Cost Optimization in Sheet Metal Manufacturing by Tuning the Sheet Metal Nesting Strategy Based on Sheet Utilization and Downstream Part Handling Costs

by
J. Chandler Liggett

B.S. Mechanical Engineering
Georgia Southern University

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Authored by: J. Chandler Liggett
Department of Mechanical Engineering
August 11, 2023

Certified by: David Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering

Accepted by: Nicolas G. Hadjiconstantinou
Professor of Mechanical Engineering
Chairman, Department Committee on Graduate Theses
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ABSTRACT

The cutting of sheet metal blanks from raw sheet stock is a crucial process in the sheet metal fabrication industry. One of the primary cost drivers for this process is sheet utilization, which is the amount of raw material processed into a usable blank compared to the total raw material processed. Nesting is a method that efficiently packs blanks onto raw sheets with the aim of reducing scrap generation by improving material utilization. Modern nesting algorithms are quite successful at maximizing sheet utilization given an explicit set of available raw sheets and a set of blanks defined as candidates for nesting. Because of this, nesting efficiency and thus sheet utilization are primarily determined by the characteristics of the candidate blanks and the number of candidate blanks that can be nested together. Nesting strategies may be chosen to include the maximum number of possible candidate blanks for maximized efficiency. On the other hand, nesting strategies may instead restrict the available part candidates for the purpose of reducing sorting and handling complexities downstream of the cutting operation. In between these two extremes, it is hypothesized that there exists an optimum nesting strategy that balances improved sheet utilization with the negative cost effect of more intensive handling requirements. In this work, the effect of varying nesting strategies on sheet utilization is studied in the context of a sheet metal manufacturing operation with plant locations across the globe. Cost models are produced that inform the selection of a globally optimized nesting strategy, and throughput models are considered which inform the validity of cost-optimized strategies. Additionally, regional differences in cost drivers are studied, and an optimized nesting strategy is validated for deployment across global plant locations. This work provides a detailed approach to optimizing sheet utilization in sheet metal manufacturing through selection of an optimized nesting strategy.

Thesis supervisor: David Hardt
Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
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This thesis, in partial fulfillment of the requirements for the degree of Master of Engineering in Advanced Manufacturing and Design, is not an individual endeavor. Rather, it is the capstone of a long process of collaboration and partnership with others along the way. For this reason, it is my pleasure to take a brief moment to thank those who have been instrumental in the success of this project.

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I would also like to acknowledge the support and enthusiasm demonstrated by the organization partnering with us in this case study. Although the organization will remain unnamed, I am nonetheless grateful for the many ways in which they actively sought to make this project a success.

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Colossians 3:23-24
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Chapter 1: Introduction

1.1 Background and Motivation

Amidst incredible advances in materials and manufacturing technology, sheet metal manufacturing remains an indispensable part of the manufacturing landscape today. A 2020 report predicts the industry to reach a total value of $4.4 billion by 2026. [1] Of the many sheet fabrication processes, bent sheet metal fabrication demonstrates the largest growth, accounting for the majority of the global market share. The solid growth in this industry can be traced to the prevalence of bent sheet metal components in industrial, construction, and residential manufacturing. [1]

Given the prevalence of bent sheet metal fabrication and the size of the industry, the importance of process optimization in manufacturing sheet metal components cannot be understated. Low cost, high throughput manufacturing of bent sheet metal components enables economic growth and empowers innovation, delivering critical products to consumers. Additionally, innovations that reduce cost and improve throughput of sheet metal components offer sheet metal producers the potential for significant investment returns. In the face of rising demand experienced which is expected to continue over the next decade, manufacturers are seeking to respond by optimizing their manufacturing processes with the goal of increasing throughput at reduced cost. [1]

1.2 Context

In this work, sheet metal manufacturing will be examined in the context of a global organization specializing in large scale sheet metal assemblies. To preserve the integrity of sensitive information while also allowing information to be released in detail, the manufacturer will remain unnamed. Nonetheless, some background on the company is necessary to provide context for the work which will be presented in this thesis.

The global organization studied here produces large scale, highly customizable assemblies primarily constructed of sheet metal. These assemblies, referred to as “units” in this work, can each fall into a “product family” which is defined by functional characteristics of the completed unit. Units within the product family can then differ by size, material of construction, and presence or absence of add-on modules or features, and other customized characteristics. A key feature of the organization which must

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1 Bent sheet metal fabrication is a process by which a blank shape is cut out of a two-dimensional raw sheet of material and then bent at strategic locations for form a final three-dimensional part. Please see chapter 2, section 2.1 for further details.
not be overlooked is the highly customizable nature of their products. The sheet metal manufacturer operates within manufacturing space which will be referred to as “high volume, high mix” because the plant location regularly processes large quantities of parts which are highly varied.

Vertical integration is an important value within the organization, with parts and components being produced in-house whenever possible. Thus, the operations within the manufacturing facility range from sheet metal fabrication to the fabrication of a variety of other components by other methods, coating and painting, and final assembly. In this work however, the focus will be constrained to the sheet metal fabrication process and thus, although the organization deals with a wide range of manufacturing and assembly processes, the organization will be referred to as a “sheet metal fabricator”.

Additionally, the organization operates globally with manufacturing facilities world-wide. As such, the organization has defined regions of operation within which plant locations are able to share similar operating conditions such as product demand, capital labor cost, material cost, and others. There are three regions currently considered: North America (NA), Europe (EU), and Asia (AS). Within each region, conditions which vary based on the geographic location of the plant will be considered to be static. All plants operating in the NA region will be assumed to produce the same product mix because they experience the same customer demand. Plants within the region will be assumed to share the same capital labor and material cost. In this way, global regions are used to standardize conditions which vary by geographic location.

Lastly, the sheet metal fabricator is has adopted Lean manufacturing principles as a global strategy. The organization firmly believes in the value of just-in-time manufacturing, and seeks to eliminate costs arising from excess held inventory and work in progress. Based purely on a Lean perspective, the optimal fabrication methodology would be single part flow in which single parts are nested and cut at a time. However, practical restrictions on sheet inventory size and the need to group parts together to save on setup time and improve sheet utilization mean that some balance exists where Lean principles push toward the smallest group of parts processed together as possible while achieving optimal cost.

1.3 Problem Statement

The directive for the work provided by the sheet metal fabricator was to “build a durable, parameter driven process simulation of the cost of fabricating sheet metal parts at all global facilities.” Within this directive, two important foundations are set for the work. First, models should be developed that are parameter driven. The ability to create a parameter driven model is important to promote a metrics driven
understanding of the effects of parameter changes as well as transparency of the model output. It is common in manufacturing to make decisions based on intuition or experience. However, in the context of a global operation, a more robust data driven approach to decision making is crucial. This also ties into the second foundation of the work, which is to approach the problem from a global perspective. The resulting process models should be generically applicable to all global sheet metal fabrication facilities.

Sheet metal scrap and manufacturing waste is an important aspect of the process to simulate. Reducing scrap by improving raw material utilization presents significant cost savings for the company globally. This model should be developed in a way that provides insight into process conditions affecting raw material utilization, thereby enabling the selection of an optimal set of processing conditions. A key process condition which the fabricator is eager to understand is the effect of nesting strategy, which is the choice of which parts to make available for grouping together on raw material sheets. Thus, this model is specifically tailored to give insights into the effects of the choice of nesting strategy.

Therefore, this work aims to develop cost and throughput models based upon a process simulation which allows for informed decision-making. The resulting models should allow for a complete and transparent understanding of the effects of nesting strategy on the cost and throughput of the fabrication process, enabling the selection of an optimal nesting strategy.

1.4 Challenges

Due to the nature of the organization being studied, certain conditions exist that pose significant challenges to be overcome when developing cost and throughput models. These conditions are both those existing within the company structure and those derived from the product being produced. For this work to be successful, ways of mitigating these challenges or adopting a methodology which accounts for these is critical.

The company is a global company operating in multiple different fabrication facilities. In the past, the company has valued regional autonomy in allowing plants to make decisions which best suit the conditions they experience. Thus, regional operational, layout, and equipment difference exist between plant locations. As the company has grown, however, a need exists to push toward a uniform process. This means that layout, equipment, and process differences must be reconciled when proposing a global solution.

Secondly, the wide variety of parts produced to construct a large range of products means that the part pool is massive with a high disparity in part characteristics. The organization produces over 200,000
unique part numbers annually. Of these 200,000 parts, some may be 6 inches square, others may be over 4 feet by 6 feet. Additionally, these parts may be made with one of two available material choices and one of five possible gauge thicknesses. This part variation presents an added level of complexity when seeking to understand raw material optimization.

1.5 Thesis Structure and Acknowledgment of Collaborative Contributions

The work presented in this thesis was performed under the guidance of the Advanced Manufacturing and Design Program at the Massachusetts Institute of Technology (MIT). This thesis is a capstone of the program and was performed under the guidance of Professor David Hardt, a Ralph E. and Eloise F. Cross Professor of Mechanical Engineering at MIT. Additionally, this work was a collaborative effort between the author and another program graduate, Vineeth Gowra.

This thesis is focused primarily on analyzing sheet metal optimization from a cost standpoint. However, cost is just one part of a project of much larger scope that was completed by the author of this thesis and by Vineeth Gowra. The collaborative nature of the project allowed this thesis work to be presented as a more specific look at certain aspects of the optimization and modeling problem. Vineeth Gowra’s work presents the project from a throughput perspective in his work titled “Optimization of Throughput in Sheet Metal Manufacturing by Tuning the Sheet Metal Nesting Strategy Based on Sheet Utilization and Downstream Part Handling Costs”. [2] If a specific study on throughput modeling is desired, Vineeth Gowra’s work should be referred to. For a comprehensive view of the full project scope, both theses may be examined together.
Chapter 2: Overview of Key Concepts

2.1 Sheet Metal

2.1.1 Sheet Metal Features, and Applications

Sheet Fabrication is a manufacturing process by which a desired geometry is achieved by cutting, forming, joining, or otherwise manipulating sheet stock material [3][4]. Sheet operations differ from other forming operations in that the cross section of the raw stock material is preserved while the shape and geometry may be considerably changed [4]. Raw material, either discrete or continuous sheets, are reduced to a desired flat panel geometry through subtractive (cutting) methods, and then may be formed to expand into a third dimension by processes inducing plastic deformation in the sheet material. Depending on the design requirements, the formed component may then undergo further processing. In this manner, a final desired three-dimensional geometry may be manufactured from raw sheet stock.

Commonly used metal alloys in sheet fabrication include steel and aluminum alloys. Of the two, sheet steel accounts for the highest volume of sheet metal manufacturing due to high strength and formability combined with lower costs [5]. These sheet steels may be of varying compositional grades depending on the desired material properties, and may be either coated or uncoated [5]. Because of the wide variety of properties and features available in sheet steel, and the low material and manufacturing cost, sheet steels are widely used in sheet fabrication for applications from commercial roofing to the aerospace-defense industry.

Bent sheet metal components are of particular interest, as the introduction of line bends of varying angles at specific locations can create a rigid structural member at low weight and cost. Bent sheet metal is also uniquely suited for applications requiring panel or channel components featuring a relatively high surface area to cross section ratio.

2.1.2 Processing Methods: Manufacturing Sheet Metal Blanks

Bent sheet metal fabrication starts with the formation of a flat two dimensional geometry from sheet stock, commonly referred to as a “blank” or, with the advent of Computer Aided Design (CAD) techniques, a “Flat Pattern” [6] [7]. Traditionally, these sheet metal flats are formed manually from combinations of punch and shear techniques. Today however, they are often developed using CAD software and cut using an numerically controlled machinery [8].
For high mix production, computer numerical control (CNC) laser cutting is becoming increasingly popular due to the manufacturing flexibility offered by the technology [9]. A wide variety of shapes can be cut without the need for part-specific tooling. Laser cutting, being a point-wise CNC operation, is also capable of creating complex curves and cutouts that would be difficult to achieve with more traditional methods such as punch/shear sheet metal processing. Lastly, laser cutting can produce very accurate cuts (typical tolerances of ±0.025 mm) with much cleaner edges compared to punch/shear techniques [9]. The capability of laser cutting to produce accurate, clean edge cuts eliminates the need for post-processing operations aimed and cleaning up the sheet metal edges [9]. For these reasons, laser cutting is an extremely popular choice for high mix production of sheet metal blanks.

Although CNC laser cutting machines offer distinct advantages in sheet metal production, this process is not without drawbacks that should be considered. When compared to most other sheet metal cutting techniques, the cutting speed is lower for laser systems [9]. Laser cutting machines also require much higher up-front capital investment compared to punch/shear machines [9]. Despite these drawbacks however, these machines continue to grow in popularity. This is largely due to the high accuracy, better nesting efficiency, and lower tooling/setup times offered by this manufacturing method that, when applied to high mix production, outweighs the disadvantages posed by lower cutting rates and higher capital cost [9].

2.1.3 Processing Methods: Sheet Metal Bending

After blanks are cut, they are often formed by introducing bends in a direction normal to the surface of the sheet. These bends extend the shape of the blank from a two-dimensional sheet to a three-dimensional shape, with the objective of increasing rigidity or obtaining a desired shape [10].

Brake forming is one important means of introducing such bends in sheet metal blanks. In this manufacturing process, a two piece die and ram are used to produce a line bend in a sheet metal blank. [10] Brake Press machines commonly used for brake forming. These machines can be either hydraulic or mechanical, and can produce precise line bends in sheet metal material [10].
Figure 1: Brake Forming Schematic featuring Ram, Die, and Sheet Metal Part

2.1.4 Processing Methods: Sheet Metal Weld Post Processing

Welding is an important post processing step that may be necessary for certain components depending on their application. Sheet metal components may require welding for joining purposes, or they may require welding for sealing gaps between bent flanges. A detailed discussion of the welding process will not be presented in this work; however, it is an important and frequently occurring post-processing step to consider.

Specifically relevant to this work, however, is the use of the welding process to seal gaps between bent flanges in the sheet metal component. This process is referred to as “Corner Welding”. When a sheet metal component has adjacent bends that form a flanged edge, as shown in Figure 2(a), a gap exists between the two adjacent flanges. A simple weld can be applied across this weld to seal the gap, depicted in Figure 2(b). This corner weld may provide additional structural strength, or it may simply provide a water-tight seal at the gap. Regardless of the desired function, the corner weld is an important post processing step that is relevant to this work.
Figure 2: Sheet Metal Corner Welding. (a) Unwelded Flange Corner and (b) Welded Flange Corner

2.2 Part Nesting Theory

2.2.1 Sheet Metal Part Nesting: An NP-Complete Problem

To produce a sheet metal blank from a raw sheet using CNC processing technology, a digital representation must be obtained that shows how the desired sheet metal blank should be laid out on the raw sheet. This digital representation is converted to CNC code for controlling the machine and performing the desired cutting operations necessary to obtain the desired blanks. This CNC program can then be run on a laser cutting machine as one job requiring a setup operation, and a run operation.

In order to minimize the number of setups required, it is often desirable to use a larger raw sheet size and place multiple blanks on the same sheet. The process of placing multiple blanks on a single raw sheet is called nesting [11]. Nesting takes multiple blanks that require the same material and sheet metal thickness and lays them out on the raw sheet in their orientation and placement for cutting.

To reduce material consumption and cycle time, the process of nesting becomes a complex optimization problem. Blanks often possess complex perimeter geometries and as such they often cannot be laid out in such a way that the entire sheet is used to produce a part. Some material will remain unused in the gaps between blanks and forms a remaining “skeleton” that is discarded as scrap. Because this inter-blank waste material is unavoidable and comes from the designed shape of the blank, this scrap is often referred to as “engineered scrap”.
Efficient nesting is in essence a two-dimensional bin-packing problem, and the determining an optimal nest has been proven to be NP-complete\textsuperscript{2} [11] [12]. This means that no efficient solution algorithm currently exists for optimally nesting an array of potential candidate geometries within a given raw sheet, and the problem only becomes more complex when multiple raw sheet sizes are possible. Although no efficient solution algorithm exists for the nesting as a bin packing problem, extensive work has been performed to develop heuristic approaches and approximation. These methods often require assumptions such as the “bounding box” assumption, in which irregularly shaped geometries are approximated by a rectangular bounding box, or they may leverage heuristic methods for approximating the optimal layout [13].

2.2.2 Nesting Software

Due to the complexity of the two-dimensional bin packing problem, sheet metal nesting in large scale manufacturing is often performed using powerful software packages with built-in approximation algorithms. RADAN is one such software package released by Hexagon, which has been used with great success in high mix sheet metal nesting applications. According to one case study released on the software, RADAN was able to reduce scrap by 15%, and was able to complete nests in 20% of the time required to nest parts using other methods. [14] The sheet metal fabricator partnering with this thesis also is currently using RADAN nesting software, and thus this program will be used in the remainder of this work to obtain utilization data from nesting experiments, and all production data that is logged and used will be derived from production nests generated in RADAN.

\textsuperscript{2} An NP-complete problem is a specific category of problems for which no efficient solution has been found
Chapter 3: Methodology

3.1 Development of a Process Model

Two possible methods for defining a process model are discussed in this work. First, an action-based method is examined, which considers each discrete action as a process step for defining the process model parameters. Next, another method for defining the process model parameters is presented that is based upon the way an Enterprise Resource Planning (ERP) system defines cost and resources needed for a process. Finally, it is shown how aspects of each of these methods will be combined to leverage the strengths of their respective approaches while mitigating their unique disadvantages.

3.1.1 An Action-based Approach to Process Modeling

The action-based approach to process modeling considers each distinct step performed by each resource in the system as an action having an associated input of materials, time, and capital to produce a defined output. Each stage in the process model may be composed of a single action or multiple action steps which are aggregated to make up the overall stage. These outputs may be value-add or non-value add outputs, but each action is a necessary function performed as a part of the process.

An example of an action-based approach to process modeling would be as follows. The cutting operation may be represented by a block diagram where each block represents a discrete action with inputs and outputs. Raw material is pulled from inventory, which is the first discrete action and a block in the diagram. The raw materials are staged in the cutting operation buffer, which is another block. A cutting program is loaded into the cutting machine, yet another block, and then the setup process would be an additional block in the process model. The final action step would be the cutting operation, with the output of this final block moving on to brake press related action steps. In this way, a very granular approach may be used to model the cutting process, with each discrete action being represented by a block in the process model.

Action-based process models are advantageous because of their transparency and their granularity. This allows the effects of each action or of each action modification to be clearly reflected to the system output. Because all distinct actions are considered, the effects of changing an input to any action may be fully realized by the model and reflected to the outputs. The process model is also transparent in that each action step may be individually defined and understood. When changes to the system are made, the effects may also be easily studied by observing the specific action steps in reality and comparing the
expected changes to actual changes. Thus, an action-based process model may be highly granular and helpfully transparent.

3.1.2 An ERP-Based Approach to Process Modeling

With ERP systems becoming an indispensable part of today’s manufacturing landscape, it is often desirable to build a process model upon the same framework as the ERP system. In most modern ERP systems, a manufacturing process is broken down into a set of discrete steps known as routing steps. For each routing step, resource inputs are defined along with expected processing times. This method of defining routing steps can be used as a framework for developing a process model.

ERP-based process models provide three primary advantages. First, if an ERP system is currently in place, it may serve as an existing framework, reducing the need to perform or compile time studies that can often be extremely costly both in terms of time and labor. The use of an existing framework allows for a process model to be developed rapidly without the need for extra studies. Secondly, because an ERP system is integral to the business, it is often considered to be a sort of “gold standard” that is kept up to date and maintained, while time studies may change, become obsolete, or grow obscure over time. Lastly building the process model upon an ERP system framework may increase compatibility between the model and other data sources within the company as a good ERP system often serves as a central hub from which other systems are grounded. The ERP system would therefore be a sort of common denominator between the process model and other resources. From these three points, some distinct advantages can be observed from building the process model based on the ERP system.

Despite the compelling advantages of the ERP-based approach, some real limitations of this method should be considered. First, an ERP system’s routing steps tend to represent the process at a high level and certainly lack the granularity of the action-based process model. This is because routing steps are based on input needs and distinct value-add outputs. If an action does not produce a value-add output, it is generally lumped together with another stage which produces such an output. Because of the lower granularity, system changes that affect non-value add steps may not be representable in the model.

3.1.3 A Hybrid Action-Based ERP-Based Process Model

A hybrid process model framework is proposed in this work to represent the manufacturing process. This hybrid process model framework would leverage the granularity and flexibility of the action-based process model while drawing from the established resources of the ERP routing system. In doing so, a compromise may be reached where the process model is built upon the robust gold standard of the ERP
system, but additional action steps are broken out. This would result in a hybrid process model featuring the strengths of both systems.

An important consideration in developing a hybrid process model like this would be to ensure that the additional action steps that are broken out of the cost model are not “double counted”. In the ERP system routing parameters, these individual action steps are often considered but lumped together with other action steps into a larger whole. This means that individual action steps cannot be distinguished or modified. If the desired granular action step were to be added in as an additional consideration outside of the ERP system, it would be double-counted since it is already buried within a given routing step.

One simple but effect way to overcome this problem would be to consider the conditions under which the ERP routing was defined as the action step baseline. Under the conditions in which the routing definitions were compiled, the additional action step effect could be considered as zero. However, if a process condition or parameter were changed such that the individual action step was changed but the remainder of the routing were to remain the same, the difference in the action step output could be added on top of the routing output as a “routing modifier”. In this way, the action step could not be double counted but its effect on the overall system would not be neglected.

3.1.4 Generic Process Model for Representing Global Manufacturing

Examining sheet metal fabrication at a global scale requires detailed understanding of the processing commonalities that exist between plant locations as well as the unique and important differences. However, the range of manufacturing process deviations that might exist across individual plant locations globally can be quite broad and may confound meaningful results. For this reason, a single representative manufacturing facility was chosen from each business region to act as a representative plant location. The highest volume, most standardized manufacturing facility in each region was chosen and it was assumed that, as sheet metal manufacturing processes continue to move toward uniformity, the results from these plants would adequately approximate the results from any other plant in the region.

Three representative manufacturing plants were chosen from each of three global regions, North America (NA), Europe (EU), and Asia-Pacific (AP). Based on the existing manufacturing process flow specific to each of these plants, a generic process flow was developed that adequately approximates the actual sheet metal fabrication process existing at any plant globally. The process model is an important means of defining part flow and processing costs, specifically in terms of labor hours required and throughput costs. Material costs are important, but better represented through other means and so the process model is
developed here strictly for the purpose of analyzing material flow and the costs associated with labor and handling.

The generic process model is presented in Error! Reference source not found.. The model features distinct processing steps, that are depicted as rectangles as explained in the figure legend. Buffer placement and characteristics are also indicated in Figure 3, with infinite buffers shown as gray ovals and finite buffers shown by red circles.
Figure 3: Process Flow Model Describing Global Sheet Metal Fabrication in a Manner Generically Applicable to each Manufacturing Plan
At each facility, infinite de-coupling buffers exist at the front and end of the sheet metal manufacturing process. These buffers essentially isolate the fabrication process from most upstream or downstream variability while also preventing the choice of nesting regime from appreciable affecting processes upstream. A large raw material inventory buffer is held just upstream of sheet metal fabrication, featuring a daily reorder point and sufficient safety stock to ensure it functions as an infinite starting buffer from which the manufacturing process can draw. Additionally, between one and two days of sheet metal parts inventory are held upstream prior to further manufacturing and assembly that isolate the downstream manufacturing from any potential effects of nesting strategy changes. The starting and ending buffers can therefore be modeled as infinite de-coupling buffers that allow the effect of nesting strategy adjustments to be isolated within the sheet metal fabrication process alone.

In between the de-coupling buffers, a series of discrete, generic processes were identified. In the first processing step, raw materials in the form of stocked sheet steel are gathered into “kits”. These kits are groups of sheets of predetermined sizes and quantities as required by the cutting program generated by the nesting software. In the second step, the sheets from the kit are fed one by one into a laser cutting machine that cuts sheet metal blanks from the raw sheet steel. The sheets now consist of a nest of parts that are cut out and must be removed from the offcuts and scrap material left over. An operator will then remove the parts from the scrap material, identify the parts, and pass them on to the next processing step, which is the brake press. At the brake press an operator will apply specified bends to create the bent parts before passing them along to the weld step, where corner welds will be applied as needed to the parts. Lastly, the finished parts will be sorted into carts to be taken to the final decoupling buffer in the fabrication process. In between each discrete processing step, a finite buffer exists that can hold a volume of parts constrained by space limitations.

3.1.5 Nesting Strategy and its Effect on the Generic Process Flow

Each processing step presented in Error! Reference source not found. was examined to understand how changes in nesting strategy might affect the processing step. As discussed earlier in section 3.1.4, the process model is concerned with three key metrics: material flow, processing times, and handling time. Therefore, the process model will only be affected by the nesting strategy to the extent that the nesting strategy affects these three key aspects.

The primary manufacturing processes, consisting of the cutting operation (Laser), the forming step (Brake), and the corner weld operation (Weld), were determined to be independent of nesting strategy.
The latter two steps, Brake and Weld, are independent of nesting strategy because they are truly indifferent to how the sheet metal blanks are grouped. In these processing steps, a single work-in-progress piece from the intermediate buffer is fed into the process, an operation is performed on the piece, and it is moved into the next buffer downstream. These two steps are single piece flow independent of the size of the buffer being drawn from or the number of available part candidates, and thus are not affected by the nesting strategy.

The first primary manufacturing process, the laser cutting operation, may also be simplified to be independent of the nesting strategy. It is true that a nesting strategy yielding higher sheet utilization would also increase the overall throughput at this step, since the necessary setup time would be reduced. However, on a macro scale, the expected setup time from a given percent increase in utilization is insignificant compared to the total cycle time and processing rate. Beyond the setup time reduction, the processing time is again driven by the individual part characteristics and independent of the size of the buffer it is pulling from or of the number of available part candidates. For this reason, the Laser processing step is also considered to be independent of nesting strategy selection.

This process model represents a generic perspective of the sheet metal fabrication process that exists at each plant location. As such, it will serve as a foundation for building cost model and throughput model assumptions. While details at a more granular level may differ from region to region and from plant to plant, the process fundamentally follows this model.

Some assumptions and simplifications are additionally made that do not represent current reality, but rather represent a reality the global manufacturing process is moving toward. In such cases, process changes that are planned for future implementation will be assumed to hold true even though they have yet to be implemented. In such cases, a theoretical perspective will be accepted of what the future reality should be.

3.1.6 Incorporating Key Manufacturing Conditions within the Process Model

The first key manufacturing condition to be considered is how a sheet metal fabricator deals with the use of remnants. In sheet metal fabrication, and in the context of this work, remnants are considered to be excess scrap material left unused from a cut raw sheet of steel that is of a size and shape such that it may be conveniently re-used as a new albeit smaller piece of raw sheet steel. Remnant usage and handling policy varies globally from plant to plant and introduces significant deviation in raw material utilization depending on how well the remnant policy is handled. Because the proper use or choice to disregard
remnants can significantly alter the fabrication process flow and material efficiency from plant to plant, how the fabricator chooses to handle remnants globally is a key assumption that must be considered prior to developing the model.

Within the field of sheet metal fabrication and even within the company studied here, the effect of remnants on fabrication cost is hotly contested. While it is generally acknowledged that reusing remaining sheet metal of a usable size can, if handled well, improve overall utilization and decrease scrap, no consensus exists pointing to how much remnant use improves utilization. It is additionally acknowledged that maintaining an replenishing an inventory of remnants comes at non-negligible cost. These two factors have inverse effects on cost, and it is unknown which might outweigh the other. Significant study has been done within the company prior to this work that has indicated that the material savings provided by remnant use is regularly outweighed by the implementation cost of remnant reuse.

Due to the uncertain trade-off between improved material utilization and the inevitable inventory and handling cost that remnant usage produces, this study will consider a simplified case in which remnants are not kept or reused. This simplification does not represent reality at any of the global plants, however discontinuing the use of remnants is a strategic shift that is to be considered in the future.

A second key processing condition is the identification of parts as they move from through the fabrication process. Because the sheet metal fabricator being studied operates in an extremely high mix high volume market, a significant logistical challenge is posed by the need to keep track of parts as they flow through fabrication. The need to identify parts is particularly critical as operators seek to match bend programs and weld instructions to the part at their respective processing stages.

Two primary means of identification are currently being used to varying degrees across global fabrication facilities. The conventional method is the use of paper travelers that are sent downstream in the fabrication process with each job. These paper travelers contain laser programs, bend drawings, brake program information, and weld instructions that are critical for providing operators with the information they need to complete the job successfully. While this is certainly a low-cost way of linking work in process with processing instructions, the complexity of this method and room for error increases dramatically as the number and variation of parts flowing through the process increases. Because the plant conditions being studied are both high mix and high volume, the number of pages of information needed to provide work instructions for each part in the system can quickly become unwieldy.
To address the shortcomings of using paper travelers, some plant locations within the global organization use barcoding on individual parts as they flow through the fabrication process. These barcodes can be scanned at any time to obtain any required information for the part. In a high volume and high mix plant, this method for part identification is extremely advantageous compared to sorting through stacks of paper. However, the implementation of this method provides other logistical challenges, such as how to apply the marking and what kind of marking it should be (should it be a sticker attached to the part, a laser etched mark, etc.) and at what point it should be attached. Secondly, such a system often comes with a high capital cost to implement. Automated part identification is capital intensive when it comes to equipment, implementation cost, and systems integration. Thus, although this method provides significant advantages compared to the use of paper travelers, its implementation is not without significant cost.

Currently, both paper traveler and barcoding methods are in use across the sheet metal fabricator’s global facilities. Although prior studies show that automated part identification provides significant opportunity for cost saving, the transition to an automated system will take some time due to the high implementation cost. For this reason, it is important that the process model be capable of representing both conditions. In one case, the part identification portion of each process stage is a function of the number of unique parts existing in the system and scales accordingly. In the second case, the part identification time is a fixed constant regardless of the number of unique part possibilities.

3.2 Establishing a Robust Global Framework

To develop a meaningful model that can accurately predict fabrication cost and throughput, the process model should be as close to reality as possible. However, when dealing with global manufacturing, cases frequently arise in which matching the actual fabrication process at one plant location could render the model significantly less accurate when applied to another plant location that may not incorporate the same particulars. Thus, some assumptions and simplifications are necessary for developing a meaningful model at a global scale.

3.2.1 Evaluating Regional Production Methods for Coherence

As already discussed, the global sheet metal fabricator being studied in this work has facilities located across three global regions: North America (NA), Europe (EU), and Asia (AS). Each of these regions has distinct regional differences, some of which are inherent to the geographic location and others that have developed within the plants as a result of divergent management and strategy initiatives. The process
model and subsequent cost and throughput models must then be flexible enough to adequately represent regional results when regional conditions are applied. In order to ensure this flexibility, the key regional differences that might affect cost and throughput in the fabrication process must be identified. Once these regional effects have been distinguished, a decision must be made whether these differences are to remain as a degree of freedom in the models, or whether carefully selected mean conditions should be selected to bring coherence among the regional differences.

Labor rates and material rates are two regional differences that are inherent to the geographic location of the fabrication facility. These two are critical for consideration as they interact with each other to dictate the break-even point at which scrap reduction intersects with the cost of higher labor input. Regional cost differences are presented qualitatively in Figure 1. Labor rates, provided by the organization being studied, increase sharply when moving from AS to NA and to EU regions. The data for raw material cost is compiled from internal reports from the organization as well as current market reports. [15] Raw material cost is here treated as a global commodity and the market difference across the regions is ignored to bring coherence and simplicity to the model. However, regional labor cost differences are significant. The model will therefore be designed with a degree of freedom that allows this metric to be adjusted when moving from region to region.

Figure 4: A Qualitative Comparison of Regional Differences in Labor Rate and Material Cost. Magnitudes have been Removed for Anonymity, but Directional Trends Hold True.
Production mix is another regional difference that is inherent to the geographic location. Although this may to some extent be attributed to strategic production choices, this is largely due to customer demand within the region in which the plant is located. Because this regional difference has been observed to be significant, and because production mix may factor into the cost and throughput models significantly, the models will be developed with the ability to be tailored towards specific regional production mixes that may or may not shift in the future.

An example of a regional difference that has developed because of divergent strategic choices includes regional differences in manufacturing equipment. As capital investments have been made over the years, needs and preferences specific to each manufacturing facility have led to a variety of equipment types from a variety of manufacturers. These equipment differences also come with differences in process rates, process efficiency, and process requirements. However, with company growth has come global initiatives to reduce variability in equipment and processing capability. Thus, in recent years global brake presses have been updated and replaced with a single model, cutting equipment has been gradually replaced by laser cutting equipment and plans are in place to further consolidate global equipment capability. Thus, for the purpose of this work and this model, difference in equipment capability will be considered to be negligible from region to region.

The goal of this thesis work is to develop a comprehensive model of how nesting strategy affects cost and throughput. Understanding this relationship is truly a pressing need and individual plants have, on their own, come to different conclusions on nesting strategy which meets the needs of their plant. Thus, a given plant in the EU region will have a different approach to nesting than a given plant in AS and will likely have made this decision based on different plant-specific needs. This study seeks to approach this problem from a global perspective, and so regional differences in nesting strategy will be considered as unique inputs to the model that can be varied.

Different regions and different plant locations also make different choices on raw material inventory. Some regions have chosen an inventory strategy in which an extremely wide range of sheet sizes are stocked in order to help improve sheet utilization. Other regions stock fewer sheet sizes, but instead tailor the sheet sizes to the most common part types they produce. This inventory choice in its essence is driven by production mix. When production mix is extremely high, tailoring sheet sizes to common parts becomes less effective at improving overall utilization. Because some regions have a more manageable production mix, optimizing inventory could have significant returns. In other regions however, the production mix is such that optimizing a reduced inventory does not benefit overall utilization and so a maximum number
of sheet sizes are stocked to improve the likelihood that a sheet can be chosen that maximizes utilization. This regional variable can have a significant effect on material utilization, that is currently not well understood, so this will be included in the study.

A last regional difference considered is the treatment of remnants. Each plant location currently reuses remnants in the fabrication process to some extent. These remnants are used to a greater or lesser extent based on regional nesting strategies. However, as already discussed, the effect of remnant usage on sheet utilization and throughput will not be considered in the scope of this study. For this reason, a simplified perspective on remnant usage will be adopted in that no remnants will be kept or reused.

Table 1: Strategy for Resolving Regional Production Differences, Either through Simplifying for Coherence or by Accounting for Divergence

<table>
<thead>
<tr>
<th>Regional Difference treated as Variable</th>
<th>Regional Difference Simplified to a Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Rate</td>
<td>Material Cost</td>
</tr>
<tr>
<td>Production Mix</td>
<td>Manufacturing Equipment</td>
</tr>
<tr>
<td>Raw Sheet Inventory</td>
<td>Remnant Strategy</td>
</tr>
<tr>
<td>Nesting Strategy</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2 Defining Regional Production Mix

When discussing regional production differences, the effect of regional production mix was identified as an important consideration. Establishing production mix can allow other regional characteristics to be defined, as the mix can be used to develop weighted averages. Further, any effect that individual part or overarching assembly characteristics may have on utilization, cost, or throughput can be applied accurately to individual regions if the production mix is well defined. Therefore, a methodology for accurately defining regional production characteristics is of great importance to the success and validity of the model.

Production mix will be defined in this work as the percentage of overall production that consists of a given assembly type. For example, plant A may produce X number of product families, each of which have their own unique characteristics. For each product family \(X_i\), the percentage of overall production that is attributable to that specific product family will be a portion of the production mix. The total production mix will be the sum combination of the production percentages of each product family, as demonstrated in Equation (1). The individual contribution of each product family may be visualized as shown in Figure 5.
Product families are selected as the unit component of production mix rather than individual parts or individual units. This is because, at a part level and at a unit level, the high manufacturer produces at such high mix levels that a high degree of randomness would appear to exist from part to part or from unit to unit. However, when units are grouped together based on shared characteristics, they form a family of products that can be better understood. Product families generally are distinguished by size, function, and feature characteristics that dictate what types and sizes of parts made up the unit. For this reason, product families are defined in such a way that the output of the manufacturing process may be more clearly defined and characterized.

3.2.3 Identifying Product Family Representatives for Analysis

When studying the effect of varying product mix, a question of key importance is whether the product family from which a nest of parts is drawn has any influence on the expected sheet utilization. For instance, does a group of parts nested together from Product Family A demonstrate different utilization than a similar group of parts nested together from Product Family B? If so, is this caused by part characteristics within the product family? The answers to these questions may be better understood by choosing a sample of products from each product family for study.
An appropriate sample set from the product family should be shown to adequately represent the expected behavior of the entirety of the product family. Thus, the sample set chosen from within the product family should encompass the range of product features that might influence utilization. For this study, representative products that encompass the range of unit size, material of construction, and design intent were selected. Products will be grouped together according to these three categories within the product family, and high-volume products will be chosen that exhibit these features.

For the sake of feasibility within the study, the smallest group of representative products was selected that could represent all the desired feature combinations. Due to the lengthy process of running nesting studies, a cap of 20 units was selected based on the time constraints of the study. It was decided that these 20 units should then be selected in such a way that at least 80% of production was represented by the samples.

3.3 Cost and Throughput Modeling Built Upon the Process Model

Following the development of a process model, and once the production mix and types of products are defined, a cost model and a throughput model should be developed that can layer on top of the process model. These further model layers are highly dependent on the process model, as a poorly designed process model may either result in too coarse or too fine of a perspective on cost and throughput. A process model that yields a coarse resolution may not yield meaningful insights, as the effect of complex input parameters may become obscured. However, if the model is too fine then the results may be rendered unclear, or the model may prove to be too complex to solve.

Given a process model that was developed according to the aforementioned approach (a hybrid ERP-action based model), a cost model can be constructed by scaling the inputs for each process step by their designated dollar value. For the purpose of this study, only costs that are affected by the nesting strategy selection will be considered. The cost model may then be built by summing up the calculated costs affected by the nesting strategy selection for each process stage.

In a similar manner, a throughput model can be built upon the process model. Each process stage is considered to have an associated setup time, and an associated processing time. These setup and processing times may be in some way functions of the nesting strategy, or they may be independent of the nesting strategy. For this study, the process steps that are independent of the nesting strategy will be considered constant in the throughput model, while the dependent process steps will be varied with the
nesting strategy. In this manner, throughput can be examined for different nesting strategies based on the framework provided by the process model.

3.4 Nesting Strategy and Its Effects
3.4.1 Selecting Potential Nesting Strategies

The selection of achievable nesting strategies that encompass the entire range of desired solution space is of particular importance to the success of this study. The nesting strategy is a choice of what part blanks to make available as candidates for automated nesting. In a fabrication context featuring a high number of unique blanks to be cut, the grouping permutations are nearly endless, but some practical external considerations can be applied to define which blanks should be made available as candidates in a nesting pool. These considerations can then be applied in different ways to form well defined strategies for selecting nest groupings.

The sheet metal fabrication area processes parts as single piece flow, and sheet metal blanks are required in assembly for product units that are also constructed as single unit flow. Thus, sheet metal parts for specific product units are required to be in the order of assembly. Because the manufacturer values Lean manufacturing principles, a fundamental consideration should be to produce sheet metal blanks as they are needed, in the order that they are needed.

At a most basic level, blanks could be nested in single piece nests. However, due to the blank size variation and the inability to stock an infinite number of different sized raw sheets, single piece nesting is highly impractical and inefficient. The next smallest nesting option would be to nest together all blanks that will form sheet metal parts required at a single fabrication location in the assembly process. These sheet metal parts will together form a fabrication group (fab group) and form the fundamental, smallest functional pool of candidates for nesting. As such, the fab group will be the smallest nesting strategy that will be considered.

In the context of the studied manufacturing facilities, fab groups are delivered to the fabrication locations on large carts that can hold two to three fab groups each. As such, the sheet metal blanks that would form the parts for a single cart are the next functional pool of candidates that may be readily distinguished. After the cart level, blanks can be nested together as needed for a single section of an entire unit, in which a section is either an upper or a lower half of a complete unit. At the nest level up, sheet metal blanks may be grouped together as needed for producing an entire unit, or blanks required for two
units may be grouped together. Finally, all sheet metal blanks needed for a shift’s worth of production or for an entire day’s worth of production may be grouped together.

This approach allows for seven distinct nesting strategies. The candidate pool for each strategy is defined uniquely based on what parts are needed in what order, and the strategies differ by how far ahead the parts will be made. Fab groups may be delivered to the fabrication location as soon as the group is finished, and assembly on that group can begin as soon as the entire group is completed and delivered. For a candidate group that encompasses the entire day’s production however, the entire group must be processed in the fabrication area before complete deliveries can be made to the delivery locations and thus necessitates far more work-in-process and a much larger decoupling buffer between the sheet metal fabrication process and the assembly processes. Possible nesting strategies are compiled in Table 2.

Table 2: Nesting Strategies Along with the Regions where these Strategies are Available for Use.

<table>
<thead>
<tr>
<th>Nesting Strategies</th>
<th>Region Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication Group</td>
<td>NA, AS</td>
</tr>
<tr>
<td>Cart</td>
<td>NA, EU, AS</td>
</tr>
<tr>
<td>Section</td>
<td>NA, EU, AS</td>
</tr>
<tr>
<td>Unit</td>
<td>NA, EU, AS</td>
</tr>
<tr>
<td>2-Unit</td>
<td>NA, EU, AS</td>
</tr>
<tr>
<td>Shift</td>
<td>NA, EU, AS</td>
</tr>
<tr>
<td>Day</td>
<td>NA, EU, AS</td>
</tr>
</tbody>
</table>

3.4.2 Quantifying Nesting Strategy and the Resulting Raw Material Utilization

To understand which nesting strategy would yield optimum material utilization, some way of relating that strategy to expected utilization is necessary. An appropriate approach would be to design a set of experiments that would allow the effects of nesting strategy on expected utilization to be clearly understood.

The approach followed in this work brings together two effects on material utilization. It is hypothesized that both the product family and the actual nesting strategy both have a significant effect on sheet utilization. As such, a set of experiments was run to see the effect of product family and nesting
strategy on material utilization and determine whether it can be modeled. The desired outcome would be a mathematical model featuring material utilization as a function of product family and nesting strategy.

3.4.3 Correlating Nesting Strategy and Other Processing Costs

To define a set of boundaries to the selection of an optimum nesting strategy, the effect of nesting strategies on other processing costs outside of material costs should be considered. It is likely that once key factors for improving utilization are understood, these factors can be tuned to reduce material costs, perhaps reaching an asymptotic limit but never reaching a true minimum. However, considering other processing costs is quite important because there may exist some point at which the increase in utilization is outweighed by other cost factors. At this point, the model would reach a true minimum cost that can be used to inform the selection of an optimum nesting strategy.

3.5 Developing a Cost Modeling Methodology

Based on the framework laid out above, the cost model was structured in the following way. First, a utilization model was developed that allowed expected utilization to be predicted for a specific production mix and nesting strategy. From this utilization model, material cost predictions can be made based on the expected annual or order volume. Next, the process model is used to identify other non-material factors influencing the sheet metal fabrication cost. Annual estimated costs arising from these sources will be obtained as additional factors in the cost model. These two cost categories, material and process costs, are summed together to obtain the total annual expected costs expected to change as a result of nesting strategy. Each total annual expected cost are associated with a unique nesting regime and plant location and can be plotted to visualize and determine the nesting strategy that results in the lowest cost.

3.6 Developing a Throughput Modeling Methodology

The development of a throughput model based on the established process model is of great importance to this work. The throughput model serves to indicate the feasibility of low-cost solutions. As such, a highly detailed development of a throughput methodology is presented in the parallel work performed by Vineeth Gowra. [2] Please refer to the parallel thesis on optimizing sheet utilization based on nesting strategy from a throughput perspective for a detailed understanding of the throughput modeling methodology. [2]
3.7 Weighting and Prioritizing Cost versus Throughput

An important question to consider when attempting to select a nesting strategy based on cost and throughput is how the metrics should be weighted against each other when selecting a nesting strategy. An example scenario when this would become quite important is where the optimal nesting strategy from a cost standpoint may perhaps result in a throughput that is less than the demand. In such a scenario, which metric should be considered as priority?

In almost all cases, the throughput model will take priority when it comes to identifying acceptable nesting strategies because ultimately the sheet metal fabrication process within the company must meet demand. If demand cannot be met at a point that is cost feasible, then other steps must be taken to rectify the issue. Thus, the highest priority in identifying acceptable nesting strategies is given to the throughput model.

However, once the throughput rate requirement can be met, it is then entirely up to the cost model to determine the optimal nesting strategy out of the set of acceptably strategies. Once a required throughput rate is met, no additional benefit is gained by outpacing demand. This is especially true for a company that operates under Lean principles since this would result in inventory related waste along with other waste sources from high work in process volumes. Thus, within the set of acceptable nesting strategies identified by the throughput model, the cost model takes priority to identify the lowest cost nesting strategy.
Chapter 4: Development of a Model

4.1 Regional Production Mix

The model development begins with quantifying the production mix in each manufacturing region. The mix was defined based on historical production data that allowed the percentage of each product family produced in the past year to be determined. The outcome of this analysis is given in Figure 6. Product Families produced in NA, EU, and AS are shown with their mix percentage displayed.

As discussed, major product families that contribute significantly to production were chosen for analysis such that the sum of all product families examined constitute most of production. Other insignificant product families are grouped together into a product family category termed “other” that will be considered as a generic family whose attributes are determined by the average attributes of the constituent families. In this way, significant product families were identified that dominate production and together they provide a metric distinguished by unique characteristics.

![Production Mix by Product Family in The North America, Europe, and Asia Regions](image)

Figure 6: Production Mix by Product Family in The North America, Europe, and Asia Regions
These product families shown in Figure 6 provide a good picture of the production mix at each plant location. However, when specifically studying each product family, it is helpful to have specific product units that possess characteristics distinctive of the product family. These specific product units can be viewed as “representatives” by which the characteristics of the whole product family can be understood. Figure 7 shows the product families significant to each region along with certain representative units that were chosen to be used in later studies that characterize the behavior of each product family when it comes to nesting, sheet utilization, and other processing factors. In Figure 7, the relative size of each segment given to the product family and the representative unit gives a qualitative perspective of what percentage of the family the representative unit corresponds to.
Figure 7: Representative Units by Product Family for the North America, Europe, and Asia Regions. The Proportion of the Product Family Represented by the Unit is Indicated by the Size of the Segment

To capture the range of product characteristic possibilities within each product family, the representative units were first chosen to represent the range of characteristics (size, features, and material of construction) that may influence nesting efficiency. Then, the highest volume unit within each feature category was selected as a representative unit. These representative units shown in Figure 7 will be used as samples in subsequent studies, and their behavior in each study will be considered to characterize the behavior of all other units in the product family being represented.
4.2 Modeling Sheet Utilization Based on Product Features and Nesting Strategy

4.2.1 A Design of Experiments to Study Critical Effects on Utilization

To begin understanding in what way the sheet utilization depends on product features and on the nesting strategy, a set of nesting experiments were conducted. The representative units for NA were selected for initial analysis as NA has the broadest production mix. These units were then nested according to all nesting strategies available in NA. From these studies, overall sheet utilization for each representative unit was obtained. Further, as the studies were run at differing nesting strategies, the number of part candidates available in each nest varied as well, as the size of the candidate pool is the primary differentiator between nesting strategies. This allowed for sheet utilization to be compared to the size of the pool of part candidates. Thus, from this initial study, the effect of both the product family and the nesting strategy on sheet utilization can be observed.

Examining the effect of the nesting strategy alone on sheet utilization showed a distinct trend. As nesting strategies changed, the number of candidate parts available for nesting changed. When plotting the resulting experimental sheet utilization against the number of parts in the candidate pool for that particular nest group, the expected utilization is seen to increase in a manner consistent with a decaying growth function. Figure 8 shows the experimental results, in which rapid improvements in utilization may be observed initially as the number of available part candidates increases, but the effect of increasing the number of part candidates decays until an asymptote is reached.

The behavior of the utilization versus nesting strategy data obtained from the nesting experiments demonstrates a form of exponential growth decay. Several models for decaying growth were examined, and their quality of fit was measured by summing the square error between the experimental data and the model data obtained from the curve fit. Of these growth functions, the Gompertz function yielded the lowest overall sum of square error, and visually produced the best data fit. The Gompertz Function is a mathematical function commonly used to model behavior in which an effect saturates over time [16]. The standard form of the Gompertz Function is shown in Equation (2). Using the Solver function in Microsoft Excel, the coefficients of the Gompertz Function may be found to minimize the square error between the experimental data and the model, thus fitting the Gompertz Equation to the experimental data. The resulting model fit is shown also in Figure 8.

\[ f(x) = a e^{-b e^{-c x}} \]  

(2)
From Figure 8, a very clear and recognizable trend in sheet utilization can be observed in which the expected sheet utilization is a function of the number of parts available for nesting. The trend is distinct and recognizable, though some scatter in the data is present at small candidate pools. To distinguish whether the scatter is randomized or whether it is due to some effect of the product family, a further look at the data with respect to product family is necessary. Nonetheless, there appears to be a strong correlation between the number of part candidates available for nesting and the expected sheet utilization.

Figure 9 shows the expected sheet utilization obtained from the RADAN as a function of product family alone. As before, nesting trials were performed on each representative unit within the product family at different nesting regimes. The representative units are plotted together within each family to determine whether the product family has any significant effect on the expected sheet utilization.
Figure 9: Expected Sheet Utilization Plotted against the Product Family from which the Sheet Metal Nests were Derived. ANOVA Analysis on the Raw Data Grouped by Product Family shows that the effect of Product Family Cannot Be Ignored at 95% Confidence.

To determine the effect of product family on sheet utilization, analysis of variance (ANOVA) techniques were used to test the null hypothesis that product family has no effect on the sheet utilization. This methodology is applicable because it is hypothesized that each data point is drawn from a fixed normal distribution, having a defined mean value and error component. These data points have a defined treatment effect from group size, and product family which could shift the underlying distribution if the effect is significant. From ANOVA analysis on the raw utilization data shown in Figure 9, it was determined from that the hypothesis could not be rejected at a 95% confidence interval, thus there appeared to be some statistically significant effect from the product family.

Although statistically the effect of product family seemed significant, it seemed quite possible that the effect of nesting group size might be confounding with the effect of product family. This was considered likely because, first, the significance was just under the 95% confidence level and thus if the product family did have an effect, it was much less pronounced than the group size effect. Second, some product families
contain more parts in each unit on average than other product families, and it was hypothesized that the apparent effect of product family was actually just the effect of group size apparent within the product family rather than true characteristics intrinsic to the product family.

To test this further hypothesis, residuals between the actual utilization values and the modeled utilization given by the Gompertz Fit were examined for product family effects. If the Gompertz Function appropriately models the effect of group size, the residuals would be devoid of any group size effect. ANOVA analysis on the residuals showed that, to a 95% confidence level, the hypothesis that product family has no effect on the expected sheet utilization is accepted. The residuals for each product family are shown in Figure 10.

![Figure 10: Residuals from the Gompertz Fit model for Expected Sheet Utilization Compared to the Actual Experimental Sheet Utilization Predicted by RADAN Nesting Software. The Residuals are Plotted by Product Family to Visualize Possible Product Family Effects. ANOVA Analysis on the Residual Data Grouped by Product Family shows that the effect of Product Family is Insignificant and can be Ignored at 95% Confidence.](image)

Thus, from this set of experiments, statistically it can be seen that the sheet utilization expected from a given nest is not affected by product family characteristics. Sheet utilization can instead be shown to
strongly depend on the size of the part candidate pool, and expected sheet utilization is well approximated by the Gompertz function for decaying growth. Therefore, expected sheet utilization can be modeled purely as a function of nest group size, which is determined by the nesting strategy.

4.2.2 A Note on Sheet Utilization and Part Size Distribution

As a side note, an additional correlation was noted between part size (surface area) distribution, with nesting groups having higher surface area standard deviation demonstrating better utilization than nesting groups having lower surface area deviation. This means that sheet utilization shows some correlation to the standard deviation of part size. This intuitively makes sense when considering nesting as a two-dimensional packing problem. The magnitude of this effect was observed to be of greatest significance at smaller nest group sizes. Although this was an interesting discovery that could improve the overall accuracy of the model, the effect was not considered in this work for some important reasons.

Primarily, part size distribution is not a function of nesting strategy or product family, but rather depends on what portions of the unit could be nested together. To some extent, nesting strategy does effect this, if a small nest group consists of only larger panels while another group may consist of assorted brackets and channels then because of the nesting regime selection one group will demonstrate poor sheet utilization compared to the other. However, if the nesting regime changes to a larger group size these two groups will “merge” together to form a larger group with higher part size deviation and therefore better utilization. This then means that part size distribution is itself a function of the nest group size.

In the model of sheet utilization as a function of nest group size, this effect is visualized as higher scatter in the data at lower group sizes with decreasing scatter as the group size increases. Thus, overall, the effect of part size distribution is only significant in nesting strategies with small numbers of part candidates.

To maintain simplicity in the model, the effect of part size distribution was excluded, however a separate model for part size standard deviation as a function of group size will be considered to account for this effect. In this way, the model can represent the mean or expected sheet utilization and the upper and lower limits as defined by +/- 3σ away from the mean will also be a function of the nesting group size. Thus, the effect of part size deviation will be accounted for by defining the standard deviation as a function of the nest group size and establishing +/- 3σ limits accordingly.
4.2.3 Incorporating Plant Production Data to Obtain a Relevant Model for Sheet Utilization

Based on the framework established by the nesting studies, a model for expected sheet utilization can be developed. From the nesting studies, it is seen that sheet utilization is highly dependent on the size of the nesting candidate group. It is also known that the effect of candidate group size behaves as a decaying growth effect and is well modeled by the Gompertz function. Lastly, it is known that part size deviation within the nest group has an effect on the sheet utilization, but this effect diminishes as the nest group becomes larger and so that upper and lower bounds of the model should likewise be dependent on the nesting group size.

To build the model, production data was obtained for a year’s production in two regions. In this case, the NA and EU regions were selected. Data from the AS region was less available and so was not used to develop the model, but as data availability improves in the future this can be added on top of the available dataset. Shown as green and gray makers in Figure 11, the production Data between the two regions can be seen to overlap. In the EU region, the current nesting strategy results in smaller group sizes compared to the NA region, and so a correspondingly low overall sheet utilization is observed. In a region between groups of 50 and 150 parts, overlap in regional data is observed, further verifying that the expected utilization is a function of group size, and the region has little effect. From this data, a curve fit may be used to develop a model simulating the expected sheet utilization.
Figure 11: Model of Expected Sheet Utilization Developed based on a Gompertz Function fit to Historical Production Data from the NA and EU Regions. The Red Line Represents the Expected Sheet Utilization as a Function of Nest Group Size, while the Black Lines Delineate +/-3σ Bounds. The Blue Shaded Region is a Region wherein Potential Sheet Utilization can be Expected for a Given Nest Group Size. The Blue Vertical Line Represents a Threshold above which the Expected Utilization and the Deviation in Utilization Changes by less than 5% Each Time the Nest Group Size is Increased.

When performing the model fit, it was observed that the fit resulting from using the standard Gompertz equation resulted in a sharp knee that inflated the utilization values in the critical transition region. Additionally, fitting this equation did not allow the function to gently increase to reach an asymptote, but rather forced the model to predict a rigid upper threshold prematurely that was actually lower than the predicted utilization at large group sizes. For this reason, an additional scaling factor was added to improve the fit of the model, reducing the square error between the model and the production data by just over 7%. The modified Gompertz function with the scaling factor is shown below in Equation (3). A comparison of the modified versus the unmodified models are given in Figure 12. A visual inspection of the modified Gompertz fit in Figure 12 as well as from Figure 11 show that this modification does not overfit the model but rather improves the ability of the model to represent the trend in the data.
\[ f(x) = ae^{-bx - cx^d} \]  

Figure 12: A Comparison of Two Model Fit Equations. The First being the Unmodified Gompertz Fit from Equation (2) shown in Blue. The second being the Modified Gompertz Fit from Equation (3) shown in Red. The Sum of Square Error resulting from each Model Fit is also given in the Figure (SSE).

Therefore, the model given by the Modified Gompertz Fit was adopted as a means of approximating the expected sheet utilization for a nest based on the number of candidate blanks available. The coefficients for the Utilization Model are given in Table 1.

Table 3: The Sheet Utilization Model and its Coefficients; Allowing Expected Sheet Utilization to be Determined given the Number of Candidate Blanks Available for Nesting

<table>
<thead>
<tr>
<th>Utilization Model:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f(x) = ae^{-bx - cx^d} )</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>d</td>
</tr>
</tbody>
</table>
Further, upper and lower limits were developed for the model as a function of the number of candidates. The available production data was divided into bins incremented by ten. For example, all nests run that had between zero and ten part candidates were grouped into a single bin, and all nests that had between ten and twenty part candidates were grouped into the next bin. The standard deviation of the sheet utilizations occurring within each bin was calculated, and is graphed alongside the frequency chart, shown in Figure 13. A visual inspection of the utilization standard deviation shown in Figure 13 reveals a power law decay behavior. This fit was confirmed to have a lower sum of square error compared to exponential or polynomial fit equations and was selected for development of a standard deviation model. The coefficients and equation for the utilization standard deviation model is given in Table 4.

Table 4: The Sheet Utilization Standard Deviation Model and its Coefficients; Allowing the Standard Deviation in Sheet Utilization to be Determined given the Number of Candidate Blanks Available for Nesting

<table>
<thead>
<tr>
<th>Utilization Standard Deviation Model:</th>
<th>$\sigma = ax^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.63</td>
</tr>
<tr>
<td>b</td>
<td>-0.775</td>
</tr>
<tr>
<td>x</td>
<td># of Candidate Blanks</td>
</tr>
</tbody>
</table>
Figure 13: A Frequency Table showing the Number of Nests Run of a Given Size Range along with the Standard Distribution of the Utilizations Resulting from the Nest Runs.

Lastly a threshold was identified and is depicted in Figure 11 above which increasing the number of candidate blanks has no appreciable effect on utilization. As observed in Figure, at a group size of 150 parts, the % change of the 1st derivative (the rate of change) of the expected sheet utilization and the standard deviation of the expected sheet utilization both drop below 5%. Thus, at a threshold number of 150 candidate blanks, any increase in group size has minimal effect on the expected sheet utilization.
4.2.4 Modeling Material Utilization as a Function of Nesting Strategy

As seen, the expected utilization of raw materials can be predicted for producing sheet metal blanks. This model is built upon actual production data, and predicts utilization purely as a function of the number of candidate blanks available for nesting. The dependent variable, the number of candidate blanks, is determined by the nesting strategy, as the strategy determines what parts are available for nesting. Because of this, this utilization model presents a means by which the expected sheet utilization can be determined for different nesting strategies.

Translating the model to directly providing material utilization predictions as a function of nesting strategy can be done by identifying the number of parts available to each representative unit in each nesting strategy. Once these representative unit characteristics are identified, the expected utilization for the representative unit may be determined at the given nesting strategy. Further, the expected utilization of each representative unit may be weighted against the production mix in each region to obtain a regional
sheet utilization prediction. In this way, regional sheet metal utilization can be determined for each nesting strategy based on the utilization model and the number of parts expected in each nest group.

4.3 Nesting Strategy and its Effect on Non-Value-Add Costs

4.3.1 The Cost of Part Identification

The selected nesting strategy determines what candidate blanks are available for nesting together. This selection not only affects throughput, it also affects processing cost. As more candidate blanks are made available for packing efficiently on a series of sheets, the complexity of part identification and part handling increases. Moreover, as more candidates from different subgroups are mixed together, each subgroup may not be completed until the entire nest group is processed as members of the subgroup will be randomly distributed throughout the nest group. This means increases in work-in-progress and space limitations must be considered. Thus, many other cost factors must be considered when considering the effects of nesting strategy selection.

One of the largest non-value-add cost factors that should be considered is the effect of nesting strategy on part identification. As discussed earlier, two primary means of identifying sheet metal blanks are in use at the sheet metal fabricator. The first is a manual form of part identification where after the blanks are cut, they are matched to an associated paper traveler which resides in a stack of pages provided at the beginning of the job. This is a highly time-intensive task that provides significant opportunity for error.

Time studies were performed at one of the plant locations to determine the time it takes to identify a part, matching it to its work instruction, as a function of the number of unique part candidates in the system at the time. This was done by compiling the time study data to obtain an average time and the standard deviation of the time per page it takes to compare the paper traveler to the part being identified. This was used to set up series of process simulations in which different sized groups of unique parts were identified by use of a stack of pages containing the part information randomly ordered through the stack. The results of the process simulation are shown in Figure 15. The coefficients of the second order polynomial fit used to model the data is given in Table 5.
Figure 15: Part Identification Time Model Based on a Polynomial Fit of Process Simulation data. The Process Simulation Data was built on Time Studies Performed at a North American Plant

Table 5: The Equation and Coefficients of the Part Identification Time Model Based on a Polynomial Fit of Process Simulation data.

| Model for Part ID using Paper Travelers:          |
|----------------------------------|--------|
| Part ID Time = ax^2 + bx + c       |        |
| a                                | 0.101 X 10^{-3} |
| B                                | 1.581 X 10^{-3} |
| C                                | 0.00    |

The model for part identification time was used to estimate the expected cost effect of part identification. This was accomplished by applying the expected number of unique parts for each representative unit to the model. The number of unique parts per group will change with the nesting strategy as larger part candidate pools are enabled. The part identification times per nest group for the representative units were combined to get the part identification time by representative unit for each nesting strategy. This was then multiplied by the production mix to determine the annual expected time spent in part identification for each nesting strategy. Lastly, cost was obtained by scaling the time value by the capital labor cost established by the sheet metal fabricator.
4.3.2 The Cost of Final Sort

Similar to modeling the cost of part identification, the effect of nesting strategy on the final sorting step in the process was determined by time studies and development of an empirical model. Figure 16 illustrates the final sorting process, where parts that are processed in the final value-add stage (Corner Weld) are then sorted into their respective carts destined for the staging area that serves as an infinite decoupling buffer. Time studies obtained from operating conditions at a plant in NA were undertaken for sorting identified finished parts into sets of delivery carts. The results were used to build a model predicting the cost of final sorting as a function of the nesting strategy, that dictates the number of cart options available.

![Diagram Depicting Final Sort Process](image)

**Figure 16: Diagram Depicting Final Sort Process wherein Parts from the Corner Weld Stage are Placed into the Correct Final Delivery Cart**

The results of the time studies are presented in Figure 17. The time required for the final sort follows a linear trend in that the sorting time required per part is a function of the number of carts available to choose from. This trend incorporates two effects that must be understood. First, the special effect of increasing the number of carts contributes to the strong linear trend. As the number of delivery carts increases, the time it takes for an operator to walk to the cart and deposit the parts also increases on average over a sample number of parts. This is because the time it takes to travel from the processing station to the cart position also increases. Second, there is an increase in decision-making time, as a higher
number of potential carts exist for matching with a part. This decision-making time would potentially add nonlinear effects as the number of carts increase. However, within the scope of the potential number of carts required by the nesting strategies studied, the time effect of increased choices is minimal against the travel time, and thus the linear behavior of the time model dominates.

Since a linear model fit well fits the time required for final part sorting as a function of the nesting strategy, which is what drives the number of carts required, a linear model was adopted. The equation and coefficients of the model are provided in Table 6. Using this equation, the number of carts required for each nesting strategy can be used to determine the time requirement of the final cart sort. This time requirement can then be scaled by the capital labor cost to obtain the total cost incurred at each nesting regime by this non-value-add step.

![Figure 17: The Results of the Time Study for Sorting Finished Parts into Delivery Carts. The Datapoints Exhibit a Linear Trend with Cart Increase](image)
Table 6: The Equation and Coefficients of the Final Cart Sort Time Model Based on a Linear Fit of Time Study Data

<table>
<thead>
<tr>
<th>Model for Final Sort:</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Final Sort Time = mx + b</em></td>
</tr>
<tr>
<td>( m )</td>
</tr>
<tr>
<td>( b )</td>
</tr>
</tbody>
</table>

4.3.3 The Cost of Kitting

At the kitting stage, in which the raw sheet steel required is picked from inventory to form a kit, the processing time required is largely dependent on the number of sheets in the job. A fairly constant start-up time and delivery time are present for this stage, and there exists a constant time to pick each raw sheet. Thus, the kitting time required can be modeled as a function of the number of sheets required.

The kitting time at different nesting strategies can be determined by the number of sheets required at the different nesting strategies. As the overall material utilization improves, the number of sheets required decreases. However, as already discussed, the increasing the group size by changing the nesting strategy has diminished effect on expected utilization. For this reason, the decrease in number of sheets required will also have a diminished effect. Kitting time is thus a function of the group size that has diminished effect on the time required as the group size increases.

The actual model for kitting time is built upon the nesting studies performed that give averages of the number of parts per sheet expected for each nesting strategy. Production averages are obtained by averaging the number of parts per sheet expected for each representative unit. When plotted as shown in Figure 19, it can be seen that a logarithmic fit well approximates the change in parts per sheet expected from each nesting strategy, and can be extrapolated to larger nest group sizes using the model. The parts per sheet can be multiplied by the pick time per sheet obtained from time studies, and the constant setup times can be added on to obtain a complete picture of the kitting time required as a function of the nesting strategy.
Figure 18: Expected Part per Sheet Density that can be Used to Calculate the Kitting Cost for Each Nesting Strategy. The Model Features Group Sizes up to a Unit in Size, but can be Extended to Multi-Unit Nesting Strategies.

4.3.4 The Cost of Remade Parts

A final but significant cost that must be considered is the cost of errors resulting in parts that must be made over again. Some causes of such remake errors that have been identified and logged by the sheet metal fabricator are brake press errors, corner weld errors, and missing parts. Production logs recording remake causes and their frequencies are available for two nesting strategies: nesting in two-cart groups and nesting by complete section. These remake frequencies are given in Table 7, and shown graphically in Figure 19.

Table 7: Production Logs from Two Years of Data, Each Year of which was Entirely within a Given Nesting Strategy

<table>
<thead>
<tr>
<th>Recorded Parts Requiring Remakes (% of Total Parts Produced)</th>
<th>Nest by Two-Cart Group</th>
<th>Nest by Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake Errors</td>
<td>0.24%</td>
<td>0.33%</td>
</tr>
<tr>
<td>Weld Errors</td>
<td>0.11%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Misplacement Errors</td>
<td>0.39%</td>
<td>0.48%</td>
</tr>
</tbody>
</table>
Several observations and some critical conclusions may be made drawn from this production data. First, a significant increase in errors occurred in conjunction with the change in nesting strategy. From discussion with plant supervisors and operators, an appropriate assumption would be that this increase is due to the change in nesting strategy and is not confounded with other factors that may have affected the plant process. Thus, a distinct trend may be observed with larger nest groups resulting in more potential for error. Second, while the processing errors at the brake and the percentage of missing parts increases, the processing errors at the weld stage remained constant. At the plant where this data was drawn, the parts are identified first prior to the brake press and then manually marked before being send to the corner weld station. Because of this, an increase in processing errors does not occur between the two nesting strategies because the work to identify the parts and the potential for error largely occurs prior to or at the brake press rather than prior to or before the weld area. In summary, a significant increase in expected processing errors would occur when moving to a larger nesting strategy at the brake press and when dealing with missing parts.

Because remake data currently exists for only two nesting strategies, it is assumed that the potential for error increases linearly with the size of the part candidate pool. However, as more data is collected for other nesting strategies, this assumption should be reevaluated to see if another model fit may better represent the data. For this study and the scope of the current work, a linear model will be considered to
be the best representation of the data trend. The coefficients of the linear model are presented in Table 8. The model was chosen to be a function of the number of carts in the delivery group, as this is a representation of the size and complexity of the nesting group when it comes to missing parts. Although this may not be the most ideal metric for use in modeling brake errors, it still represents the size and complexity of the nest group driven by the number of brake errors.

Table 8: The Equation and Coefficients of the Model for Remade Parts Based on a Linear Fit of Production Log Data

<table>
<thead>
<tr>
<th>Model for Remade Parts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Remakes = (mx + b)</td>
</tr>
<tr>
<td>m (= 0.101 \times 10^{-3})</td>
</tr>
<tr>
<td>b (= 1.581 \times 10^{-3})</td>
</tr>
<tr>
<td>x (=) Number of Carts in the Group</td>
</tr>
</tbody>
</table>

4.3.5 The Cost of Underutilizing Materials when Producing Aftermarket or Remade Parts

Another consideration that must be accounted for when modeling the cost of remade parts is the cost associated with quick turnaround. Because a missing part significantly disrupts assembly, it is necessary to reproduce parts quickly. According to plant logs and discussion with plant supervisors, remade parts are often nested together in groups ranging from one to 75 parts. Aftermarket parts production are often mixed in with the remake parts to result in larger nest groups, but despite this, the average batch of remade and aftermarket parts remains around twelve parts. According to the utilization model, nest groups consisting of 12 candidate parts can be expected to have a utilization of around 60%, much less than that achievable by standard production nesting. Thus, remake and aftermarket parts are produced at lower efficiency compared to production parts.

4.4 Nesting Strategy and its Effect on Throughput

The thesis published by Vineeth Gowra in parallel with this work on cost development is critical for a thorough understanding of the effect of nesting strategy on throughput [2]. In this work, it is shown that throughput increases slightly with larger nesting groups due to decreased setups required at the cutting operation since that is the bottleneck stage. However, when manual part identification and sorting occurs, the bottleneck shifts in a way that decreases throughput after parts are nested in 2-unit groups. Please refer to this work for a more detailed perspective on the ways the nesting strategy affects throughput.
4.5 Consolidating Subsidiary Models into Cost and Throughput Models

4.5.1 Cost Equations and Inputs from Subsidiary Models

The specific effects of nesting strategy on fabrication cost from a global perspective can be obtained by overlaying the results of the various subsidiary models which impact cost. These models, discussed already in this ``, outline the specific cost effect of nesting strategy on all points in the process model which are affected by the selection of nesting strategy. The costs predicted from these can then be summed to get a picture of how the cost changes with nesting strategy selection. This is represented mathematically in Equation (4), and variable definitions are given in Table 9.

\[
Cost = C_{MP} + C_{MA} + C_{MR} + C_K + C_{ID} + C_{FS} + C_{RL}
\]  

(4)

Table 9: Variable Definitions for Equation (4)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{MP})</td>
<td>Cost of Materials for Parts Required for Production</td>
</tr>
<tr>
<td>(C_{MA})</td>
<td>Cost of Materials for Aftermarket Parts</td>
</tr>
<tr>
<td>(C_{MR})</td>
<td>Cost of Materials for Remade Parts</td>
</tr>
<tr>
<td>(C_K)</td>
<td>Labor Costs Associated with Kitting</td>
</tr>
<tr>
<td>(C_{ID})</td>
<td>Labor Costs Associated with Part Identification</td>
</tr>
<tr>
<td>(C_{FS})</td>
<td>Labor Costs Associated with the Final Sort</td>
</tr>
<tr>
<td>(C_{RL})</td>
<td>Labor Costs Associated with Parts that must be Remade</td>
</tr>
</tbody>
</table>

It should be reiterated that this approach considers only costs which are affected by the selection of nesting strategy, and this model makes no claim on the total fabrication cost. Rather, it consolidates the costs which will vary as a function of nesting strategy to allow for the expected change in cost to be obtained. Costs which are not a function of nesting strategy are not considered in this analysis. This approach allows claims to be made on cost changes expected from adjusting nesting strategy rather than focusing on the actual total cost.

Material cost of standard unit production \((C_{MP})\) is presented in Equation (5). Here, the total weight of parts produced in a fiscal year is divided by the production utilization expected from a given nesting strategy. The means of determining the expected production utilization is given in Equation (6). The total weight of parts produced in the fiscal year divided by the production utilization is equivalent to the
purchased material required to produce the parts. This can be multiplied by the cost of the material to calculate the total cost of production materials. The cost of material is then weighted by the material mix if multiple materials of construction are used.

\[
C_{MP} = \frac{W_{\text{parts}}}{U_{\text{production}}} \cdot M_{\text{cost}} \tag{5}
\]

\[
U_{\text{production}} = \sum_{i=1}^{N_{\text{groups}}} a_G e^{-b_G x_i} e^{-c_G x_i} e^{-d_G x_i} \cdot \%_{\text{mix}_i} \tag{6}
\]

Table 10: Additional Variable Definitions for Equations (5) and (6)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W_{\text{parts}})</td>
<td>The weight of all production parts for the analysis period</td>
</tr>
<tr>
<td>(U_{\text{production}})</td>
<td>The expected sheet utilization for production</td>
</tr>
<tr>
<td>(M_{\text{cost}})</td>
<td>The cost per unit measure of raw materials</td>
</tr>
<tr>
<td>(N_{\text{groups}})</td>
<td>The number of groups required by the nest strategy</td>
</tr>
<tr>
<td>(x_i)</td>
<td>The size of the (i^{th}) group in the nesting strategy</td>
</tr>
<tr>
<td>(%_{\text{mix}_i})</td>
<td>The production mix percentage of the (i^{th}) group</td>
</tr>
<tr>
<td>(a_G)</td>
<td>The 1(^{st}) coefficient of the Utilization model</td>
</tr>
<tr>
<td>(b_G)</td>
<td>The 2(^{nd}) coefficient of the Utilization model</td>
</tr>
<tr>
<td>(c_G)</td>
<td>The 3(^{rd}) coefficient of the Utilization model</td>
</tr>
<tr>
<td>(d_G)</td>
<td>The 4(^{th}) coefficient of the Utilization model</td>
</tr>
</tbody>
</table>

Next, Equation (7) presents a means for calculating the material cost of aftermarket parts production. Here, the total weight of aftermarket parts produced in a fiscal year is divided by the utilization of material run in “quick response" batch sizes, which are generally batches of 12 parts as discussed earlier. Equation (8) then also shows the cost of producing parts in “quick response” batches such as would occur when remake parts are required. In this case, the total volume of parts produced, both production and aftermarket, is multiplied by the expected percentage of errors that require the parts to be remade. The expected utilization of quick response batch sizes is shown in Equation (9).

\[
C_{MA} = \frac{W_{\text{aftermarket}}}{U_{\text{Quick Response}}} \cdot M_{\text{cost}} \tag{7}
\]
\[ C_{MR} = \frac{\%_{\text{remakes}} \cdot (W_{\text{parts}} + W_{\text{aftermarket}})}{U_{\text{Quick Response}}} \cdot M_{\text{cost}} \]  

(8)

\[ U_{\text{Quick Response}} = a_G e^{-b_G e^{-c_G x_{QR} d_G}} \cdot \%_{\text{mix}_t} \]  

(9)

Table 11: Additional Variable Definitions for Equations (7), (8) and (9)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{aftermarket}} )</td>
<td>The weight of all aftermarket parts for the analysis period</td>
</tr>
<tr>
<td>( U_{\text{Quick Response}} )</td>
<td>The Expected Utilization of a Quick Response Batch Size</td>
</tr>
<tr>
<td>( %_{\text{remakes}} )</td>
<td>The Percent of Total Production Attributable to Remakes</td>
</tr>
<tr>
<td>( x_{QR} )</td>
<td>The Batch Size for Quick Response Groups (Fixed Size)</td>
</tr>
</tbody>
</table>

Moving on to non-value-add costs, the cost of part identification time when using manual part identification methods discussed in this work is given in Equation (10), with supplemental definitions listed in
Table 12. In Equation (10), the model for identification time as a function of the number of pages is used to determine the identification time required for a given unit. This is calculated for each group of each representative unit defined in the production mix and then weighted by the percentage of the total mix represented by that group within the unit. This process gives an expected identification time per unit, which may be scaled by the number of units produced in a fiscal year and the capital labor cost to achieve the total part identification cost.

\[
C_{ID} = \left( \sum_{i=1}^{N_{\text{groups}}} \left( a_{ID} \cdot N_{pages_i}^2 + b_{ID} \cdot N_{pages_i} + c_{ID} \right) \cdot \%_{\text{mix}_i} \right) \cdot N_{\text{units}} \cdot L_{\text{cost}}
\]
Table 12: Additional Variable Definitions for Equation (10)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{pages}}_i$</td>
<td>The number of work instruction pages in the $i$th group</td>
</tr>
<tr>
<td>$N_{\text{units}}$</td>
<td>The number of units produced</td>
</tr>
<tr>
<td>$L_{\text{cost}}$</td>
<td>The labor cost for each time unit of measure</td>
</tr>
<tr>
<td>$a_{ID}$</td>
<td>The 1st coefficient of the part ID polynomial model</td>
</tr>
<tr>
<td>$b_{ID}$</td>
<td>The 2nd coefficient of the part ID polynomial model</td>
</tr>
<tr>
<td>$c_{ID}$</td>
<td>The 3rd coefficient of the part ID polynomial model</td>
</tr>
</tbody>
</table>

A similar procedure is followed for determining the cost of kitting at the given nesting regime, shown in Equation (11), again with supplemental definitions provided in Table 13. The number of sheets required for each group in each representative unit is determined by the sheet metal nesting algorithm in use. This is weighted against the percentage of the production mix attributed to the representative unit and to the group within the representative unit. The constant pick time per sheet is multiplied into this number, and the constant setup time is added. This represents the total kitting time expected for a single unit, which can be multiplied by the number of units produced in a fiscal year and the capital labor cost to get the total cost of kitting.

$$C_K = \left( T_{\text{setup}K} + T_{\text{pick}K} \cdot \sum_{i=1}^{N_{\text{groups}}} N_{\text{sheet}i} \cdot \%_{\text{mix}i} \right) \cdot N_{\text{units}} \cdot L_{\text{cost}}$$

(11)

Table 13: Additional Variable Definitions for Equation (11)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{setup}K}$</td>
<td>Setup Time per Job for the Kitting Operation</td>
</tr>
<tr>
<td>$T_{\text{pick}K}$</td>
<td>Pick Time per Sheet for the Kitting Operation</td>
</tr>
</tbody>
</table>

The cost of the final sorting process along with variable definitions is shown in Equation (12) and Table 14. Here, the model for the final sorting process is used to determine the sorting time for the nesting group as a function of the number of carts required. The number of carts required may be determined from the number of delivery locations required for delivering all the parts within the group to the assembly area. This yields the expected sorting time per part that can be scaled by the number of parts in the group, and
then the total time for all the groups in a unit are added up for the nesting strategy. This is multiplied by the number of units and the capital labor cost to achieve the total cost of the final sorting step.

$$C_{FS} = \left( \sum_{i=1}^{N_{groups}} \left( m_{FS} \cdot N_{carts_i} + b_{FS} \right) \cdot N_{parts_i} \right) \cdot N_{units} \cdot L_{cost}$$  \hfill (12)

Table 14: Additional Variable Definitions for Equation (12)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{carts_i}$</td>
<td>The number of final delivery carts in the $i^{th}$ group</td>
</tr>
<tr>
<td>$N_{parts_i}$</td>
<td>The number of parts in the $i^{th}$ group</td>
</tr>
<tr>
<td>$m_{FS}$</td>
<td>The 1$^{st}$ coefficient of the final sorting process linear model</td>
</tr>
<tr>
<td>$b_{FS}$</td>
<td>The 2$^{nd}$ coefficient of the linear model for final sorting</td>
</tr>
</tbody>
</table>

Lastly, additional cost is incurred for remake in terms of labor required that goes beyond simply the material cost of each remake. This is represented by a constant labor cost per remake that has been studied and quantified by the sheet metal manufacturer and provided for use in this work.

$$C_{RL} = %_{remakes} \cdot (W_{parts} + W_{aftermarket}) \cdot L_{perRemake}$$ \hfill (13)

Table 15: Additional Variable Definitions for Equation (13)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$%_{remakes}$</td>
<td>The percent of all parts produced needing to be remade</td>
</tr>
<tr>
<td>$L_{perRemake}$</td>
<td>The labor requirement per remake</td>
</tr>
</tbody>
</table>

4.5.2 Modeling the Effect of Nesting Strategy on Global Cost

Global costs are presented first, which represent the combination of costs arising from each region's representative plant. The costs are combined as an average weighted against the percentage of total volume attributed to each plant. This allows for the effect of regional conditions to be scaled to match
their global significance. An example of this would be the labor cost effect of production in a high cost labor region such as EU or a low cost labor region such as AS. As seen in Figure 20, each region contributes toward global production at different magnitudes, so the region’s effect on the global cost should be scaled accordingly. For confidentiality, the specific regions are not labeled in the figure.

![% of Global Volume Attributed to Each Region](image)

*Figure 20: The Percentage of Global Production Volume Attributable to Each Region. Region Captions Obscured for Confidentiality.*

When global costs derived for each relevant cost effect are overlayed for each nesting strategy being studied, the resulting cost models shown in Figure 21 and Figure 22 are obtained. In these models, the cost of raw materials, the cost of remake parts both in materials and in labor, the cost of kitting, the cost of part identification, the cost of final sorting, are considered. Together, these costs encompass the costs presented by the process model presented in Figure 3 that are expected to change as a result of changing nesting strategy. Thus, when changes are made to a nesting strategy, the difference in cost between the existing nesting strategy and the new nesting strategy given by the model will be equivalent to the expected change in total cost. It should be noted that the upper and lower bounds of the cost axis are provided for providing a sense of magnitude, but precise financial information is obscured for confidentiality.
Figure 21: Global Cost Model Representing the Costs that are Affected by Nesting Strategy Choice for conditions in which Manual Part Identification is in Place. Nesting Parts Together by Section is Shown to Yield the Optimum Cost for this Set of Conditions. The Throughput Model is Overlaid in Parts Produced per Hour per Fabrication Line.
Figure 22: Global Cost Model Representing the Costs that are Affected by Nesting Strategy Choice for conditions in which Automated Part Marking is in Place. Nesting Parts Together in Groups of 2 Units is Shown to Yield the Optimum Cost for this Set of Conditions. The Throughput Model is Overlayed in Parts Produced per Hour per Fabrication Line.
Additionally in Figure 20 and Figure 21, the throughput model is presented in red, showing expected parts per hour from a single manufacturing line. This is overlayed with the cost model to identify at what nesting strategies the throughput begins to drop as a result of increased non-value-add labor requirements. Nesting strategies where throughput has not decreased are available for consideration, but when the throughput begins to drop a nesting strategy would be considered infeasible even if it were promising cost savings.

In the models, dashed line represents the summation of all material costs, both for the new part production (blue) and the remake materials (pink). This line represents the cost of all purchased steel. The dotted line on the other hand represents the theoretical minimum material cost attainable is all parts were produced at the utilization predicted by the model and no remakes were required. This allows for a means of comparing the current process with a theoretically achievable lower bound to material cost.

The optimum nesting strategy from a cost perspective is indicated by the black diamond. At this point the cost savings of improved utilization resulting from increasing the candidate group size intersects with the increased costs arising from this move. From a global perspective then, the nesting strategy indicated by the lowest cost indicator is the optimum nesting strategy to adopt provided that the throughput does not begin to decrease at this point.

4.6 Observed Regional Differences

In addition to a global perspective on cost, cost models specific to the operating conditions in each region were compiled. This allows for an understanding of the optimal nesting strategy specific to each for each global region. The cost and throughput models for NA is given in Figure 23, Figure 24 presents the cost and throughput models specific to EMEIA, and the cost and throughput models specific to AS is shown in Figure 25. These incorporate certain regional considerations such as the use or lack of automated part marking, differences in aftermarket production volumes, and other such differences.
Figure 23: North America (NA) Regional Cost Model for Sheet Metal Fabrication Incorporating Costs Specifically Affected by the Nesting Strategy with Regional Operating Conditions Considered. Nesting Parts Together as a Section is Shown to Yield the Optimum Cost for this Set of Conditions. The Throughput Model is Overlayed in Parts Produced per Hour per Fabrication Line.
Figure 24: Europe (EU) Regional Cost Model for Sheet Metal Fabrication Incorporating Costs Specifically Affected by the Nesting Strategy with Regional Operating Conditions Considered. Nesting Parts Together in Unit Groups is Shown to Yield the Optimum Cost for this Set of Conditions. A Throughput Model is Overlaid in Parts Produced per Hour per Fabrication Line.
Figure 25: Asia (AS) Regional Cost Model for Sheet Metal Fabrication Incorporating Costs Specifically Affected by the Nesting Strategy with Regional Operating Conditions Considered. Nesting Parts Together in Groups of 2 Units is Shown to Yield the Optimum Cost for this Set of Conditions. A Throughput Model is Overlaid in Parts Produced per Hour per Fabrication Line.
In addition to the specific features pointed out for the global models, the regional models present actual reported material consumption measured in lbs. of steel purchased at specific nesting strategies. In NA, one year’s worth of production data was available for the 2-cart nesting scenario and another year’s worth of production data was available for the section nesting strategy. The actual materials purchase cost is shown in Figure 23 and can be compared to the cost model predictions. The same can be done for the Section nesting strategy in EU and for the Unit nesting strategy in AS.

Key operating conditions for each region that are considered in the model are given in Table 16. These conditions, in addition to differences in production mix and how that effects the expected cost, drive the differences in curve quality and shape between Figure 23, Figure 24, and Figure 25.

Table 16: Operating Conditions Specific to Each Global Manufacturing Region that would Influence Cost

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>NA</th>
<th>EU</th>
<th>AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Nesting Strategy</td>
<td>Section</td>
<td>Section</td>
<td>Unit</td>
</tr>
<tr>
<td>Inventory Condition</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td>Part Marking</td>
<td>Manual</td>
<td>Manul</td>
<td>Auto</td>
</tr>
<tr>
<td>Remnant Consumption</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Production Logging</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Chapter 5: Results and Discussion

5.1 Observations and Key Take-aways from the Cost Model

5.1.1 Diminishing Returns on Increasing Group Size

Considering both the utilization model shown in Figure 11 and the global cost model presented in Figure 21, it is immediately apparent that diminished returns exist for increasing group sizes. From Figure 11, it is seen that a threshold exists at group sizes of about 150 part candidates above which larger groups have no significant effect on utilization. When looking at the cost model presented in Figure 21, it may be observed that only insignificant improvement in utilization results from shifting the nesting strategy from nesting by section versus nesting by unit versus nesting by two units. This diminished return in cost savings is attributed to the size of nests increasingly crossing the 150 part threshold as the nesting groups change above the section level.

When studying the production mix, it can be seen that only 10% of the units produced globally have less than 150 parts in the unit. Furthermore, small units that would be at or under the 150 part range would be considered single section units, and two-section units would be double the parts. Thus, for both section and unit nesting, only 10% of products produced would experience any benefit from moving to a nesting strategy above nesting by section.

Understanding the threshold effect that group size has on expected sheet utilization is critical to selecting an optimized nesting strategy. Based on the current production mix at the sheet metal fabrication facilities across the three regions, at the nest by section and nest by unit strategies, 90% of groups will be above the critical threshold. In grouping two units together, additional utilization is achieved, where units less than 150 parts can be combined with other units to cross the critical threshold. By the time nesting by shift and nesting by unit is reached, enough units are grouped together than the chance of encountering a group of parts less than the threshold is insignificant.

Thus, purely based on the thresholding effect, any nesting strategy above the 2-unit level would result in virtually no change in expected utilization. Proper pairing of units together within the typical flow of production could further ensure that the utilization threshold is reached by matching a small unit with a larger unit. Even disregarding other cost effects, it can be seen that nesting groups larger than 2 units of parts together has virtually no effect on expected utilization.
5.1.2 Underutilized Raw Materials

The difference between the actual total material cost indicated by the dashed lines versus the theoretical minimum cost indicated by the dotted line in the cost model represents additional material costs arising as a result of process inefficiencies from under-utilizing materials. Under utilizing material is a significant problem contributing to higher cost and should be further studied to understand the source of the inefficiency.

As observed in the NA and EU cost models, the predicted material consumption matches the actual material consumption at the plant locations for the nesting strategies that have historical data available. Figure 23 shows the actual material consumption for two-cart and section nesting strategies, that match quite well with the cost models predicted material consumption. The same can be observed in Figure 24 for EU. Significantly less data was available for the AS region, and thus some assumptions were made that potentially do not reflect the reality in AS that resulted in the slight difference observed in Figure 25 between the model’s prediction and the actual recorded utilization in AS. However, the actual consumption data is also similar to the cost model results for this region.

Because the cost model is verified by actual material consumption data, the cost factors that form the model can be accepted with a fair degree of certainty. The difference then between the theoretically achievable minimum utilization and the actual observed utilization lies in the utilization drop for aftermarket and remake parts production as well as the disposal of scrapped parts made incorrectly. The theoretical minimum material cost is obtained by the total materials required if every part were made correctly at the expected throughput for the selected nesting strategy. The actual material cost however incorporates the fact that remade parts and aftermarket parts are made in smaller batches with poor utilization. If the batch size of aftermarket and remade parts were the reach the utilization threshold group size, the theoretical and actual material cost models should match as at this point the aftermarket and remade parts would be produced using the same production utilization.

Thus, a key takeaway from this is that significant underutilization results from batching aftermarket and remade parts in small “quick response” batches. In Europe, as seen in Figure 26, this results in nearly a 10% drop in efficiency, as 20% of the total production volume consists of aftermarket parts that are produced along with remade parts in small batches. Significant opportunity for scrap reduction exists in increasing the batch sizes of such parts to improve the expected material utilization.
5.1.3 The Cost and Frequency of Remakes Drives the Nesting Strategy Selection

In the global cost models presented in Figure 21 and Figure 22, it can be seen that the cost of processing errors resulting in remade parts is a significant cost effect of the nesting strategy selection. In Figure 21, the material effect alone causes the material cost curve to increase after nesting by section.

Unfortunately, the cost effect of the nesting strategy is one of the less understood effects in this model as data has only been able to be collected at a single plant for two nesting strategies. If, instead of a linear correlation, the percentage of processing errors followed some diminishing growth function, this effect may not prove to be as severe at the larger nesting strategies. However, what is clear from the data is changing nesting strategies from nesting two carts of parts together to nesting an entire section together resulted in a 0.2% increase in remade parts. Combined with the fact that remade parts are produced at significantly lower utilization, this effect is more than sufficient to render the change of nesting strategy from section to unit to be pointless if it holds true for the extrapolated region.

More data will need to be collected and sets of experiments will need to be run over extended time periods to build out a reliable and accurate model of the effect of nesting strategy on remade parts. However, based on the data that is available, increasing complexity seems to increase the number of errors that incurs a high enough cost to diminish any material savings obtained by increasing the nesting strategy beyond nesting parts in a section together.
5.1.4 Larger Nesting Groups and Better Utilization Enabled by Automated Part Marking

The implementation of automated part marking at global facilities is an exciting future state that could reduce the non-value-add production costs of larger nesting strategies. Automated part marking allows parts to be instantly identified and allows for a permanent link to relevant work instructions. This means that the cost effect of part identification time drops to a constant value for all nesting strategies. Additionally, the potential for processing errors which is driven by the increased complexity of more part candidate choices would be significantly mitigated as much less opportunity exists for misidentification and for sending parts to the wrong delivery area. This is because parts may quickly and easily be identified repeatedly throughout the fabrication process. Part marking opens the opportunity for improvements in utilization by the selection of nesting strategy that is less impaired by the cost effect of part identification and processing errors.

Figure 22 shows a potential cost model in which automated part marking is applied to global production. In this scenario, nesting of two units is seen as the optimal nesting strategy. As discussed, nesting by two units allows for small units under the utilization threshold to be grouped together, ensuring that no part candidate groups are nested that are below the utilization threshold. Because part marking is implemented, the cost of remakes remains constant at the recorded processing errors percentage obtained from the 2-cart nesting strategy, the lowest nesting strategy studied by the sheet metal fabricator. Thus, nesting by two units is optimal when automated part marking is implemented.

5.2 Nesting Strategy and its Effect on Throughput

The throughput models predicting the rate at which parts are produced in the fabrication process is important to consider when selected an optimal nesting strategy. As discussed, an optimal nesting strategy selected from a cost perspective is only valid if the throughput required by the downstream assembly process can be achieved. Because of this, eligible nesting strategies must be selected based on throughput prior to selecting the lowest cost nesting strategy.

Regional plant locations have historically nested by 2-cart groups as a nesting strategy, and thus this is taken as a baseline for acceptable throughput. Nesting strategies that present an increase in throughput from this point will be considered acceptable, but nesting strategies that demonstrate a drop in throughput relative to this strategy will require further validation before they may be implemented. The throughput achieved by the 2-cart nesting strategy will be taken as a baseline, and a directional
comparison of other throughput results will be examined to see which strategies result in and increase in
throughput and which result in a decrease.

From the global models presented in Figure 21 and Figure 22 for manual and automated part
identification respectively, it can be observed that throughput in both cases increases moderately as with
the larger nest groups up until two units are grouped together. This increase in throughput is attributed
to the reduced setups required at the cutting operation as fewer sheets are required due to higher
utilization. Thus, for both manual and automated part identification conditions, moving from 2-cart
nesting strategy to the 2-unit nesting strategy is acceptable from a throughput standpoint because it
offers an overall increase in throughput.

However, after grouping parts together in 2-unit groups, the laser operation is no longer the
bottleneck when manual part identification is used. For manual part identification, the throughput
begins to drop as handling time required increases. This means that nesting strategies involving groups
larger than 2 units require more intensive validation before they may be considered viable when manual
part identification is in use.

A nesting strategy at 2 units is viable when automated part marking is implemented because the
non-value-add handling time is greatly reduced with properly applied part marking techniques. Thus, the
cutting device will remain the bottleneck with increasing part group sizes. When automated part
marking is used, throughput does not need to be considered as nesting groups increase.

5.3 Selection of an Optimized Nesting Strategy for Application in Global Manufacturing

Although this model can be applied to specific regions and specific plant conditions to obtain an
optimum nesting strategy tailored to reach facility, significant benefit exists in selecting an optimized
nesting strategy that may be applied globally to every facility. The reasons for this have already been
discussed, and thus some care should be given to the selection of an optimum nesting strategy.

From the cost models presented in Figure 21 and Figure 22, it can be seen that the selection of an
optimum nesting strategy is dependent upon the part marking condition. If globally available automated
part marking is implemented, nesting by larger groups up to 2-unit groups is optimum. However, if manual
part identification is in use, nesting by section offers the lowest cost.

This conclusion is proven out to some extent by the operating conditions of the representative plant
locations for the global regions. At the NA and EU facilities, part identification is done manually by paper
travelers, and they currently nest by section at these facilities. In NA, nest by section is predicted to be the optimal nesting strategy in Figure 23. In EU on the other hand, although nest by unit is predicted to be the optimal strategy in Figure 24, it should be noted from the production mix that the units produced in EU are significantly smaller on average than in NA, thus requiring a larger group in order to cross the utilization threshold. Although this is the case, the additional cost incurred in NA by changing to unit nesting would far outweigh the cost reduction in EU by moving to unit nesting. This validates the recommendation that nest by section is the globally optimized nesting strategy for regional conditions incorporating plant marking.

In the AS region, some rudimentary part marking is in fact in use, and they currently group parts together by unit nests or even by 2- or 3-unit nests. In doing so, the AS region achieves better scrap rates compared to other global regions which do not incorporate part marking. As seen in Figure 25, the regional cost model follows the same trend as the global cost model, where the introduction of part marking reduces handling costs to allow for the cost savings of 2-unit nest groups to be realized.

Therefore, if automated part marking is not implemented, nesting by section is the optimized nesting strategy for global deployment. However, if automated part marking is implemented, material savings may be realized by nesting groups up to 2 units worth of parts together.
Chapter 6: Conclusion

In this work, the effect of nesting strategy on the cost and throughput of sheet metal fabrication was examined. A mathematical model for utilization as a function of the number of part candidates available for nesting was developed that was used to provide the expected utilization for a variety of available nesting strategies. Further, models for other non-value-add costs were produced where cost is a function of the nesting strategy selection. From these, a cost model was developed allowing for the identification of an optimized nesting strategy. This was achieved by balancing improved material utilization with the increased non-value-add cost of dealing with the complexity of larger nest groups. It was discovered that two globally optimized solutions were possible, depending on key operating conditions. When automated part marking is implemented, large nest groups are possible consisting of all parts necessary for one or two large assemblies. However, when automated part marking is not implemented, a medium nest group is optimum, consisting of the parts required for a section of the large assembly. Additional takeaways from this study include the importance of structuring the nesting strategy such that the minimum group size achieved is above the threshold provided by the utilization model, the importance of considering the batch size of aftermarket and remade parts and its effect on overall material utilization, and benefits offered by the deployment of automated part marking. This study resulted in the selection of two globally relevant nesting strategies, one where manual a method for part identification is the predominant plant processing condition, and another where automated part marking is considered. For automated part marking, nesting together all parts required by 2 assembly units yields optimal cost without experiencing a drop in throughput. For manual part marking, nesting by section is the optimal operating condition.
References


[15] *Steel Prices & Indices*.