2005).

3 Methodology and Formulation

The methodology and formulation section details the approach for the cost, capacity, and optimization models. An overview of the types of data used, the data's relevance to the research, and the relationships between the datasets is provided. The detailed optimization model is then formulated. This section is followed by a section that examines the results of the optimization model under different scenarios.

3.1 Data

This model relies on two primary data sources: plant data and part data. Plant data encompasses details about each plant's capabilities and capacity over time, labor costs, and shipping rates to plants within the OEM's North American manufacturing network. These data enable the model to identify viable production scenarios. In conjunction, part data provides specifics about asset allocation for each part, load factor, labor hours, and logistics parameters.

3.1.1 Plant Data

The section describes the plant data used for the optimization, gives an overview of the operational status of each plant, and describes the relationships between the plants. The OEM has several plants, each with unique capacity and capability, in the North American region. The selected plants for this research will be referred to as plants A, B, C, D, and E. While each plant has several dimensions, such as the number of production lines, vehicle allocations, vehicle volumes, assets, and workshops, this thesis focuses on stamping capacity, labor, and interplant logistics.

The OEM's plants are in the southern region of the United States and central Mexico. Plants A and B are in the United States while plants C, D, and E are in central Mexico. The locations of the plants give rise to an internal supply chain network not seen in other OEM operations. While many OEMs have plants in Mexico, their United States plants are in the northern regions of the Midwest rather than the southern regions of the United States. The position of the OEM's plants allows them to take advantage of the lower labor costs of Mexico and shorter lead times between plants.

Data from 2023 (Lu, 2023) show that the United States' monthly minimum wage is $1,550 and Mexico's is $315. This ratio of wage rates is reflected in the wage rates of the OEM's

North American operations. Lower wage rates can lead to advantages in manufacturing costs, but logistics costs may outweigh them. Figure 3-1 provides a qualitative comparison of labor rates between plants.

Figure 3-1: Labor Rates by Plant

Historically, accounting for transportation costs was not a part of the costing methodology at the OEM. Over the past few years, the OEM has taken strides to integrate logistics costs into their costing methodology. If this analysis were done when logistics costs were not considered, sourcing parts from Mexico would have appeared to be a viable approach. There are, however, other sourcing standards that would have limited that approach. Nonetheless, this approach must arrive at the total delivered cost of the part or assembly and to do so logistics costs need to be considered. Some routes may combine rail freight and truckload freight to supply parts to their destination. The interplant logistics rates follow standard logistics rates logic and scale with the distance between the origin and destination. For example, shipping a part from Plant A to Plant B costs less than shipping a part from Plant A to Plant C. Each plant, except for Plant E, has a logistic rate associated with the route. A description of the relative logistics rates is provided in Table 3-1.

Table 3-1: Comparison of Inter-Plant Logistics Rates

Qualitative Inter-Plant Logistics Rates					
Plant	**A**	**B**	**C**	**D**	**E**
A	0	Low	High	High	-
B	Low	0	Moderate	Moderate	-
C	High	Moderate	0	0	-
D	High	Moderate	0	0	-
E	-	-	-	-	0

Notice that Plant E does not have any logistics rates available. An estimate could have been made, but Plant E also does not have stamping capability available in its facilities. For these two reasons, Plant E will be excluded from further analysis.

3.1.2 Stamping Press Capacity

Stamping press capacity is the primary operational constraint within the scope of this thesis. Press capacity is critical due to the nature of the OEM's operations, which run lean – meaning any unplanned downtime longer than 3 days can severely impact the plant if the affected press's load can't be distributed to other presses. Each press has an strokes per hour (SPH), which can also vary by part, acceptable material type, and tonnage. Tonnages are obfuscated but are divided into four categories. These three attributes define the parts that can be loaded on the press. The values each attribute can take are listed below:

- SPH
    - Numeric value from 200-2000
- Material Type
    - Steel (S)
    - Aluminum and Steel (A/S)
- Tonnage
    - Type 1
    - Type 2
    - Type 3
    - Type 4

Table 3-2 gives an overview of the press capabilities available at each plant.

Table 3-2: Tonnage and Material Capability by Plant

Tonnage	Plant A	Plant B	Plant C	Plant D	Plant E
Type 1	A/S	A/S	S	S	-
Type 2	A/S	-	S	-	-
Type 3	A/S	-	S	-	-
Type 4	S	-	S	-	-

In addition to these attributes, time series information on the expected utilization of the presses is available. Utilization can be represented in available strokes or hours. To simplify the representation of press capacity, presses with the same attributes for tonnage and material type are represented as one group, with the utilization represented in hours. The shift pattern drives capacity and can fluctuate given the business plan of the OEM. The types of shift patterns and their hours are listed below.

Table 3-3: Shift Patterns

Shift Pattern	Hours
1 Shift, 5 Days	7.5
2 Shift, 5 Days	14.2
3 Shift, 5 Days	21.4

There are more styles and types of shifts of patterns, but the focus will be on these three types.

Figure 3-2 through 3-5 show capacity information of the OEM’s press capacities. Each graph shows a the type of press and its expected utilization into the early 2030s. The monthly available hours are superimposed on the utilization levels, and each shift pattern described in table 3-3 is shown.

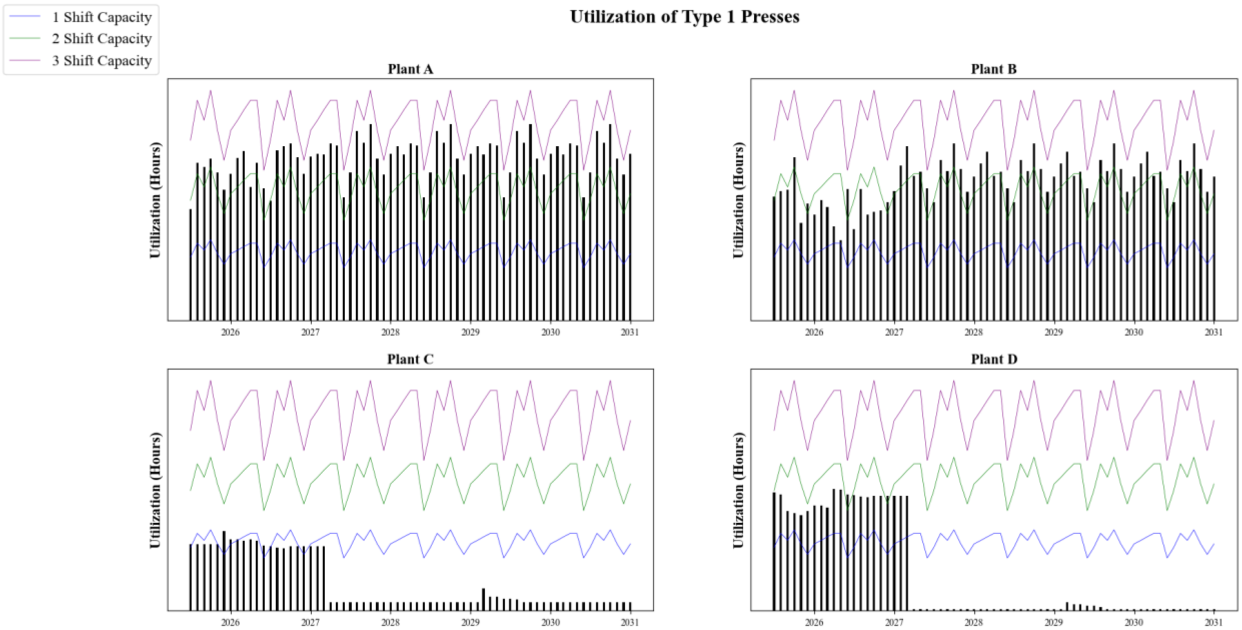

Figure 3-2: Regional Utilization of Type 1 Presses

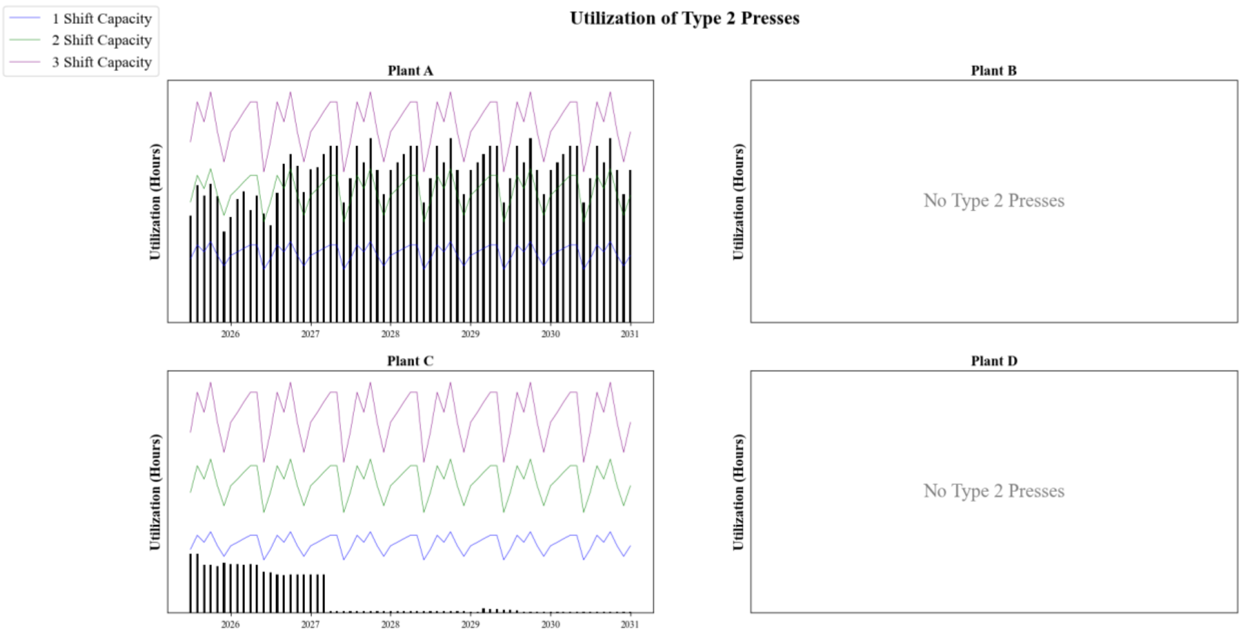

Figure 3-3: Regional Utilization of Type 2 Presses

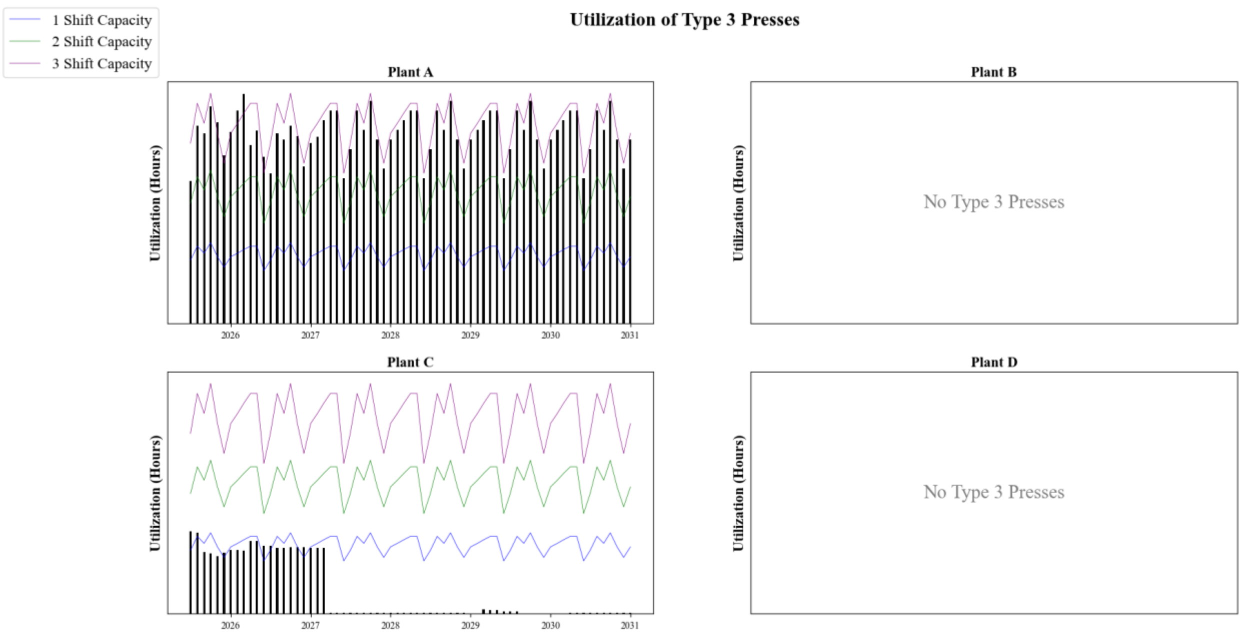

Figure 3-4: Regional Utilization of Type 3 Presses

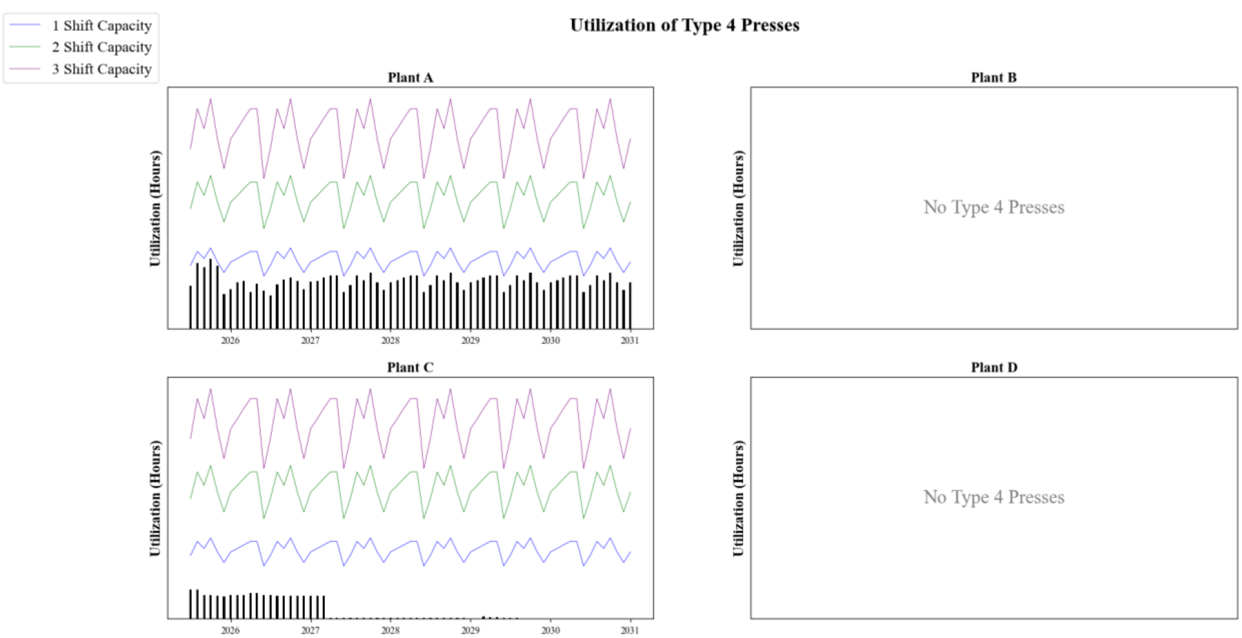

Figure 3-5: Regional Utilization of Type 4 Presses

To summarize the above data, Plants A and B, the US plants, are near maximum utilization on a 3 shift pattern, across all their press lines, except type 4, well into the early 2030's. However, Plants C and D, the Mexico plants, see their utilization encounter a valley in 2027. These low utilization levels may be due to pending volume allocations to these plants. In reality, the OEM will more than likely allocate production volume to these plants in the future.

These data taken at face value show polarized operational conditions between the OEM’s plants. What can be done to relieve the potential capacity challenges in the United States? On the other end, how can the Mexico plants improve their utilization? Operating at their limits, Plant’s A and B press lines will certainly struggle to take on any work. What impact will in-sourcing more parts have on their utilization? The next section will cover the parts/assemblies in the Make vs. Buy study.

3.1.3 Part Data

The part dataset comes from Model Z’s Make-or-Buy study and Model Y’s service parts. Model Z start of production (SOP) date is in FY26 and Model Y EOPs in FY26. Model Z is based in Plant A, and Model Y is based in Plant B. The optimization model will assume Plant A could service Model Y’s service part demand. The dataset for both sets of parts differs but both have some measure of outsourcing cost, insourcing cost, and utilization. The datasets themselves and the differences are described in the following section.

3.1.4 Model Z’s Make vs. Buy Study

Model Z is expected to SOP in FY26 and its study contains 7 of the 8 stamped assemblies within the scope of the OEM’s Make vs. Buy candidates. The assemblies each have at least one stamped part Plant A can produce. Each assembly will appear on every trim of Model Z and will have a volume in the low six-figure range. There is one supplier for each assembly. Each supplier can produce the assembly and the stamped part and produce or source the imposed parts at the required volume. An exhaustive list of the data available for the Make vs. Buy study is listed below.

The attributes in focus are the load factor and cost-related characteristics that the strategy team can influence at this point in Model Z’s lifecycle. The cost-related characteristics are influence by sourcing from a lower labor cost region or sourcing from a nearby plant to lower logistics costs. Some of the fundamental part characteristics that cannot be changed are:

- Mass of raw material
- Mass of bulk material
- Labor Content
- Capital Costs

- Bought-out Parts Cost
- Packaging Dimensions and SNP
- Press Type
- Hourly Yield
- Model Allocation
- Volume
- Supplier Costs

Table 3-4 shows a summary of the parts under Model Z's study. The table is not exhaustive but should allow an understanding of the number of parts, their relationships, and the relative insourcing and outsourcing costs. The cost differences are provided in percentages, a negative percentage means an assembly cost less to outsource. A positive percentage means the assembly cost more to outsource. The objective of the model is to decide whether to make or buy a part based on the lowest-cost option. The model achieves this by determining the lowest feasible (feasibility is determined by capacity and capability) in-house total delivered cost and comparing that cost to the outsourcing cost. The model then recommends the lowest-cost sourcing strategy.

Table 3-4: Baseline Study Results

Part	Cost Difference to Outsource (%)
Assembly 1	-10.57
Stamped 1-1	
Assembly 2	-9.51
Stamped 2-1	
Assembly 3	31.21
Stamped 3-1	
Assembly 4	25.07
Stamped 4-1	
Stamped 4-2	
Assembly 5	-32.81
Stamped 5-1	
Assembly 6	12.80
Stamped 6-1	

Stamped 6-2	
Assembly 7	-14.88
Stamped 7-1	

From Table 3-4, we see that Assembly 1, 2, 5, and 7 should be outsourced while Assembly 3, 4, and 6 should be insourced. To reiterate, these are results from a historical study and all the comparisons are made between a supplier and plant A.

3.1.5 Model Y's Aftersales Service Parts

The aftersales dataset for Model Y differs from Model Z's dataset. The aftersales dataset shows a few key characteristics. Each part has a different forecasted volume, each part's make cost is lower than the buy cost, and each stamped part requires a Type 1 press – no part in Model Z's dataset requires a Type 1 press. Should the capacity be available, it is always cost-effective to insource an aftersales part. But if the capacity isn't available or there is only space for one production or past model aftersales part, when does it make sense to choose an aftersales over a production part? Historically, aftersales parts are outsourced to make room for production parts. The make vs. buy decision for aftersales parts occurs at their respective model's EOP.

From an operational standpoint, aftersales parts have much lower press load demand, but their tooling requires the same floor space to support manufacturing as a production part. To give an idea of the difference in required production hours between Model Z and Model Y, all the forecasted aftersales parts for Model Y would require 400 production hours over 10 years to satisfy the forecasted demand. A single production part for Model Z would require 400 production hours in 1.3 years. The volume of aftersales parts for Model Y is plotted in Figure 3-6.

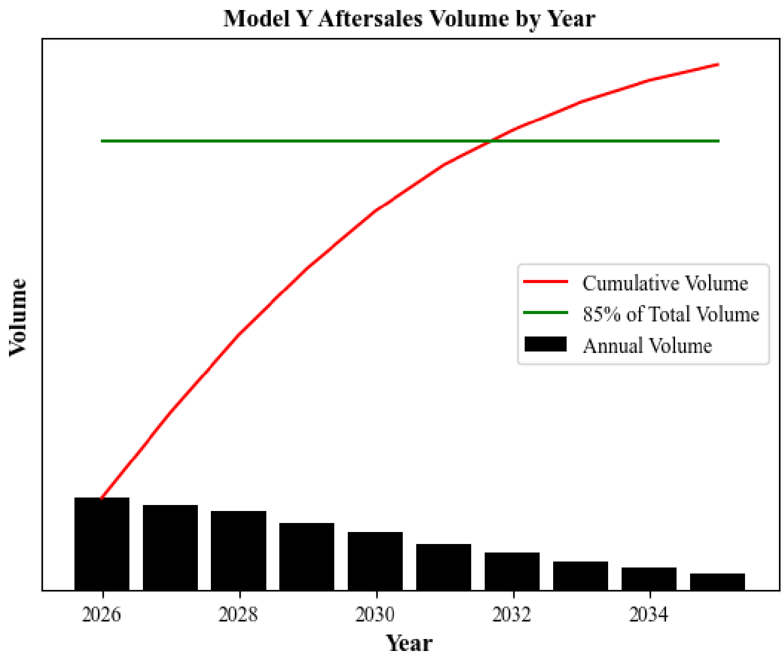

Figure 3-6: Total Volume of Aftersales for Model Y

Approximately 85% of Model Y's service volume occurs between FY26 and FY31. A comparison with production parts will be evaluated through that period. The volume can be further broken down into main product lines (MPLs), as shown in Figure 3-7.

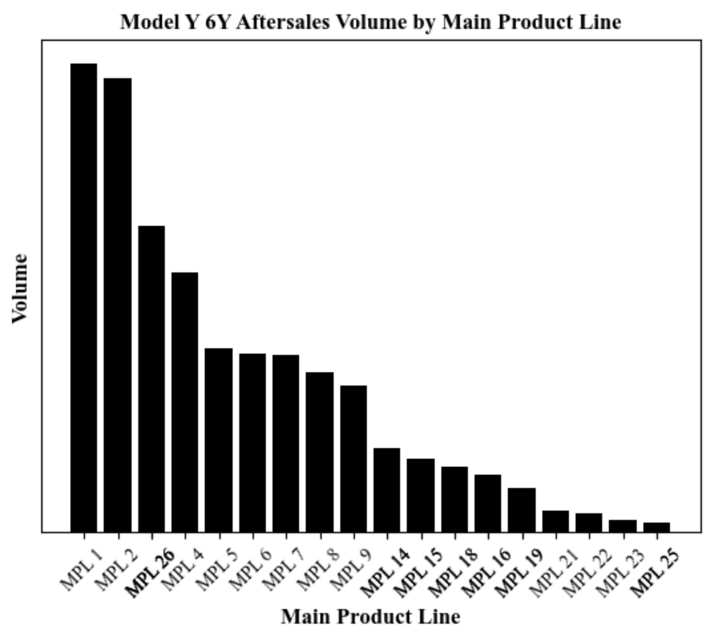

Figure 3-7: Volume by MPL for Model Y's Aftersales

Volume can vary drastically amongst main product lines. For comparison, Figure 3-7 is plotted again in Figure 3-8 with the expected volume of a single Model Z production part over the same period.

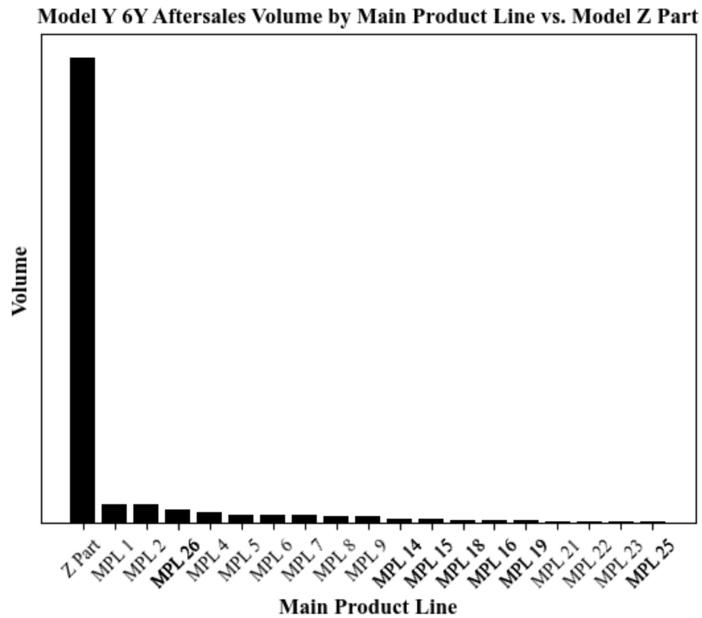

Figure 3-8: Comparison of Production Part Volume to Aftersales Volume

The question remains, do the economies of scale provided by production parts outweigh the profit margins of aftersales parts? Since the make vs. buy study for aftersales parts occurs near the model's EOP, there is no detailed quote data. Outsource costs can be determined using a percentage of revenue heuristic, or by the average cost, of the main product line from the supplier. A main product line is a door, roof, etc. The supplier produces service parts of the main product line for several aftersales models. This costing approach can be used to estimate the outsourcing cost for each main product line. Revenue, internal production costs, expected storing and shipping costs, and volume forecasts are provided. The methodology to arrive at those numbers is not within the scope of the thesis.

3.2 Modeling Cost

In the Make vs. Buy period, nearly all the direct costs of producing a part are known or can be derived from the features of a part or assembly. These costs are derived from the: labor content directly involved with producing the part, raw material used in forming or assembling the part, logistics costs incurred from shipping the part, and capital costs related to tooling or expansion. Indirect costs are applied uniformly across all parts and include, but are not limited to, energy usage, facility maintenance, and overhead. These two categories constitute most costs considered during a make vs. buy study and require inputs from engineering, manufacturing, costing, purchasing, and logistics. The discovery process of this research aimed to model as many of these inputs as possible to arrive at a cost estimate before engaging with the supporting functions. The resulting cost model does not deviate from the cost model used during the historical make vs. buy study, it instead attempts to replicate the current make vs. buy cost model while minimizing the required inputs from supporting functions. The drawback of this approach is that inputs from engineering on labor or capital costs and inputs from purchasing on raw material costs cannot be easily estimated or modeled. However, DST is relatively standardized, and labor content can be estimated based on similar parts – though this method was not used during this research. The benefit of this modeling approach is its ability to estimate the costs of producing parts in neighboring plants. By knowing labor content and logistics parameters, we can arrive at an estimate of sourcing a part for any other plant within the OEM's manufacturing network. As such, without the ability to change a part's design, reducing part cost can only be achieved with two levers: labor and logistics. Elements of cost not derived from labor or logistics remain fixed no matter where a part is produced. An element tangential to cost, Forex, can also impact cost but was out of scope for this research. The remainder of this section is dedicated to describing cost modeling for the stamping process and the assembly process.

3.2.1 Direct Labor

Direct labor is a representation of the manpower directly involved in manufacturing an assembly or stamped parts. Direct labor's contribution to the total delivered cost (TdC) of a part or assembly varies based on the process. For stamping, the staff included in direct labor costs are the operators who run the stamping press, load the raw material, and unload/store the stamped part into their packaging. The high rate of production of stamped parts leads to a low cost per unit of labor. For an assembly process, production rates have an upper bound equal to the maximum jobs per hour (JPH) of the plant and are limited by both the speed at which operators can prep an assembly operation and the speed at which the assembly cell can operate. Should an assembly process be too slow to meet required production rates, for example, a work cell can produce 15 parts per hour and the requirement is 30 parts per hour, throughput can only be increased through building additional work cells. However, incremental gains can be made through optimizing the work cell. The assembly process doesn't benefit from the high throughput seen in the stamping process and, thus, labor costs make up most of the cost of the assembly process.

The number of staff required to support production and the hourly rate at which the part is produced can be used to determine the Man Hour Unit (MHU) for a part or assembly. For example, an operation requires 1 operator, and the operator can achieve a throughput of 60 parts per hour. The MHU of that part is 1/60 or 0.016. The direct labor cost is a function of the MHU of an operation and the average labor rate of the production staff at the plant where the operation takes place.

$$Direct\ Labor\ Cost = MHU * \ Plant\ Labor\ Rate \tag{3.1}$$

3.2.2 Overhead

Overhead captures the indirect costs of production. These are calculated every year based on the business plan and include indirect costs from engineering, administrative, and facility maintenance. These are represented as percentages and are multiplied by labor costs to arrive at the overhead each part. The equation below describes how these costs are applied. There are five cost elements of overhead: Indirect Labor, Semi-Direct Labor, Processing Cost Variable, Processing Cost Fixed, and Tax. These rates are combined into the overhead rate. The overhead costs are applied uniformly across every type of part and scale with labor.

$$Overhead = DirectLaborCost * OvearheadRate \tag{3.2}$$

3.2.3 Capital Cost

Capital cost is divided into two categories, entry ticket and vendor tooling. Vendor tooling represents the capital equipment directly associated with the production of a part. Jigs, dies, work cells, etc. This cost is the same whether a part is insourced or outsourced. Entry ticket represents the total capital cost required to produce a part, this cost may include building expansions and capital assets. As such, entry ticket can vary depending on what needs to be done to inhouse the part. These costs are not amortized over part volume but are instead used when calculating the NPV of sourcing a part.

$$CapitalCost = Entry\ Ticket + Vendor\ Tooling \tag{3.3}$$

3.2.4 Raw and Bulk Material

Raw material cost and bulk material cost represent metals, chemicals, and consumables required to produce a part. Raw material is the sheet metals and alloys required to stamp a part. Raw material, as a cost element, is only an element of stamped parts. For assembly parts, bulk material represents the adhesives and welding resources required to assemble each part. New model engineering provides these costs. Calculating both raw and bulk materials costs follow similar formulas.

$$RawMaterialCost = LbsOfRawMaterial * \ CostPerLbOfRawMaterial \tag{3.4}$$

$$BulkMaterialCost = VolumeOfBulkMaterial \ * CostPerVolumeOfBulkMaterial \tag{3.5}$$

3.2.5 Packaging

Packaging costs represent the cost of procuring the rack fleets used to store, ship, and stage parts. Like vendor tooling, packaging costs are borne by the OEM. The capital cost of the rack fleet is amortized over the expected volume of the parts. The capital cost is influenced by the lead time from the supplier. Suppliers who are close to the destination plant require fewer racks to maintain production. In contrast, suppliers who are farther away require more racks to maintain production. Packaging is required regardless of whether a part is produced within the plant where it is assembled or outsourced to a supplier. Packaging for an in-house part requires less protection than a part that is being transported from a supplier and, therefore, costs less and may require fewer racks.

$$PackagingCostPerUnit = \frac{PackagingCapital}{PartVolume} \tag{3.6}$$

3.2.6 Logistics

The packaging efficiency of the part influences logistics and can be represented by a part property known as “M3”. M3 is a measure of the volume in meters a part takes up in the standard packaging of the part, which is a unit of measure representing the number of parts that can fit inside a standard package of the specified dimensions. For example, 20 parts can fit inside a standard package (SNP) with the dimensions of 70”x50”x60”. The dimensions are measured in inches and need to be converted to meters. resulting M3 would be:

$$M3 = \frac{L * W * H}{61024 * \frac{1}{SNP}}$$

(3.7)

The M3 of the part is multiplied by the logistics rate, which is in units of $/M3, to arrive at a logistics cost per unit for a part should it require shipping.

$$LogisticsCostPerUnit = M3 * ShippingRate$$

(3.8)

3.2.7 Bought Out Parts

The bought-out parts cost element represents the parts of an assembly that are bought from a supplier. These parts can be stamped parts or assembled parts. Bought-out parts are typically parts that the OEM cannot produce or parts that would be cost-prohibitive for them to do so. The supplier from whom these parts are purchased is the same supplier who will provide the fully assembled part. A stamped part does not contain bought-out parts.

3.2.8 Total Delivered Cost

The sum of the cost elements described in section 3.2 less the non-amortized capital costs constitute the total delivered cost of a part. The product of the per unit cost and the volume results in the total cost of production of a part over its lifecycle. This metric is useful when comparing costs between parts with different volumes. However, when evaluating whether to make or buy a set of parts from the same vehicle, volume does not impact the outcome. To summarize, Table 3-5 lists the cost elements considered in this model and whether they vary based on the sourcing decision in this model.

Table 3-5: Variable and Non-Variable Costs

Cost Elements	Variable
Direct Labor	Yes
Indirect Costs	Yes
Raw Material	No
Bulk Material	No
Packaging	No
Logistics	Yes
Entry Ticket	No

3.2.9 Cost Elements Not Included

Cost elements not directly accounted for in the current make vs. buy process that could be estimated are energy, quality, internal transportation, and storage costs. Depreciation is also not a cost that is accounted for in this model. Neither the depreciation cost itself nor the impact of increased utilization on the per-unit costs are included.

3.3 Modeling Capacity & Utilization

3.3.1 Stamping Shop Capacity

The Stamping shop houses all the raw materials, tooling, and equipment to produce panels, brackets, and structural metal parts for assembly at the Body shop. The plant receives and stores coils of steel or aluminum alloys. Workers then feed these coils into blanking lines that flatten and cut the coil into rectangular sheets, which are also known as blanks. Blanking lines can run at a rate of anywhere from 360 to 3600 SPH depending on the specifications of the blank. These blanks are then stored until the stamping line is ready to process them. Stamping is the final step in the stamping shop. Before a blank can be processed, the press must be set with the die family or recipe. Dies are moved from a storage area to the press via overhead cranes and once the die set arrives, the in-place die set is changed over and returned to the die storage area. Each set of dies is stored together in the die storage area and has anywhere from 3-5 dies. In the storage area, dies are stacked at most 2 high, any higher presents safety hazards. Once a part is on deck to be produced, the movement of the dies is scheduled to minimize the idle time of the press. However, die setting does take a non-insignificant amount of time, for both the movement and the changeover, and the production team schedules a part's runtime such that the set of dies for the part that follows can be staged on the bolsters as close to the completion of the run as possible. Once the dies are swapped in, the blanks are ready to be processed. A part is formed by passing the blank through a series of dies. Each die plays a role in forming the part and punches, embosses, or bends the blank into its final form. A press line can run anywhere from 600 to 2400 SPH. The variability in throughput of a press line is a function of the part, material, and tonnage of the press itself. Tonnage is a measure of pressure a press can exert on a part. Typically, higher tonnage presses run slower than those of a lower tonnage. Once the part comes off the press, workers inspect and rack the part. Once a rack is full of parts, a tug, AGV, or forklift moves the rack to a storage area to await assembly in the body shop.

Capacity in the stamping shop is largely governed by the SPH, or throughput, of the press lines and the availability of space in the die storage area. Upstream of the press lines, the blanking lines can exceed the throughput of the press lines by two or threefold. Downstream of the press lines, the body shop's work cells have throughput that is fractions of the throughput available to the press lines. A process flow map would show that each process feeds into a bottleneck. It follows that within the stamping shop, the press lines themselves are the main throughput bottleneck, while the die storage area serves as an auxiliary bottleneck for long-term planning since it has no impact on throughput but does limit the number of parts a plant can produce. Modeling the capacity of the press lines is straightforward. Each part assigned to a particular press needs to be produced in just enough volume to support production and service part demand. So, if there are 600 units of Model A produced in a month, there needs to be 600 units of a part stamped to support the production of Model A. After the first 3-4 strokes of a press, a part is produced for every stroke the press makes. A press running at 600 SPH can, in one hour, produce enough parts for a month of production of the hypothetical Model A. Given the long time horizon of this project, a part's monthly load factor, in hours and based on its assigned press and SPH, was used for each part. The equation below describes a part's load factor, however, it does omit some granularity, such as the impact of die set changeover time and the initial dry strokes.

$$Part\ Load\ Factor\ = \frac{PartMonthlyVolume}{PressSPH} \tag{3.9}$$

Each part has a standing load factor on the die storage area. This, too, is straightforward to model. Stamping dies are consistent in their dimensions and can be stacked two high. In general, dies from different are not stacked on another. For example, die sets of 5 or 6 would use 3 units of die storage, and die sets of 3 or 4 would use 2 units of die storage.

$$Die\ Storage\ Factor = \left\lceil \frac{DieCount}{2} \right\rceil \tag{3.10}$$

The capacity of each press is determined by the press' SPH, the number of production hours available, and the number of working days in a month. Production hours are a function of the shift pattern the shop or the press is run at. The shift pattern can be adjusted to meet the volume of the production needs of the plant. Shift patterns do not deviate from widely used 8-hour shift days and schedules. A 1-shift pattern has 8 hours, a 2-shift pattern has 16 hours, etc. The available hours for production are less than the total shift hours to account for breaks. The number of working days available is a function of the month, its holidays, and planned shutdowns. For example, OEMs typically have planned shutdowns to perform maintenance, install upgrades, or move/remove lines or work cells. In those months, both monthly production volume and monthly asset capacity are drastically reduced. Available production days are largely responsible for the fluctuations in capacity seen month-to-month, barring any SOP or EOP events. Production time is also reserved for planned maintenance and to avoid over-capacity situations, which could starve the line, manufacturing firms plan for 85% OEE.

$$MontlyProductionHours = ShiftPatternHours * ProductionDays \tag{3.11}$$

3.3.2 Body Shop Capacity

The Body Shop's operations differ significantly from that of Stamping's. Instead of several press lines producing multiple unique parts at a relatively high throughput, the Body Shop assembles multiple unique parts at a throughput roughly equal to the production rate of the vehicle it is for. At most of the OEM's plants, this assembly process is automated using robotic work cells. Some work cells are fully automated to the point where workers can load a rack of parts adjacent to the cell, and the robots unload the parts, assemble them, and rack the assembly. Other work cells require workers to load and prep the parts for the assembly while the robot performs the assembly operation. Assemblies are then fed into the main body line, which is fully automated, to be assembled onto the main structure or body of the vehicle. The term capacity can be a homonym with regards to the Body Shop. There is capacity in the sense of throughput, and capacity in the sense of floor space to house the work cell in the plant. The throughput of each work cell is designed and tuned to the JPH of the vehicle it supports. For example, if an assembly is produced for a vehicle with an expected JPH of 15, then the work cell supporting that assembly can be tuned to match the 15 JPH rate. If that vehicle needs 30 JPH, then the work cell is designed to meet 30 JPH. The increase in JPH can be facilitated by adding more robots or adding a 2nd cell, if one were to use the work cell tuned to 15 JPH. The actual JPH can vary marginally, being influenced by several factors. For this project's purposes, it is assumed that a work cell's throughput can meet the desired production rate. The other measure of capacity, floor space, is much more salient. Space is a premium at the OEM's plants since each plant supports the production of several vehicles. This complexity gives way to a balancing act when determining the future layout of the body shop. If a new work cell is added, another must be removed. The work cells that are removed are always the work cells of models expected to EOP by the time the work cell for the incoming vehicle is required. Despite the importance of floor space, it isn't a metric that is tracked across all plants. One limitation of this project is its lack of data on the estimated available floor space in the Body Shop. Constraints can be applied to systematically test the value of the space of an assembly cell, however.

3.4 Model Formulation

The objective of this model is to minimize sourcing costs, which include production and logistics, subject to capacity constraints – in this case, available production hours. Each assembly is assigned to a home plant, which represents the destination for the assembly. The assembly does not have to be produced in its home plant, but the assembly must ultimately arrive at its home plant. In addition, an assembly can have its subassemblies sourced from different plants, or the entire assembly can be purchased from a supplier. However, each subassembly must arrive at the location of its next higher assembly. In general, most assemblies have one fabrication node and one assembly node. Figure 3-9 represents an entire assembly. Each circle is a stamped part, and each triangle is an assembly process. The square is the home plant. Each edge represents a logistics cost. If, say, a fabrication step and an assembly step occur in the same plant, then the logistics cost is zero. If the fabrication and assembly occur in different locations, then a logistics cost, which is based on part characteristics and the shipping rate between the two plants, is incurred.

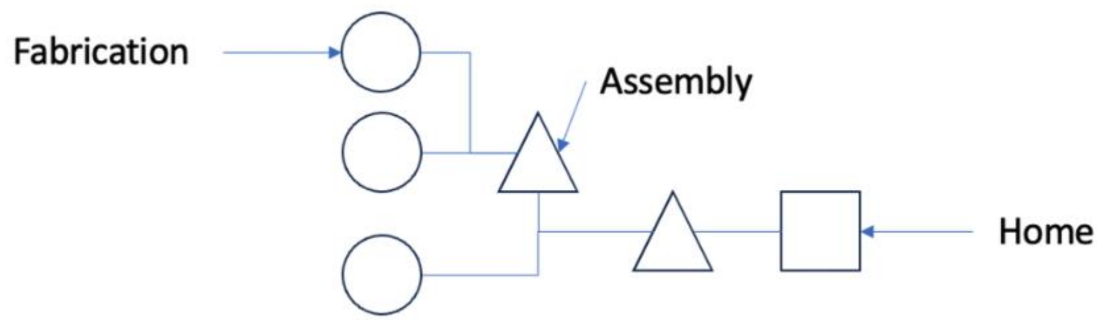

Figure 3-9: Example Assembly Structure of a Stamped Assembly

3.4.1 Model Summary

This section provides a brief overview of the logic, constraints, and objective function of the model. To restate, the objective is to minimize the total cost of production of a set of parts subject to capacity constraints. The output of interest is whether a part, assembly, or process is made or bought. To simplify terminology, a "process" can describe a stamped part or an assembly step. A "series of processes" defines the entire assembly. Whether a process is made is governed by a handful of continuity constraints. The continuity constraints are as follows:

1. A process can allocated to any plant, so long as the plant has capacity in every month for the duration of the processes' production lifecycle. In other words, for a process that has a lifecycle 72 months, the plant must have capacity in all 72 months to "make" the process.

2. For a series of processes to be made, all the processes within the series must be made within the OEM's manufacturing network.

If these constraints cannot be satisfied, the process, or series of processes, is bought. Another condition for a buy is if the model is unable to find a lower cost make scenario. These continuity constraints are strict but guarantee that the OEM has the capacity to produce the parts in-house. At face value, the capacity charts seem highly variable, but the fluctuations are due to the impact of the working days in each month changing due to weekends and holidays. It follows that demand for parts follows the same pattern or variability. Production utilization is consistent on a day-to-day basis. In addition, highly utilized assets will always appear to have some available capacity. This is simply due to maintaining OEE levels. If these continuity constraints are violated for a cost competitive make scenario, it more than likely means that a process would lead to an over capacity condition on its respective asset(s). The second continuity constraint applied to a series of processes, such as that found in Figure 3-9, would likely be overly conservative. For example, if the OEM did not have capacity in one of the steps for a cost-competitive production scenario, the assembly and its subassemblies would be bought. In practice, however, a single fabrication and assembly step represents the highest level of complexity seen in this dataset. Multi-level series and parallel processes are not represented.

The objective function considers the variable costs of production: labor, raw material, and logistics, and seeks the lowest cost production scenario. For a supplier, these costs are inputs and are aggregated into a single value from an estimate or quote for an entire assembly or series of processes. For the OEM, each process's cost is calculated based on its allocated plant, which drives labor costs. Then the appropriate logistics costs are calculated based on the location of the next process, and these two values are summed to determine the total delivered cost of the process. This calculation is repeated until the total cost for the series of processes is determined. If the resulting cost is lower than the outsourcing cost, all the processes are made, provided capacity is available.

One of the most debilitating constraints is the second continuity constraint. Removing this constraint can improve the granularity of the optimization. Removal of this constraint would allow flexibility in determining what individual processes to make or buy but requires more information than may be available when the optimization model is at its most useful - which is far upstream of any decision-making. The flexibility would allow the model to recommend making only the assembly step or the stamped part. But having the flexibility to allocate a process to any plant can introduce more data requirements. For example, logistics rates between each plant and the supplier of a process would need to be known. For example, if there are 8 eight different suppliers. Logistics rates between each plant and supplier would need to be known for an accurate cost model. To date, this information is known for the plant where the vehicle is made. One could simplify the model to only evaluate the cost between the vehicle's plant and the supplier, but the decision space of this approach does not require optimization and decomposes into a traditional make vs. buy approach.

The following sections provide a detailed formulation of the model.

3.4.2 Sets And Indices

$i \in I = \{1,2,\ldots,n\}$: Index and set of parts.

$j, p \in J = \{1,2,\ldots,n\}$: Index and set of plants, j and p are the same set of plants but are made distinct because of the logistics cost matrix and the need to iterate through the plants twice.

$m \in M = \{1,2,\ldots,n\}$: Index and set of months.

3.4.3 Parameters

$TotalCPU_{i,j}$ *Represents the manufacturing cost of producing part i and plant j*

$PartLoadPress_i$ *The press load factor of part i*

$PartLoadDie_i$ *The die load factor of part i*

$PartLoadAssembly_i$ *The assembly load factor of part i*

$NextHigher_i$ *Part i's next higher assembly*

SOP_i *The starting month of production of part i*

EOP_i *The ending month of production of part j*

$Type\ 1\ PressCapacity_{j,m}$ *The capacity of XL presses at plant j in month m*

$Type\ 2\ PressCapacity_{j,m}$ *The capacity of L presses at plant j in month m*

$Type\ 3\ PressCapacity_{j,m}$ *The capacity of M presses at plant j in month m*

$Type\ 4\ PressCapacity_{j,m}$ *The capacity of S presses at plant j in month m*

$DieCapacity_{j,m}$ *The capacity of die storage at plant j in month m*

$AssemblyCellCapacity_{j,m}$ *The capacity of assembly cells at plant j in month m*

3.4.4 Decision Variables

$MakeOrBuy_i \in \{0,1\}$: 1 if part *i* is made; and 0 if part *i* is bought

$PartAllocation_{i,j} \in \{0,1\}$: 1 if part *i* is allocated to plant *j*; and otherwise 0

$PartAllocationByMonth_{i,j,m} \in \{0,1\}$: 1 if part *i* is allocated to plant *j* in month m; and otherwise 0

$PartDestination_{i,j} \in \{0,1\}$: 1 if part *i* needs to be shipped to plant *j*; and otherwise 0

$PartLogistics_{i,j,p} \in \{0,1\}$: 1 if part *i*'s origin is plant *j* and destination is plant *p*; and otherwise 0

3.4.5 Objective Function

The objective function seeks to minimize the total cost of production for all parts in the dataset. The function below is for production parts. Aftersales parts follow a similar, but simplified, function and are confined to a single plant. The resulting function captures the total production cost between the supplier and a specified plant.

$$Min\ PartVolume_i * (1 - MakeOrBuy_i) * SupplierPrice_i + \sum_{ij} PartAllocation_{i,j} * TotalCPU_{i,j} + \sum_{ijp} PartLogistics_{i,j,p} * LogisticsCPU_{j,p}\ \ \forall i \in I,\ \forall j \in J,\ \forall p \in P \quad (3.12)$$

3.4.3 Constraints

This constraint forces an assembly to be made entirely within the OEM's manufacturing network or entirely bought out from a supplier.

$$MakeOrBuy_i = MakeOrBuy_{NextHigher_i} \ \forall i \in I \quad (3.13)$$

This constraint limits a part's allocation to at most one plant.

$$\sum_j PartAllocation_{i,j} \leq 1 \ \forall i \in I \quad (3.14)$$

This constraint synchronizes a part's make or buy decision to the part allocation decision variable. If a part is bought, it cannot be allocated to a plant. If a part is allocated to a plant, it cannot be bought from a supplier.

$$\sum_j PartAllocation_{i,j} = MakeOrBuy_i \ \forall i \in I \quad (3.15)$$

The following set of constraints ensures a part is only allocated to an OEM's plant within its SOP and EOP range.

$$PartAllocationByMonth_{i,j,SOP_i} = PartAllocation_{i,j} \ \forall i \in I, \ \forall j \in J \quad (3.16)$$

$$PartAllocationByMonth_{i,j,m} = PartAllocationByMonth_{i,j,m-1} \ \forall i \in I, \ \forall j \in J, \ \forall m \in M \quad (3.17)$$

$$PartAllocationByMonth_{i,j,EOP_i} = PartAllocation_{i,j} \ \forall i \in I, \ \forall j \in J, \ \forall m \in M \quad (3.18)$$

$$PartAllocationByMonth_{i,j,m} = 0 \ \forall i \in I, \ \forall j \in J, \ \forall m \notin SOP_i \cup EOP_i \quad (3.19)$$

The following set of constraints ensures there is enough press capacity over the part's lifecycle. Only parts with load factors relevant to each constraint are included in the constraint. For example, a part assigned to a Type 3 press would not be considered in the constraints for the Type 2 presses and, in the same vein, a part assigned to a press would not appear in the constraints for an assembly cell. There is an additional constraint introduced that mimics the capacity of a work cell. This constraint is integer-based and used to determine if a plant has floor space.

$$\sum_i PartAllocationByMonth_{i,j,m} * PartPressLoad_{i,m} \leq Type\ 1\ PressCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.20)

$$\sum_i PartAllocationByMonth_{i,j,m} * PartPressLoad_{i,m} \leq Type\ 2\ PressCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.21)

$$\sum_i PartAllocationByMonth_{i,j,m} * PartPressLoad_{i,m} \leq Type\ 3\ PressCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.22)

$$\sum_i PartAllocationByMonth_{i,j,m} * PartPressLoad_{i,m} \leq Type\ 4\ PressCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.23)

$$\sum_i PartAllocationByMonth_{i,j,m} * PartLoadDie_{i,m} \leq DiePressCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.24)

$$\sum_i PartAllocationByMonth_{i,j,m} * PartLoadAssembly_{i,m} \leq AssemblyCellCapacity_{j,m} \quad \forall j \in J,\ \ \forall m \in M$$

(3.25)

The remainder of the constraints determine the logistics costs of a part.

A part's destination is equivalent to the location where its next higher assembly is allocated. If a part does not have an explicitly defined next higher assembly, then its destination is the final assembly plant.

$$PartDestination_{i,j} = PartAllocation_{NextHigher_{i,j}} \quad \forall i \in I, \ \forall j \in J \tag{3.26}$$

A part's route, denoted by the part's logistics decision variable, is determined by the plant the part is allocated to and the plant to which its next higher assembly is allocated.

$$PartLogistics_{i,j,p} \geq \left(\left(PartAllocation_{i,j} + PartDestination_{i,p} \right) - 1.9 \right) \quad \forall i \in I, \ \forall j \in J, \ \forall p \in P \tag{3.27}$$

For each part, the sum of its Part Logistics matrix is equal to the make or buy decision variable. If a part is bought, this decision variable is 0, nullifying the logistics decision variable. If a part is made, the logistics variable is forced to 1.

$$\sum_{j,p} PartLogistics_{i,j,p} = MakeOrBuy_i \quad \forall i \in I \tag{3.28}$$

3.5 Systems and Software

The optimization model was solved using Python and Google OR Tools, an open-source solver. This software suite was chosen over Excel. When developing the model, it was clear that the number of decision variables and constraints made the model infeasible to solve in Excel. Commercial solvers, such as CPLEX and Gurobi, could solve the model but access to them would require licenses. Given these limitations, Google OR Tools, an open-source optimization engine, was used to formulate and solve the model. While not as powerful as a commercial solver, Google OR Tools was able to solve the optimization model in seconds.

3.6 Model Validation on Test Case

To validate that the model outputs are in line with the logic and the objective function described herein, a simple test case was developed. The test case analyzes the cost-optimal allocation of three assemblies: Test Assy 1, Test Assy 2, and Test Assy 3. The “Test Assy’s” have a single stamped part and a supplier “quote.”

Each process has labor hours, raw material costs, an M3, the logistics parameter, and, for stamped parts, a press tonnage. Plants A-D are candidates to which these processes can be allocated. The test data was crafted to test edge cases and ensure the logic was sound, as such, some of the data are extreme. The part data are shown in Table 3-6. Note the differences in the supplier quotes, Test Assy 1 has a quote of $1,000 and the Test Assy 2 and 3 have quotes of $1. Test Assy 2 will always be bought as there are no production scenarios that have costs less than $1. However, Test Assy 3 has near zero costs should the OEM produce it, so it should be made. In addition, capability constraints are included in these scenarios. Type 3 parts cannot feasibly be allocated to plants B or D. However, type 1 parts can be allocated to any plant. All parts must ultimately arrive at Plant A, but, from Table 3-7, Plant A has seen a marked increase in labor costs, whereas Plant B and C have been able to lower labor costs significantly. However, favorable transportation infrastructure has made shipping parts from C to B and B to A very low-cost as shown in Table 3-8. Unfavorable transportation costs have rendered all other routes extremely costly. With the given parameters:

1. Test Assy 1 should be made as there are several production scenarios with costs that are less than $1,000, with its stamped part allocated to plant C due to its capability and low labor costs and the assembly allocated to B due to Plant Bs low-cost logistics to plant A.

2. Test Assy 2 should be bought as there are no lower cost internal production scenarios due to the raw material costs.

3. Test Assy 3 should be entirely allocated to Plant B due to its type 1 compatibility, which allows it to avoid the shipping costs from C to B. From a cost perspective, B and C are virtually the same.

Table 3-6: Test Part Data

Part	Labor Units	Raw Material Costs ($)	M3 (m^3)	Tonnage	Supplier Quote ($)
Test Assy1	0.250	-	1.00		1,000.00
Test Part1	0.010	5.00	1.00	Type 3	
Test Assy2	0.500	-	0.01		1.00
Test Part2	0.100	5.00	0.01	Type 3	
Test Assy3	0.001	-	0.01		1.00
Test Part3	0.001	-	0.01	Type 1	

Table 3-7: Test Plant Labor Rates

-	Labor Rate ($/Hr)
Plant A	1000
Plant B	1
Plant C	1
Plant D	1000

Table 3-8: Test Interplant Logistics Rate

$/m3	Plant A	Plant B	Plant C	Plant D
Plant A	-	1.00	10,000.00	10,000.00
Plant B	1.00	-	1.00	10,000.00
Plant C	10,000.00	1.00	-	-
Plant D	10,000.00	10,000.00	-	-

The results of the optimization are shown in Table 3-9.

Table 3-9: Test Case Results

Part	Make or Buy	Allocation	Cost ($)
Test Assy1	Make	Plant B	85.00
Test Part1	Make	Plant C	5.00
Test Assy2	Buy	Supplier	1.00
Test Part2	Buy	Supplier	-
Test Assy3	Make	Plant B	-
Test Part3	Make	Plant B	-

4 Results

The research was performed under the supervision and direction of the manufacturing strategy team. The organization's primary focus is to develop and orchestrate the OEM's long-term investments in capacity and technological advancement, ensuring future programs can operate cost-effectively at volume. Make vs. Buy is a relatively small subset of their overall responsibility but falls squarely within their wheelhouse. Common questions asked during a make vs. buy study are: "Do we have the capacity?" and "Do we have the capability?" The answer to these questions at the time they are asked may be "No." But the answer doesn't preclude the possibility of the capacity or capability being created by the time they are needed. While the model developed for this thesis can serve many purposes, the results most salient to the manufacturing strategy team are related to the value of capacity. With the looming unraveling of the relationship with their sole supplier for aftersales parts, how should the OEM respond? Should future production parts be outsourced to ensure capacity is available for aftersales parts? Should the OEM invest in capacity? To answer those questions, one must first be able to put a number to the opportunity cost. The following section examines results under multiple scenarios, beginning with running the model under the same conditions as a standard make vs. buy study and ending with the evaluation of how to source, at the lowest cost, both aftersales and future production under capacity constraints.

4.1 Make vs. Buy Scenarios, Baseline Study

The subsections of Chapter 4 analyze the outputs of the optimization model under constraints the OEM could face in the future. Each case will have a summary of the constraints, the dataset used, and the output of the optimization model with the respective constraints and dataset. As a refresher, Table 4-1 shows the expected outcome of the ongoing Make or Buy study for Model Z at Plant A. The total production cost of this scenario is called the "Baseline Cost".

Table 4-1: Model Z Make vs. Buy Cost Comparison

Part	Cost Difference to Outsource (%)
Assembly 1	-10.57
Stamped 1-1	
Assembly 2	-9.51
Stamped 2-1	
Assembly 3	31.21
Stamped 3-1	
Assembly 4	25.07
Stamped 4-1	
Stamped 4-2	
Assembly 5	-32.81
Stamped 5-1	
Assembly 6	12.80
Stamped 6-1	
Stamped 6-2	
Assembly 7	-14.88
Stamped 7-1	
Baseline Cost	

4.1.1 Base Case Make vs. Buy – Scenario 1: One Plant, One Supplier

This case is constrained to: only allow parts and assemblies to be produced either at Plant A or at their respective supplier; to run at three-shift capacity in the stamping presses; and to only allow an assembly to be made if there is capacity for all the assembly's sub-parts. Model Z's dataset is used. Table 4-2 shows the outputs of the scenario.

Table 4-2: Scenario 1, Plant A

Part	Make or Buy	Allocation	Δ From Optimal Cost (%)
Assembly 1	Buy	Supplier	0
Stamped 1-1	Buy	Supplier	
Assembly 2	Buy	Supplier	0
Stamped 2-1	Buy	Supplier	
Assembly 3	Buy	Supplier	+29
Stamped 3-1	Buy	Supplier	
Assembly 4	Make	Plant A	0
Stamped 4-1	Make	Plant A	
Stamped 4-2	Make	Plant A	
Assembly 5	Buy	Supplier	0
Stamped 5-1	Buy	Supplier	
Assembly 6	Buy	Supplier	+12.7
Stamped 6-1	Buy	Supplier	
Stamped 6-2	Buy	Supplier	
Assembly 7	Buy	Supplier	0
Stamped 7-1	Buy	Supplier	
+109% of Baseline Cost			

Under the standard scenario, the total production cost rises by 9%. Assembly 3 and assembly 6 should be insourced. Stamping capacity constraints inhibit the insourcing of those cost-competitive assemblies. This is not an uncommon occurrence at the OEM. Given that this is the optimal scenario under the highest capacity shift pattern available, investment in additional assets would be required to insource assembly 3 and 6. It would be beneficial to understand how additional capacity can impact the total cost of production. The following case examines the cost of production with capacity unconstrained at Plant A.

4.1.2 Base Case Make vs. Buy – Scenario 2: Plant A, One Supplier, Lowest Cost Allocation

The output of this case can be used to show two key aspects of the model. One is that it produces similar outcomes to that of the ongoing study. The results do not match one-to-one, but the model makes the same recommendations as the study. Second, the ideal production cost results in cost savings of 9% of the baseline cost. The rightmost column in Table 4-3 shows the percentage cost delta from the OEM's study, which is the basis for the baseline cost.

Table 4-3: Scenario 2, Plant A, One Supplier, Lowest Cost Allocation

Part	Make or Buy	Allocation	Δ From OEM Study (%)
Assembly 1	Buy	Supplier	0
Stamped 1-1	Buy	Supplier	
Assembly 2	Buy	Supplier	0
Stamped 2-1	Buy	Supplier	
Assembly 3	Make	Plant A	1.01
Stamped 3-1	Make	Plant A	
Assembly 4	Make	Plant A	0.12
Stamped 4-1	Make	Plant A	
Stamped 4-2	Make	Plant A	
Assembly 5	Buy	Supplier	0
Stamped 5-1	Buy	Supplier	
Assembly 6	Make	Plant A	0.07
Stamped 6-1	Make	Plant A	
Stamped 6-2	Make	Plant A	
Assembly 7	Buy	Supplier	0
Stamped 7-1	Buy	Supplier	
101% of Baseline Cost			

Are savings of 9% enough to justify the purchasing of a new stamping asset? Most likely no. Historically, the OEM would burden the outsourcing costs and pursue the buy scenario, or supporting shops, realizing capacity is limited would have declined to study the inhouse production scenario, which could end up being cost competitive. One question the optimization model has yet to answer is what is the best internal cost for parts that thus far have not had a make recommendation?

4.1.3 Base Case Make vs. Buy – Scenario 3: Best Plant A Make Case

One limitation of the model is its lack of information on the best in-house cost. If a part is “bought”, there is no information on a feasible make case, which may be close in cost and therefore should be analyzed further. There are 2 “buy” conditions. The first condition triggers if there are no make scenarios that are lower cost than buying from a supplier. The second buy condition triggers if the lower cost make scenarios are not feasible due to capacity constraints – there could be several competitive in-house production scenarios, but if the capacity isn’t available, the model recommends buying the part. To overcome this, the model can be forced to make the part and, to avoid the model not solving, internal capacity must be unlocked. Capacity is added only to assets that categories that exist in the respective plant. Below is the output of finding the best make case. The percentages rightmost column should be close to Table 4-1’s, the baseline study, percentages.

Table 4-4: Scenario 3, Plant A Best Make Case

Part	Make or Buy	Allocation	Δ From Optimal Cost (%)
Assembly 1	Make	Plant A	-10.72
Stamped 1-1	Make	Plant A	
Assembly 2	Make	Plant A	-13.14
Stamped 2-1	Make	Plant A	
Assembly 3	Make	Plant A	29.9
Stamped 3-1	Make	Plant A	
Assembly 4	Make	Plant A	24.93
Stamped 4-1	Make	Plant A	
Stamped 4-2	Make	Plant A	
Assembly 5	Make	Plant A	-32.45
Stamped 5-1	Make	Plant A	
Assembly 6	Make	Plant A	12.72
Stamped 6-1	Make	Plant A	
Stamped 6-2	Make	Plant A	
Assembly 7	Make	Plant A	-9.35
Stamped 7-1	Make	Plant A	

+113% of Baseline Cost

With this output, the OEM can determine what studies are worth pursuing, decreasing the workload on supporting functions. For example, assembly 5, which costs 12% more to outsource, would be worth studying to insource, whereas assembly 3's make cost may be too far off from the buy cost to justify a detailed study. This output also serves to validate the model, the resulting in-house costs are very similar to that of the study.

Returning to the dilemma at hand, what can the OEM do to reach the total production cost in section 4.1.2 without significant investment? The case below examines a scenario where parts and assemblies can be sourced from anywhere within the OEM's manufacturing network, treating internal plants as suppliers.

4.1.4 Base Case Make vs. Buy – Scenario 4: Several Plants, One Supplier

This scenario allowed assemblies and parts to be allocated to any plant within the OEM's manufacturing network, subject to the press capacity constraints running a three-shift pattern and to only allow an assembly to be made if there is capacity for all the assembly's sub-parts. Scenario 2, which is the best case under the OEM's current make or buy strategy, is used as benchmark for comparison.

Table 4-5: Scenario 4, All Plants, One Supplier

Part	Make or Buy	Allocation	Δ From Scenario 2 (%)
Assembly 1	Buy	Supplier	0
Stamped 1-1	Buy	Supplier	
Assembly 2	Buy	Supplier	0
Stamped 2-1	Buy	Supplier	
Assembly 3	Make	Plant A	1.05
Stamped 3-1	Make	Plant C	
Assembly 4	Make	Plant A	0.12
Stamped 4-1	Make	Plant A	

Stamped 4-2	Make	Plant A	
Assembly 5	Buy	Supplier	0.00
Stamped 5-1	Buy	Supplier	
Assembly 6	Make	Plant A	0.17
Stamped 6-1	Make	Plant C	
Stamped 6-2	Make	Plant A	
Assembly 7	Make	Plant C	-13.18
Stamped 7-1	Make	Plant C	
99% of Baseline Cost			

This scenario results in a lower total production cost than scenario 4.1.1, but a higher cost than the total production cost of the study. The drivers of this are the packaging efficiency of the parts and the relatively low labor costs at Plant C. This model is meant to provide directionality on cost as opposed to a detailed study. Changes to packaging costs and logistics costs could increase the total production costs while lower costs for raw material and positive externalities from forex may decrease the total production costs. This is a viable scenario so long as the increased costs are not over 10% of the baseline cost and the lead times are viable. There are still a handful of assemblies that the model still recommends buying even given these expanded constraints. The following scenario examines the best internal make cost within the OEM's manufacturing network.

4.1.5 Base Cave Make vs. Buy – Scenario 5: Best Internal Make Case

This scenario is like section 4.1.3; the model is forced to make the assemblies internally, and the capacities are unlocked. Scenario 3, which models the best make case under the OEM's current make or buy strategy, is used as benchmark for comparison.

Table 4-6: Scenario 5, Lowest Cost Internal Make Case

Part	Make or Buy	Allocation	∆ From Scenario 3 (%)
Assembly 1	Make	Plant A	-0.35
Stamped 1-1	Make	Plant C	
Assembly 2	Make	Plant A	0
Stamped 2-1	Make	Plant A	
Assembly 3	Make	Plant A	0
Stamped 3-1	Make	Plant A	
Assembly 4	Make	Plant A	0
Stamped 4-1	Make	Plant A	
Stamped 4-2	Make	Plant A	
Assembly 5	Make	Plant A	-0.43
Stamped 5-1	Make	Plant C	
Assembly 6	Make	Plant A	0
Stamped 6-1	Make	Plant A	
Stamped 6-2	Make	Plant A	
Assembly 7	Make	Plant C	-21.30
Stamped 7-1	Make	Plant C	
∆ 111% of Baseline Cost			

This output can serve to validate the model as well as provide confidence that the production scenario under study is the best possible or close to the best possible. Ideally, parts are sourced as close as possible to the plant. One item to note is that this scenario regularly sources parts from Plant C, but the resulting cost is only cents lower than producing the assembly at Plant A. When capacity is available, producing those parts in Plant A is more than likely the ideal path, but when capacity is a limiting factor at Plant A, it can be competitive to source parts from Plant C. Sourcing from under-utilized plants may be a solution to capacity constraints at Plant A.

The next section will examine the results of the model when production and aftersales parts are included and again will seek to minimize total production costs.

4.1.6 Make vs. Buy with Aftersales: One Plant, One Supplier – Plant A

The production part dataset and the aftersales dataset are from different plants. This hypothetical scenario analyzes the optimal make vs. buy decision for production and aftersales parts at Plant A. Historically, aftersales parts were deprioritized when production parts were insourced. This scenario seeks to minimize the total production cost of production and aftersales together. Since this scenario takes place at plant A and several production scenarios at plant A have been analyzed, this section can be condensed into two scenarios. The first scenario's main constraint is press capacity. The figure below shows the output for aftersales parts. Note, the bars for the aftersales are nearly undiscernible when compared to overall production capacity.

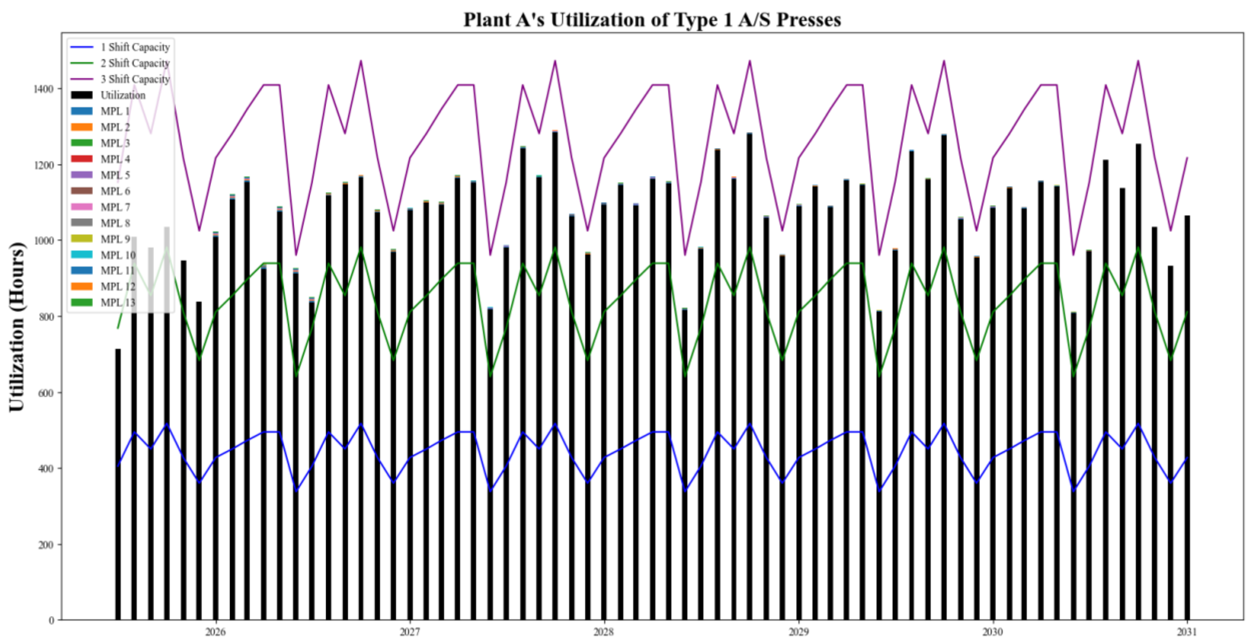

Figure 4-1: Sourcing Aftersales Parts with Production Hours as the Primary Constraint

Press capacity is not an ideal constraint when studying aftersales parts. All of them can be produced, and these parts don't compete for press capacity with the Model Z production parts, from a tonnage perspective. Instead, a constraint on the number of parts the OEM can insource will be introduced. For example, the plant has space for one assembly cell and one stamped part, between aftersales and production, which part should be insourced? The constraint will then be incremented by one, such that the plant can then insource a total of two parts. As this constraint is incremented, the resulting total production cost and the type of part insourced will be tracked. The results of the analysis are below.

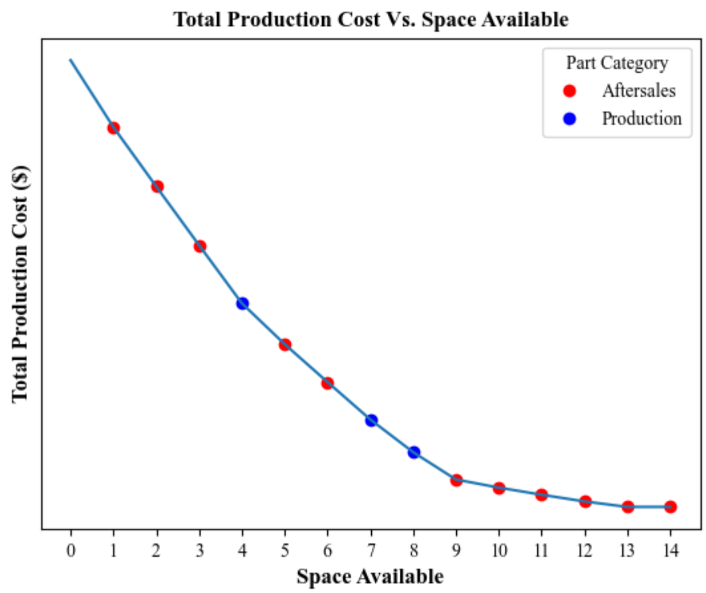

Figure 4-2: Total Production Cost Vs. Space Available

At the beginning of the thesis, we sought to answer the question of how the OEM can integrate aftersales into their make vs. buy strategy. This model can provide an answer to that question. From a pure total cost perspective, it is optimal to keep doors, trunks, and fenders in-house before in-housing production parts. Those categories represent the largest drivers of production cost for aftersales, most likely due to their volume. The steepest part of the curve, from 1-7 spaces, represents a 35% reduction in total production cost reduction over 6 years. For this dataset, that value represents the most the OEM should invest in additional capacity should it be required. This model is not strategic and there may be other considerations that need to be factored into sourcing decisions for the OEM. For example, this model does not account for the cost of not being able to procure aftersales parts. The inability to source these parts could lead to costly vehicle buybacks, turning a part that costs $300 from a supplier into a part that costs tens of thousands due to a buyback. Souring supplier relations were the impetus for this research and the OEM may not be able to outsource these parts in the future.

In systems where production hours are the binding constraint, keeping aftersales parts in-house can be an economically viable tradeoff to investing in more capacity. Aftersales parts require very few production hours and, if kept in-house, provide millions of dollars in production cost savings, while minimizing the load on a plant. However, there are detractors to keeping an aftersales part in-house over in-housing a cost-competitive production part.

The main detractor is the increase in TdC, or per unit cost, of the vehicle the production part is for. While overall production costs will be lower, the TdC of the vehicle will inherently be higher if a cost-competitive production part is outsourced. TdC is a critical key performance indicator (KPI) for the vehicle's program management team. If incentives are aligned with a myopic approach, leadership should expect resistance to the total production cost approach. In the OEM's case, aligning incentives to a broader goal and being cognizant of the tradeoffs an organization must make for the benefit of the entire firm must be considered.

5 Discussion And Conclusion

Section 5 discusses the broader implications of these findings and recommends areas for future work.

5.1 Sensitivity Analysis

Sensitivity analysis is a valuable feature of optimization that is not well-defined for mixed integer programs. Shadow prices of the constraints can tell a business how valuable a unit of capacity is by mapping the change in the objective function to an increment increase in the constraint. In other words, it provides a ceiling for how much a business should invest in capacity. This MIP cannot take advantage of this approach. A unit change in a constraint, for example, an additional hour of capacity for a type 3 press, more than likely will not change the objective function. The objective function will only change once the capacity is incremented to a level where all demand can be satisfied. After reaching that point, an increment in capacity will not change the objective. Nonetheless, the OEM would like to know how much capacity they will need to insource a part. It could be 1 unit of capacity or 3000 units of capacity. In this case, the answer can be determined using arithmetic. The capacity is a known value, the current utilization is known, and the expected demand is known. By adding the current utilization and the expected demand, and then subtracting the capacity, the number of hours needed to change the objective can be determined.

The cases highlighted a lack of capacity in the type 3 press at Plant A. Following the approach outlined above, the number of additional production hours a month for the OEM to source the type 3 stampings at Plant A can be determined. First, the average amount of excess capacity while running a 3-shift pattern is -1.75%, meaning this type of press is expected to be near capacity over this time horizon. Second, the amount of capacity required to source the two type 3 stampings is 15% of the total capacity for type 3 presses at plant A. The total production hours required for these parts is ~3,400.

Given the required production hours and the cost savings incurred by sourcing this part in-house, the "shadow price" of a unit of type 3 capacity is $3,000. While this may seem high, the additional Capex required to bring this capacity online, when depreciated, can exceed the shadow price. However, if there is another method to enhance capacity without significant capital investment, such as a more efficient shift pattern or weekend production, the OEM could take advantage of the shadow price. This shadow price also applies to sourcing from other plants.

Another approach is evaluating this problem using a linear model. If allocation can be split between the OEM and supplier. For example, if the OEM is cost-competitive for a part and can insource 75% of its volume, a linear model would allocate 25% of the volume to a supplier. With each hour of production, the OEM can insource 500 additional units. The objective function would improve by the product of the additional units and the cost difference between the supplier and the OEM. This approach gives a similar shadow price of $3000 per hour of production.

The shadow price with alternative production options tells us more about the value of capacity. For example, in scenarios 1 and 2 we saw that the lack of capacity in type 3 presses increased production costs by 11%. However, these scenarios only evaluated production scenarios at plant A. When allowed to source from Plants B-D, the shadow price of type 3 presses is much less. Adding more type 3 capacity to Plant A under the regional optimization scheme improves the objective by less than a percent.

5.2 Additional Capacity Constraints

There are a handful of capacity constraints not included in the scenarios evaluated in section 4. For example, die storage, part storage, and assembly cell capacity. There are even more constraints a manufacturer can consider, however. For example, capacity can be modeled down to the number of forklifts or automated guided vehicles available and a part's incremental load on those assets. An OEM can even consider staffing levels as a constraint. Adding additional constraints will provide insight into the binding constraint, or the bottleneck, of the system. Those bottlenecks can then be targeted for investment. Like the shadow price analysis in section 5.1, the value of a unit of capacity can be weighed. For example, if assembly cell capacity constraints were added and found to be a binding constraint, the shadow price of a unit of assembly cell capacity would be millions of dollars. Economies of scale in the automotive industry can have an outsized impact on total production costs. If the OEM can save $5 on part with a volume of one million units, but the binding constraint is one assembly cell, it can be difficult to not economically justify an expansion or developing a method to accommodate the assembly cell without expansion. The value of insourcing motivates the “creep” of high-value asset categories into spaces they didn’t previously occupy.

5.3 Depreciation

One element that can be of importance is the expected utilization of production assets and the resulting depreciation per unit costs. While depreciation is not accounted for in this model, discussing its implications should depreciation be included remains pertinent.

As an asset is utilized more, its depreciation is spread across more volume. Given that this problem deals with the allocation of high-volume and low-volume parts, we can relate this to the task at hand. A single past model part annually consumes 0.2% of a single press’s capacity. Whereas a production part annually consumes 7.5%-10% of a single press’s capacity. Keeping past model parts in-house over a production part can have a large negative impact on depreciation per unit relative to a production part. However, as we’ve shown, total production costs are minimized by insourcing select past model parts over production parts. What is the solution to this problem? Depreciation is an important metric, but so are production costs.

For example, an asset depreciates $10,000 a year and has a yearly capacity of 5,000 units. Using all its capacity, depreciation per unit is $2. Using half of its capacity, or 2,500 units, depreciation per unit is $4. Using a fifth of its capacity, depreciation per unit is $10. These swings in costs can give the impression that in-house production is not cost-competitive if expected utilization is low. For example, say the OEM is deciding whether to insource or outsource a production part fully using the asset previously described. The part’s cost is $10, and depreciation is $2, for a total cost of $12. Outsourcing the part would cost 15$. Insourcing the part would allow the OEM to save $3 per unit. 1 month later, volume estimates are revised, and the part now will only use a fifth of the asset’s capacity. Depreciation per unit jumps to $10, and the insourcing cost is now $20. In this scenario, the OEM can save $5 by outsourcing the part, but now the asset isn’t utilized at all. Where does its depreciation get allocated to? Does the OEM allocate its depreciation to similar assets or the entire production area? Now, per unit costs rise overall, which could be another tipping point. Depreciation based on volume can be a dangerous metric to use as it causes a firm’s costs to spiral. A better approach would be to use the capacity of the asset when determining depreciation costs. Taking our previous example and utilizing this approach, a shift in part volume would not change the per-unit depreciation costs, allowing the OEM to avoid spiraling costs while also considering depreciation. This methodology can be applied to an entire production line by determining the volume bottleneck of the system and using that metric as the volume by which to determine indirect per-unit costs.

5.4 Past Model Service and Complexity

Complexity is an attribute of manufacturing systems and describes how varied the system is. Complexity can be broken down into two categories: Static and Dynamic. Dynamic complexity describes the uncertainty and variability the system experiences. For example, machine failures, fluctuations in customer demand, or variances in a supply chain are factors that impact a system's dynamic complexity. Static complexity describes the elements within the system and their relationship to one another. For example, product design, which influences the bill of materials, the production floor layout, and the number of unique outputs define the static complexity of a system. A manufacturing system with low complexity would produce one configuration of a widget, whereas a system with high complexity would produce several variations of multiple widgets. Producing a variety of products allows a manufacturer to serve more consumer segments but the variety comes with negative externalities (Zhu et al., 2008). Manufacturing systems with higher complexity come with higher costs (Fisher & Ittner, 1999). In the OEM's case, widgets are the models, and the many configurations they come in.

The OEM manages both categories of complexity across their production lines for new models. Static complexity is managed by minimizing the number of models produced and maximizing the commonality of parts between models. Dynamic complexity is managed through building resilient supply chains, improved forecasting, and predictive maintenance. Building a strategy to in-house more past model service/aftersales parts should include minimizing the static complexity of their manufacturing system. This research examined one to one tradeoffs of past model and new model parts – by determining which part has the most cost savings by being brought in-house. The tradeoff is brought on by a lack of capacity. However, if more commonality is designed into both parts upstream, for example by iterating on a previous model's design or using similarly designed assembly processes. A potentially fruitful mode of "in-sourcing" more past model parts could be gaining by creating commonality between future model parts and high value past model parts, allowing the OEM to produce the two categories of parts using the same tooling or equipment. This approach would require alignment with design, engineering, and past model functions far upstream during the design phase but could alleviate the capacity challenges the OEM could face going forward.

5.5 Conclusion

To summarize, this research examined scenarios to minimize production costs by determining the optimal sourcing strategies for the OEM through leveraging internal manufacturing capacity. The resulting model characterized key aspects of the OEM's manufacturing network and uncovered viable production scenarios in Mexico for the firm to pursue should they lack the capacity in the United States. In addition, a case study was developed that examined how the OEM should source aftersales/past model service parts should they compete for floor space with one another and new model parts. A select category of past model parts should be sourced internally ahead of a new model. Following these analyses, a discussion of future work and the limitations of the model and the research were developed.

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