

Aerospace Automated Drilling and Fastening Technology Product Selection Framework

by
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B.S.E. Mechanical Engineering, University of Michigan, 2012

Submitted to the MIT Sloan School of Management and the Department of Aeronautics and Astronautics Engineering in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Aeronautics and Astronautics Engineering

In conjunction with the Leaders for Global Operations Program at the
Massachusetts Institute of Technology

June 2019

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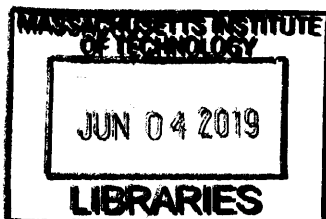
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Abstract

Ascent Aerospace is a global tooling and factory automation supplier for the Aerospace industry. Ascent's customers are typically introducing automation for the first time, or have already introduced automation to their production systems and are wary of its challenges. Choosing the appropriate technology is essential in ensuring successful implementation for both Ascent's customers and Ascent itself.

Ascent has two different business units that produce equipment to automate the drilling and fastening of aerospace structures. These two units each come with vast product portfolios, and distinct approaches to address customer needs. This thesis focuses on an efficient method of evaluating how Ascent's current products align with customer's requirements, as well as identifying any technology gaps needing further exploration. This thesis argues that Ascent's multiple business units are not currently equipped to advise their customers on investing in the appropriate technology for their production systems.

To investigate such a vast solution space, a framework developed by the Systems Engineering Advancement Research Initiative (SEARI) at the Massachusetts Institute of Technology (MIT) is utilized called Multi-Attribute Tradespace Exploration (MATE). Using this framework, a software package called the Product Selection Tool, was developed to analyze how Ascent's product portfolio satisfies the customer's requirements for specific applications.

The Product Selection Tool visualizes Ascent's 71 different product offerings on a single graph of utility versus cost per fastener. The interface that displays the graph is dynamic, allowing Ascent's customers to adjust their requirements and preferences in real time, and visualize the sensitivity, or risk, of the recommended solution based on their specific requirements. This new approach allows Ascent to closely work with their customer in selecting a solution, identify areas of concern early on in the product selection process, and introduce cost-effective technology. This model can be applied to a variety of applications that have a vast solution space, reducing the complexity of understanding and communicating one's product line and/or capabilities.

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Acknowledgments

I would first like to acknowledge my MIT academic advisors, Michael Cusumano and Julie Shah, for their guidance and support in shaping the direction of this project. I would also like to thank both the AIP and Ascent teams, who worked with me to navigate the numerous stakeholders involved in this research.

I would especially like to thank my supervisors, Marek Kos and Karl Bumgarner, who provided so much of their time to help me understand the products we analyzed, further refine my research topic, and dive into the extremely technical elements of the analysis.

Additionally, I would like to acknowledge the Leaders for Global Operations (LGO) program staff and my fellow LGO classmates for their guidance in making the internship and thesis writing process progress go so smoothly.

I would also like to thank my parents for their support and for encouraging me to always challenge myself.

Finally, I would like to thank my fiancé, Amy Henson, for embarking on this two-year LGO journey with me and, most importantly, spending countless hours helping me edit this thesis.

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1 Introduction

Aerospace automated drilling and fastening technology has been around since World War II. However, with pricing pressure in the global economy, as well as rapidly increasing technological advancements, today's Original Equipment Manufacturers (OEMs) have increased the adoption of automating the joining of aerospace structures. OEMs' demand for fast, reliable, flexible solutions has led several automation suppliers to over promise and under deliver[1]. Now, OEMs are looking at their own product portfolios and questioning whether they align with their customers' needs and will meet the manufacturing requirements of the future.

The drastically different products in the aerospace industry, from small helicopters and engine nacelles, to twin aisle airplanes and large rockets, demand a wide range of drilling and fastening solutions. Accuracy might be critical to one OEM, where reliability and speed might be critical to another. Today, the OEMs assume the responsibility of defining and communicating requirements, expecting suppliers to select the solution that meets their needs.

To investigate such a vast solution space, a framework developed by the Systems Engineering Advancement Research Initiative (SEARI) at the Massachusetts Institute of Technology (MIT) was utilized called Multi-Attribute Tradespace Exploration (MATE)[1]. Using this framework, a software tool was developed to analyze how Ascent's product portfolio satisfies customers' requirements for a specific application. This project analyzes the current drilling and fastening landscape to assess if Ascent's product portfolio needs rationalizing, as well as identify any technology gaps that require further exploration.

1.1 Ascent Aerospace

Ascent Aerospace (Ascent), a portfolio company of American Industrial Partners (AIP), is a vertically-integrated tooling, factory automation, and assembly line integration supplier.

With approximately 1,100 employees located across California, Washington, Michigan, New York, and Toulouse, France, Ascent currently supports almost every major aerospace program[2]. Ascent is comprised of five legacy companies: Coast Composites, Odyssey Industries, Global Tooling Systems, Gemcor, and Brown Aerospace. These companies were brought together for their complementary sets of expertise.

Ascent acquired both Gemcor and Brown to address the demand for increased automation in aerospace manufacturing—specifically automated drilling and fastening technology. Brown focuses on one-off, robotic based, flexible solutions. Each one of their products is custom-designed specifically around the customer’s application. Gemcor has been in business since 1937 and focuses on large-scale platforms[3]. Gemcor is known in the industry for its extremely fast and reliable equipment. These two acquisitions each came to Ascent with their own vast product portfolios and distinct approaches to addressing customer needs.

1.2 Problem Statement

Several of Ascent’s customers have struggled with introducing factory automation over the past several years. Choosing the appropriate technology is essential for ensuring successful implementation for both Ascent’s customers and Ascent itself. An example of these complex pieces of equipment can be seen in Figure 1 below.

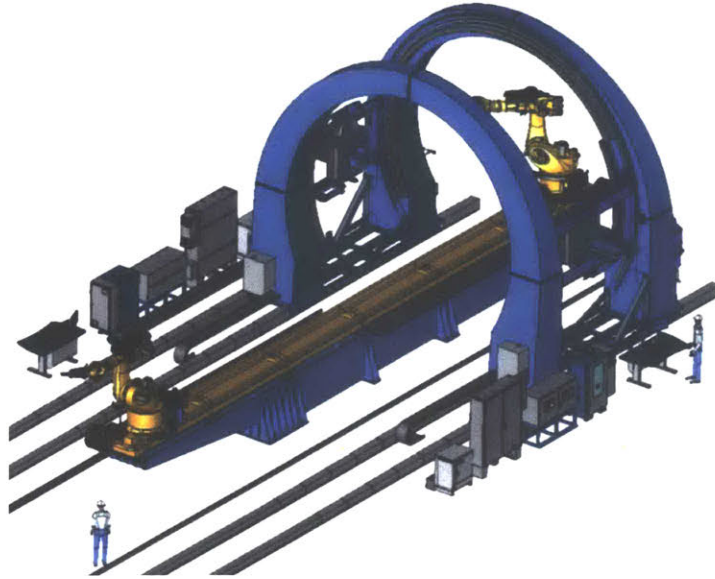


Figure 1: “Arc Frame” drilling and fastening for fuselage skin to frame join

Selecting the appropriate fastening technology system can be complicated by the vast number of product offerings and configurations; the complexity of the systems; the unique preferences of the customer; and the specific requirements of each application. The multitude of variables in the equipment selection process, however, is overshadowed by the standardized Request for Quote (RFQ) process used by Ascent and their customers. Although a solution might satisfy the requirements of a customer, it may not be the value maximizing solution.

Ascent needs an efficient method of evaluating how their current products align with customer requirements, as well as key data-driven initiatives to ensure they remain the technology leaders of the aerospace tooling and equipment industry. The hypothesis of this thesis is that Ascent’s multiple business units are not currently equipped to advise their customers on investing in the appropriate technology for their production systems.

1.3 Project Goals

The goal of this project is to assess Ascent's varied product portfolio. This project will distill Ascent's product offerings into a tool that will facilitate efficient communication between employees of Ascent, as well as between Ascent and their customers. This will enable Ascent to recommend personalized technical solutions for customer applications, understand what technology gaps exist in their product offerings, and recognize what the future of the industry might require.

1.4 Thesis Overview

Below is a high-level overview of what content to expect in building the case for adopting the Product Selection Tool.

Chapter 2 explores current aerospace automated drilling and fastening technology, and the manual processes that such automation technology is replacing. This chapter breaks down automation equipment into its major components and discusses the potential applications for these products.

Chapter 3 walks through the Product Selection Tool. This tool is used to analyze Ascent's product portfolio and assess how the portfolio satisfies customer requirements. The process begins with determining the decision makers and what attributes they value. Next, the design variables that characterize each of Ascent's products are documented and mapped to the attributes. Finally, a utility score and total cost is calculated for each product, based on the specific application.

Chapter 4 looks at Ascent's current aerospace drilling and fastening technology. This chapter discusses gaps found in Ascent's product portfolio using the Product Selection Tool, and recommends potential products to incorporate for a more complete offering. Chapter 4 also

reviews the potential value of unproven technology in the Aerospace industry, exploring the benefits and risks of taking on research and development for new technology without a contract from a customer.

Chapter 5 provides a strategy for incorporating the Product Selection Tool into the daily operation of the Sales and Proposal teams at Ascent. This chapter will also review future improvements that can be made to the Product Selection Tool that will bolster its effectiveness.

Chapter 6 reviews recommendations for the near and long-term steps Ascent can take to bolster their product offering and maintain their status as a leader in the industry. Additionally, this chapter includes a summary of the overall findings and potential research for furthering this project.

2 Drilling and Fastening Technology Overview

Aluminum and composite aerospace structures are traditionally assembled through the joining of overlapping layers. Hundreds of thousands of fasteners are installed in these joints for a single airplane. As aerospace companies continue to introduce automation into their production systems, they require increasingly complex systems to replace the labor-intensive operation of drilling and fastening parts together.

2.1 Traditional Manual Fastening

The manual task of drilling and installing fasteners is repetitive and puts immense stress on mechanics' joints. In other words, the positioning required for mechanics to perform this task is not ergonomic.



Figure 2: Manual overhead riveting[4]

Due to the physically challenging nature of this work, numerous quality defects slow down the overall process. The manual drilling and fastening process can be broken down into the following steps:

1. Back drill through pre-drilled holes (pilot holes), found on the innermost layer of the structure. There is typically one pilot hole every 12 to 24 inches.

2. Install temporary fasteners in the pilot holes to bring the layers together and secure them in place.
3. Lay drill templates on the outside of the structure that index to the temporary fasteners.
4. Using the drill templates, drill all holes in the structure.
5. Remove the temporary fasteners.
6. Separate the layers of structure, clean the interface between the layers, and deburr all holes.
7. Install permanent fasteners in all holes.

The installation of permanent fasteners requires a bolt with a nut threaded on the end or a rivet. A rivet is installed by a mechanic who hammers the fastener from one side, while a second mechanic bucks the fastener from the opposite side. This process is not only time consuming, but also puts an incredible amount of force on the mechanics' bodies, often leading to cumulative trauma disorders (CTDs) [5].

2.2 One-Up Assembly

Fully automating the drilling and fastening of aerospace structures requires a process called one-up assembly. The one-up assembly process eliminates the need to separate and deburr the drilled layers of material prior to installing fasteners. The elimination of these time-consuming steps is accomplished by sufficiently clamping the layers of material together during the drilling process, in order to prevent chips or burrs from accumulating between the layers.

There are three methods in which clamp-up between layers is achieved. The first method of clamp-up uses tooling to provide rigid backing pressure to the external, automated equipment.

The tooling is installed on the interior of the structure manually, and must be removed once the automated drilling and fastening process is complete. The second method of clamp-up uses automated equipment on the interior of the structure to provide an opposing force to the external equipment. This internal equipment is typically used when the bucking of rivets, threading of collars, or swaging of collars is automated. The third method, called adjacent-hole clamp-up, utilizes fasteners adjacent to the hole being drilled to provide clamp-up[6]. Selecting the appropriate clamp-up method depends on the material being drilled, the stiffness of the structure, and the fastener that is being installed.

2.3 Automated Fastening Equipment Sub-Systems

The equipment used in automated drilling and one-up assembly is extremely complicated and has many layers of sub-systems. To simplify the analysis and maintain a limited number of product configurations, the following three key sub-systems will be explored: the process head, the motion platform, and the positioning system. These three sub-systems cover the primary variants that make up the overall equipment.

2.3.1 Process Head

The process head, or end effector, is the automated system that performs all of the value added work. These extremely complex systems are comprised of multiple modules that each perform a different function. Below are some of the modules that are included in a multi-function process head:

1. A vision system, typically camera based, that enables accurate positioning of the process head relative to the part to be drilled.

2. A drill module, which consists of a drill bit and, depending on the complexity of the operation, a tool changer to swap out drill bits for different size holes.
3. A deburr module, to remove burrs from the backside of the drilled hole.
4. A hole probe, which inspects the quality of the drilled hole.
5. An insertion module, which securely holds and inserts a fastener into a drilled hole.
6. A squeeze or hammer module, which forms the fastener, in the case of rivets.
7. A sealant module, which applies sealant to the hole or fastener being installed.
8. A pressure and normalization foot, which controls the amount of force being applied to the part and the normality of the process head to the part.
9. A fastener flushness module, which checks the protrusion of the fastener from the part surface, thereby checking the countersink depth of the drilled hole.
10. A fastener verification module, which ensures the fastener does not fall out of the hole when the pressure foot is removed.

Process heads can be simple, including only a vision and drill module, or complex, including a majority of the modules listed above. The advantage of including multiple modules in a single process head is that doing so minimizes the non-value added work, such as set-up time, and can potentially reduce the number of motion platforms.

2.3.2 Motion Platforms

The motion platform system enables large movements of the process head. Typical aerospace applications may require drilling operations that span from one foot all the way to 100 feet. Transporting the process head to cover such a large area requires different combinations of components, depending on the application. These motion platform systems include components

such as robotic arms, space to hold a multitude of sub-systems (such as fastener feed systems and air compressors), and any control systems associated with moving these components.

Motion platforms are considered monuments if they are not easily moved around a factory[7]. These monument motion platforms require foundations installed in the factory floor, consisting of six to ten feet deep concrete slabs reinforced with rebar. The foundations support the motion platform's weight and allow the system to meet the customer's accuracy requirements.

Flexible motion platforms move around the factory on wheels or linear rails. These rails are simply bolted to the factory floor, and do not require the installation of any additional factory floor foundation. Flexible systems provide the added benefit of allowing factory reconfiguration, or even the ability to move an operation to a completely different factory, without significantly disrupting production.

2.3.3 Positioning System

The complexity of the positioning system is dictated by the accuracy of the requirements from the customer. Additionally, increasing the system's accuracy may come at the cost of increased cycle time. Automated drilling and fastening equipment is outfitted with two different positioning systems: a global positioning system and a local positioning system. The global positioning system is responsible for aligning the motion platform to the correct position alongside the part, whereas the local positioning system is responsible for aligning the process head to the next drill location.

There are two major variations of the global positioning system: an Automated Guided Vehicle (AGV) and linear rails. An AGV typically moves on wheels and positions itself using

cameras, magnets, or lasers. These systems are typically accurate to within only a quarter of an inch, but are extremely flexible, as they require little to no infrastructure in the factory.



Figure 3: Kuka AGV based motion platform[8]

Linear rails are much more accurate; rather than rely on cameras, magnets, or lasers, they are programmed to drive to a predetermined location. Utilizing linear rails drastically reduces the motion platform positioning process.

If the risk of colliding with a part structure is high, laser trackers can supplement the motion platform system to further increase the accuracy of the global positioning system. Laser trackers measure both the part and the motion platform, providing real positional data instead of nominal positional data. However, the addition of laser trackers significantly increases the time to position the motion platform.

Once the motion platform is positioned, the local positioning system takes over. This system typically consists of lasers and cameras on the process head. These measurement devices locate key features on the part and provide instructions to the process head regarding how far it must travel to the desired location. These systems are capable of positioning a process head to within several thousandths of an inch.

2.4 Potential Applications and their Challenges

Replacing the labor-intensive drilling and fastening of aerospace structures is not appropriate for every situation. The three main driving factors that lead to automating this operation are to create a safer workplace, to increase productivity, or to increase quality. However, without conservatively analyzing the equipment being installed, customers tend to overestimate the benefit of automation.

2.4.1 Large-Scale Applications

Large-scale applications often provide the most opportunity for savings in cost, time, and safety. These applications tend to have tens of thousands of fasteners that can be automated, enabling a customer to make a much stronger business case versus applications with only a couple hundred fasteners. A previous Leaders for Global Operations (LGO) thesis by Sean Caetano explores the business case for introducing automated drilling and fastening equipment into a large scale application[9]. Specifically, Caetano's thesis focuses on the Embraer E2 program. When considering the time it takes to complete an automated task, Caetano argues that customers should factor in the easy learning curve required. Such an aggressive learning curve turns the business case for implementing automated drilling and fastening equipment positive.

In the Embraer E2 case study, the customer assumed a Net Present Value (NPV) of \$16M, with an investment of only \$12M. The chart below shows the customer in the study has a significantly more optimistic business case when compared with Ascent's own estimations.

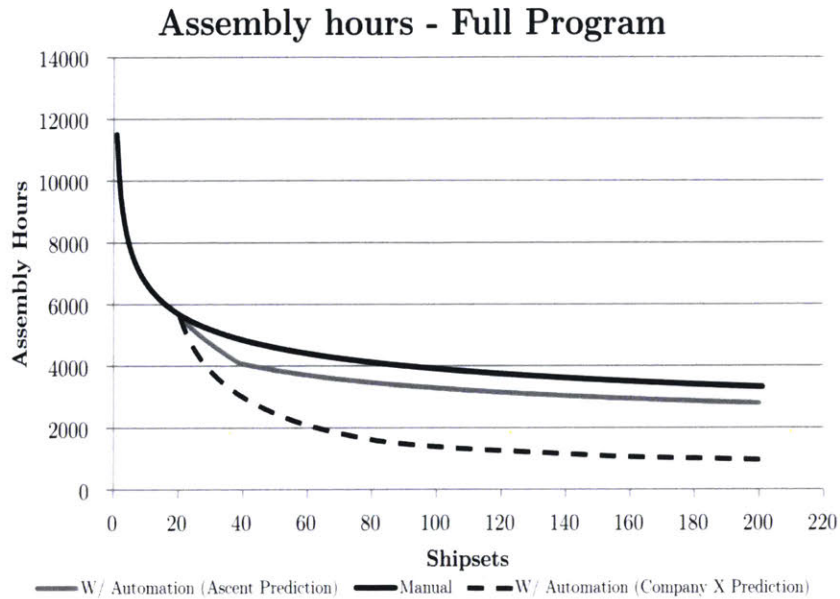


Figure 4: Optimistic approach ignores risks of introducing automation[9]

Ascent must work with the customer to show the risks that certain automation equipment can pose to their production systems. Overly optimistic business cases can lead a customer to select a much too aggressive piece of equipment.

Another example of a large-scale automation project that has struggled with adopting automation is Boeing’s Fuselage Automated Upright Build (FAUB)[10]. FAUB automates approximately 60,000 fasteners on the forward and aft fuselage of the Boeing 777 and 777X[11]. This program has found difficulties with maintaining production schedules and the necessary quality level since automation was introduced in 2016.



Figure 5: Boeing 777 FAUB automation[11]

According to FAUB, a major cause of the challenge stems from the quality of the parts they receive from their suppliers[10]. The slower-than-anticipated introduction has also impacted Boeing's downstream operations; in late 2017, several Boeing employees said the 777 production line is approximately 12,000 tasks behind schedule[12].

Automating such a large product requires the coordination of many systems, which naturally increases the number of automated interfaces and opportunities for failures. Additionally, the impact of a minor increase in cycle time is amplified by the number of fasteners. For example, if the customer does not believe they will need a quality inspection module when purchasing the equipment, that time to probe the hole will not be incorporated into the business case. However, if certain quality issues appear, or if they elect to reduce the amount of manual inspection[13], they will need to incorporate additional inspection steps.

Another scenario that could increase the cycle time of an operation is if the part, or equipment, is not sufficiently stable and requires a longer settling time. If the process requires FAUB's drilling operation to pause for even one second (to allow for a quality inspection or for the equipment to settle), it will add 60,000 seconds, or two shifts, to the overall manufacturing process.

2.4.2 Small-Scale Applications

Cycle time increases are less impactful on small-scale applications. However, automating engine nacelles, or fighter jet wings, poses other challenges. Typically, small-scale applications have smaller restrictions on physical access and require tighter tolerances. A common oversight is that 3D models, provided by customers, do not contain all of the tooling, equipment, and materials that lay on the factory floor and obstruct the path of the automation equipment. Also, brackets and Clecos are not normally shown in models when a proposal is put together[14]. All of these barriers increase the number of fasteners that the automation cannot access and therefore need to be manually installed.

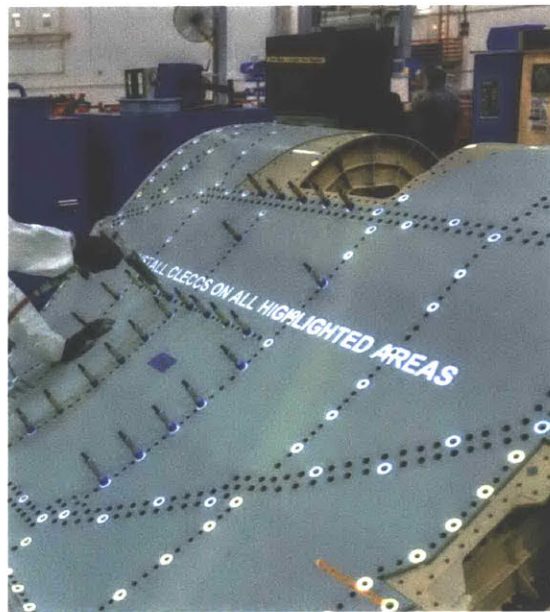


Figure 6: Mechanic removing Clecos from an F-35[14]

Also, meeting tight tolerances in a lab environment is much easier than maintaining such tight tolerances in a factory environment. Obtaining real production data, to prove the equipment capability, is difficult due to the sensitivity of the products being manufactured. Maintaining

tight tolerances in a production environment requires higher equipment maintenance standards and training than typically applied by the customers.

2.5 Summary

Replacing the manually intensive drilling and fastening process with automation may provide significant safety, quality, and productivity benefits to a production system. Though, to realize any benefits, the customer and supplier must be thoughtful when selecting equipment. The complexity of the equipment, and the environment it is introduced into, each pose a risk to the part being automated—and all downstream operations. Automation should be a highly favorable option, due to the serious safety hazards of the manual process, yet customers and their suppliers can learn from previous automation introduction programs and the fallout from an overly optimistic approach.

3 Multi-Attribute Tradespace Exploration

To reduce the complexity of using a vast set of requirements and potential solutions, the framework developed by the Systems Engineering Advancement Research Initiative (SEARI) at the Massachusetts Institute of Technology (MIT) was adopted called Multi-Attribute Tradespace Exploration (MATE)[15]. Using this framework, a software called the Product Selection Tool was designed to analyze how Ascent's product portfolio satisfies requirements for a specific application. This Chapter walks through the process of developing the Product Selection Tool.

3.1 Decision makers

Understanding the key stakeholders and decision makers is the first step in capturing the appropriate attributes, or characteristics, of the product. A stakeholder is someone who will benefit from, or be hurt by, the system in any stage of its lifecycle. The decision makers are a subset of stakeholders, notable for their ability to influence the allocation of resources[15].

The diagram below walks through the various decision makers of the automated drilling and fastening equipment, and their relationship to the product:

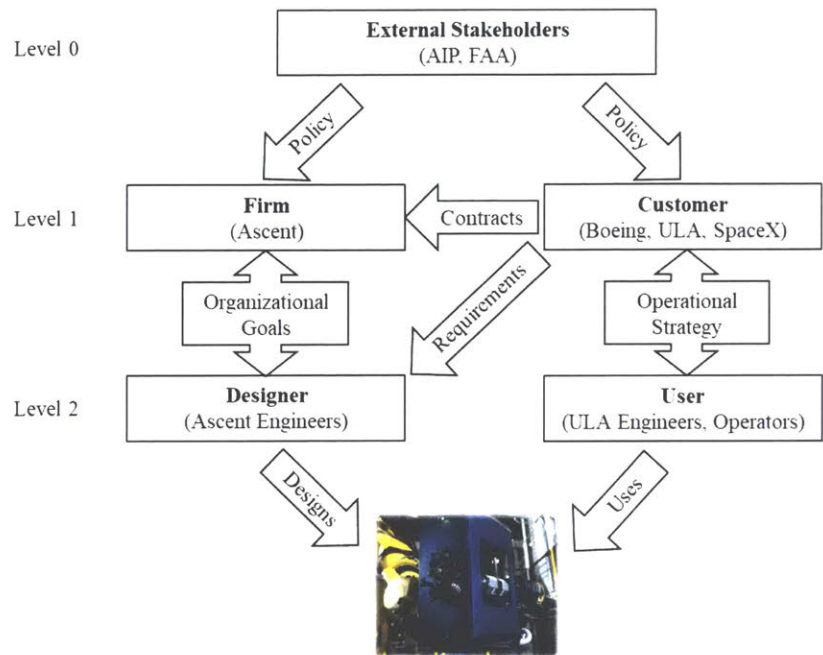


Figure 7: Decision maker's roles and levels[15]

Both Level 0 decision makers, AIP and the Federal Aviation Administration, have the broadest perspective on the product. They influence policy, which the other decision makers must observe, however, their influence over the actual design and selection of the product is minimal.

There are two categories of Level 1 decision makers identified: the firm who produces the product, Ascent, and the customers who use the products. The customer controls the money associated with the project and issues a contract to the firm. The customer also dictates requirements to the designers.

Level 2 stakeholders are the designers and users of the product. They have the greatest influence over the product portfolio and productivity of the product.

3.2 Attribute Definition

The complete set of attributes is used to assess the value of a particular product and should be complete, operational, decomposable, non-redundant, minimal, and perceived independent[16]. Each attribute is valued according to how well the product meets the intended goal of the decision maker. The value of a product is subjective and presumed to be correlated with the satisfaction, or utility, a decision maker gets out of the product.

3.2.1 Customer Attributes

Customer attributes are quantifiable measures that assess how well the system meets the customer’s objective. Customers are the management team who will be purchasing equipment.

Attribute	Unit	Description
Cost	\$	The cost refers to the cost incurred by the customer. See Section 3.6 for details.
Allows for continuous flow	Yes or No	The solution does not allow for continuous flow if the part needs to be craned from its holding fixture into the automated drilling and fastening product.
Simple	TRL 6-9	The technology readiness level (TRL) of the solution. A TRL of 9 indicates that the system has been proven in a production environment; 8 indicates that the system has been proven in a lab environment; 7 indicates that the subsystems have been proven in a production environment; 6 indicates the subsystems have been proven in a lab environment.
Uptime	%	The percentage of the available time that the equipment is capable of running.
Capacity utilized	%	

		The total number of fasteners per system divided by the total possible number of fasteners per system in the available time. Assumes a factor for downtime is taken out of available hours. Assumes the motion platform performs a global position move every time it re-indexes.
Training required to operate equipment	Weeks	The number of weeks required for a new operator to be proficient in operating the system.
Lead time	Months	The number of months required from when the order is placed to when the system is delivered to the customer, excluding any customer buyoff time.
Mobility	0-2	The foundation required to support the solution. A mobility of 0 indicates a foundation in the factory floor is required to support the system; 0.5 indicates that a small footprint factory floor foundation is required; 1 indicates that the system must be bolted to the factory floor; 2 indicates the solution is completely mobile and does not require infrastructure to be installed in the factory floor.

Table 1: Customer attributes

3.2.2 User Attributes

User attributes are quantifiable measures that assess how well the system meets the user's objective. Users are the engineers and the maintenance teams that operate the equipment.

Attribute	Unit	Description
Accuracy post vision sync	Inches	The positional accuracy of a hole, drilled with the automated equipment, relative to the indexing features.
Accuracy prior to vision sync	Inches	The positional accuracy of the vision system to the indexing features, once the motion platform is moved.

Stayouts	%	The percentage of holes intended to be automated that are outside the reach of the process head.
Design for safety	0-5	The relative safety of the automation solution, compared to the other possible solutions. A score of 0 implies a safer solution versus a score of 5.
Modules	1-8	The number of modules required to be held on a process head.

Table 2: User attributes

3.2.3 Firm Attributes

The firm attributes are quantifiable measures that assess how well the system meets the firm's objective. The firm is the Ascent management team.

Attribute	Unit	Description
Gross margin	%	The revenue generated from the product, minus the cost of the product to Ascent, divided by the revenue generated from the product.
Volume of sales	\$	The total revenue generated from a product across all markets.
Onsite support post customer acceptance	Months	The number of months beyond the intended length of the contract that Ascent employees are required to assist the customer.

Table 3: Firm attributes

The firm attributes are excluded from the model developed for Ascent, due to Ascent’s desire to tailor this tool toward the needs of the customer, as well as to obscure any sensitive data regarding the profitability of the product. When evaluating the total utility of products to Ascent and their customers, such as evaluating which products should be eliminated from Ascent’s product catalog, the firm attributes should be reintroduced.

3.3 Utility Assessment

A single attribute utility curve is used to derive the value each decision maker receives from a given attribute. The dimensionless function, U , for each attribute, X , is defined as:

$$U_i = U(X_i) \tag{1}$$

Where $U_i = 0$ is the least desirable, but acceptable value of X , and $U_i = 1$ is the most desirable value of X [16].

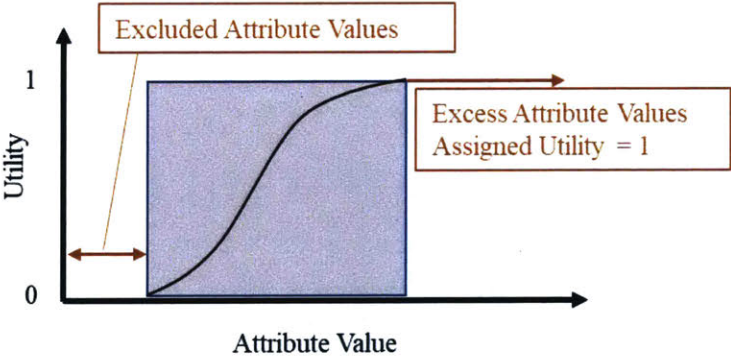


Figure 8: Single attribute utility curve definition [16]

The utility derived from each attribute’s value was found using a two-step process. First, an oral interview of the decision maker was used to establish a baseline curve. Second, the results were reviewed with the interviewee, and refinements were made if necessary.

3.3.1 Interview Process

This section reviews the interview process for the customer attribute of *accuracy post vision sync*. The first question of the interview establishes the level of accuracy that is completely unacceptable to the customer. For this attribute, the result was $X_* = 0.022$ ". The second question establishes the level of accuracy beyond which the customer received no additional satisfaction. For this attribute, the result was $X^* = 0.005$ ".

Next, the interviewee was asked a series of questions, adjusting the variables according to Table 4 below, to assess which of the two hypothetical projects was preferred, Project A or Project B. Project A has a 50% chance of having an accuracy of X_i , and a 50% chance of having an accuracy of X_* . Project B has a P_j chance of having an accuracy of X^* and a $1 - P_j$ chance of having an accuracy of X_* .

If the interviewee selected Project B, then P_j decreased and the question was asked again. If the interviewee selected Project A, then P_j increased and the question was asked again. If the interviewee was indifferent between the two projects, the variable P_j was stored and the next X_i was incorporated into the question.

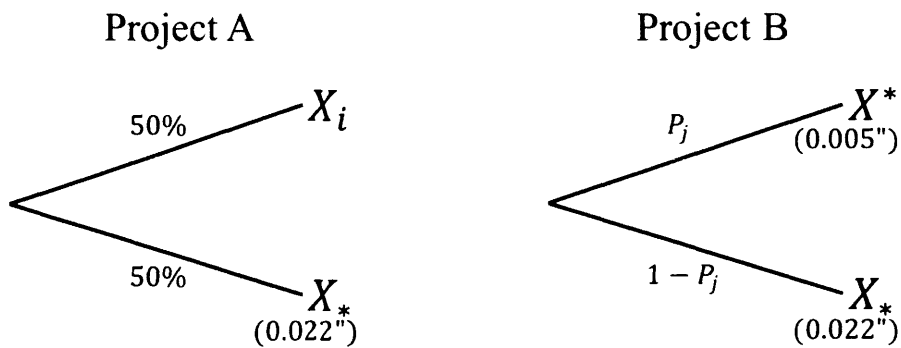


Figure 9: Project options

Question	X_i	P_j	A	B	Indifferent
1	0.020	45		x	
2	0.020	5		x	
3	0.020	2	x		
4	0.020	2.5			x
5	0.018	45		x	
6	0.018	3	x		
7	0.018	10		x	
8	0.018	4	x		
9	0.018	5			x
10	0.016	45		x	
11	0.016	8	x		
12	0.016	10			x
13	0.014	45		x	
14	0.014	15			x
15	0.012	45		x	
16	0.012	20	x		
17	0.012	30			x
18	0.010	45			x
19	0.008	49		x	
20	0.008	46	x		
21	0.008	47.5			x

Table 4: Accuracy post vision sync utility questions

At the point of indifference (X_i), the utility of the interviewee was calculated using the following equation:

$$U(X_i) = 2 \times P_j \tag{2}$$

Below is the utility graph for *accuracy post vision sync*. An accuracy below 0.005” is considered to have a utility of one, and an accuracy greater than 0.022” is considered to have a utility of zero.

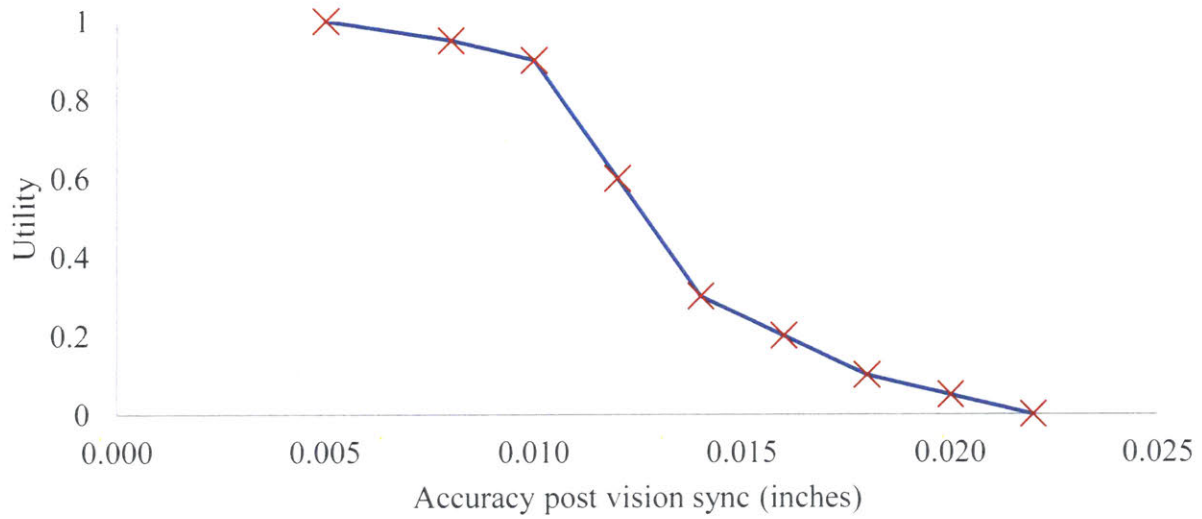


Figure 10: Utility assessment of *accuracy post vision sync*

3.3.2 Multi-Attribute Utility

To combine all single attribute utility scores into a single utility score, a weighting factor, K , where $0 \leq K \leq 1$, is required for each attribute. These weighting factors are determined by subjectively ranking the relative importance of each attribute relative to the other attributes.

Below is a table of K values established through interviews with a customer of Ascent.

Attribute	Weighting Factor
Design for safety	1.00
Capacity utilized	0.90
Uptime	0.90
Stayouts	0.80
Simple	0.80
Mobility	0.75
Onsite support	0.55
Continuous flow	0.50
Accuracy post vision sync	0.40
Modules	0.40
Accuracy prior to vision sync	0.30
Training required	0.30
Lead Time	0.20

Table 5: Attribute weighting factors

The weighting factors identified above are specific to a single customer and a single application, and should be reviewed each time the model is run. Although only one customer was used to develop the values above, Ascent should also take an average of the weighting factors across multiple customers if broader product portfolio decisions are to be made.

The combined utility score, \bar{U} , for a single product is calculated using the equation below, where, X_i is the value of the attribute for the specific product.

$$\bar{U} = \prod_{j=1}^N (K_j * U_j(X_i) + 1) \quad (3)$$

To calculate X_i , the design variables and their values for each product need to be established.

3.4 Design Variables

The design variables are the distinguishing features that characterize the product and quantify its performance. The design variables are broken down into two different categories: Design Variable Inputs and Design Variable Outputs.

3.4.1 Design Variable Inputs

The Design Variable Inputs are qualitative and breakdown the drilling and fastening product into its subsystems. There are four Design Variable Inputs: the motion platform, the process head, the positioning system, and the need for an opposing robot. Below is the list of options for each design variable input.

Motion Platforms

Gemcor G12
Gemcor G86
Gemcor G2000

Fanuc M900 on AGV
 Fanuc M900 with 7-axis (STA)
 Fanuc M900 on AGV with 7-axis (WL)
 Fanuc M900 with 8-axis (STA and WL)
 Fanuc M900 on AGV with secondary encoders
 Fanuc M900 with 7-axis (STA) with secondary encoders
 Fanuc M900 on AGV with 7-axis (WL) with secondary encoders
 Fanuc M900 with 8-axis (STA and WL) with secondary encoders
 Exechon parallel kinematic robot with 8-axis (STA and WL)
 Arc frame
 Single sided frame
 Mini flex track

Table 6: Design Variable Inputs - Motion Platform Options

Process Heads

High speed linear electric
 Small MFEE (4 Modules)
 Large MFEE (6 Modules)
 C-Frame MFEE (4
 Modules)

Table 7: Design Variable Inputs - Process Head Options

Positioning Systems

CNC rails with single control systems
 CNC rails with dual control systems
 CNC rails with metrology
 AGV positioning
 Metrology

Table 8: Design Variable Inputs - Positioning System Options

Opposing robots are required in any scenario where a simultaneous task must be carried out on the opposite side of the part from which the process head is operating. This thesis does not

include options on the various opposing robots; instead, it simplifies the options to include an opposing robot or not to include an opposing robot.

Changing any one of these design variables constitutes a brand new product. Based on the possible configurations of the Design Variable Inputs, there are 71 different product variations that the combined Ascent divisions of Gemcor and Brown can offer their customers.

3.4.2 Design Variable Outputs

The Design Variable Outputs are quantitative measures of the products output, such as speed, volume, and force. Ultimately, these measures aid in the valuation of the products. The Design Variable Outputs consist of the following:

Design Variable Output	Unit	Description
In-line speed	Fasteners / Minute	Time it takes to drill a hole (possibly insert a fastener) and move to the next hole location. This assumes there is no movement of the entire motion platform during this time. This also does not include any indexing of the process head to indexing features.
Time to reposition motion platform	Minutes	Time it takes to reposition the motion platform and index the process head to indexing features. This assumes that every time the motion platform makes a move, the process head is re-indexed.
Process head reach in length	Feet	The reach of the motion platform and process head parallel to the base of the motion platform.
Process head reach in unit width	Feet	The reach of the motion platform and process head perpendicular to the base of the motion platform.
Process head reach in height	Feet	

		The reach of the motion platform and process head in the direction normal to the factory floor.
Motion platform reaction force	Pounds	The maximum force that can be applied by the system to either the fastener or the structure, without quality concerns such as skidding or deflection.
Number of modules	0-10	The maximum number of modules that can fit within the process head. This includes optional modules as well as standard modules.

Table 9: Design Variable Outputs

The Design Variable Outputs reveal the capability of the system, however, production system requirements are required to determine how well the system integrates into the customer's production system.

3.5 Production System Requirements

The production system requirements help transform the model's output into the perspective of the individual customer. Although customers typically provide hundreds of requirements when requesting a quote for piece of equipment this complex, this model intentionally limits the set of requirements to the 16 that are most influential. The 16 requirements below have been selected for their broad applicability across almost all aerospace production environments.

Production System Requirements	Unit	Description
Drill and fasten process requirements	Select 1 of 5 options	Adjacent Hole Clamp-Up

		<p>Clamp-up of parts is achieved through a fastener that was previously installed, and manually collared, in one or more adjacent holes. No opposing process head is required.</p> <p>Drill and Fill (No Collars) The process head drills a hole and inserts a fastener into the hole. The process does not require a collar be installed on the fastener.</p> <p>Automated Swaged Collars The process head drills a hole and inserts a fastener into the hole. The process requires a collar is swaged on the tail of the fastener. This process requires either an opposing robot, or a C-Frame process head.</p> <p>Automated Threaded Collars The process head drills a hole and inserts a fastener into the hole. The process requires a collar is threaded onto the tail of the fastener. This process requires either an opposing robot, or a C-Frame process head.</p> <p>Drill Only The process head drills a hole, however, it is not responsible for inserting a fastener into the hole.</p>
Optional modules	0 - 5	The number of additional modules required by the customer. Optional modules include the hole probe module, the flushness module, the onboard tool swap module, the fastener verification module, and the backside deburr module.
Accuracy post vision sync	Inches	This requirement eliminates any product configuration that is not capable of achieving an accuracy less than the value listed <i>after</i> the vision system has synced on the target.
Accuracy prior to vision sync	Inches	This requirement eliminates any product configuration that is not capable of achieving an accuracy less than the value listed <i>prior</i> to vision sync.
Length	Feet	The length of the part to be drilled and fastened.

Width	Feet	The width of the part to be drilled and fastened.
Height	Feet	The height of the part to be drilled and fastened.
Number of fasteners	Quantity	The number of fastener locations that the customer intends to automate.
Available time	Hours	The amount of time allocated in the production system to complete the automation statement of work.
Duration of use	Years	Number of years the equipment is expected to be utilized.
Labor reallocation	%	Percentage of time labor is reallocated to different work while the equipment is not running.
Labor rate	\$/hour	The fully burdened labor rate of an equipment operator.
Number of operators	Quantity	The number of operators expected to run the equipment.
Re-position motion platform	Quantity	The number of fasteners expected to automate before the motion platform needs to move to another location. This is typically driven by accuracy requirements and should be a rough approximation.
Clamping / upset force	Pounds	The amount of force required to squeeze multiple layers of material together for one-up assembly, or the amount of force required to upset a rivet.
Discount rate	%	The discount rate used by the customer to discount their future cash flows.

Table 10: Production system requirements

3.6 Total Cost

The vertical axis of the product tradespace compares products based on total utility, while the horizontal axis compares products based on cost. Leveraging the techniques developed in Sean Caetano's LGO thesis [9], this project approximates the cost of implementing automated drilling and fastening systems into a customer's production environment. The total cost of the product is broken down into total fixed costs and total variable costs. To protect Ascent's proprietary data, no numbers will be provided in this section.

The fixed costs are broken down into the list price for the equipment and the additional development cost needed to ensure the equipment is production ready. To calculate the list price for the entire system, a list price is computed for every Design Variable Input found in Table 6, Table 7, and Table 8. Any additional development costs were a function of the TRL of that product. For example, a product with a TRL of 7 required a higher development cost than a product with a TRL of 8.

Total variable costs are comprised of three types of labor required to operate the equipment: equipment operators, manual fastener mechanics, and equipment maintenance. The model assumes that all labor is completed at the same fully burdened hourly rate. The model requires a minimum of one equipment operator to oversee the process, however, the customer can include more operators if they prefer.

The labor hours for the equipment operator are based on the number of hours that product will take to complete the desired number of fasteners. The labor hours for the manual fastener mechanic are a function of the number of *stayout* fasteners and the speed at which the mechanic

can fasten manually. Finally, the labor hours for equipment maintenance are a function of the reliability of the equipment. All variable costs are discounted over the number of years the equipment is expected to operate.

3.7 Simulation and User Interface

The Design Variable Outputs and Production System Requirements are all mapped to the applicable attributes, resulting in a total utility score, \bar{U} . Similarly, the Design Variable Inputs, Design Variable Outputs, and Production System Requirements are mapped to the fixed and variable costs, resulting in a total cost. The total cost is divided by the number of fasteners, in order to visualize the results in the unit cost per fastener, a metric typically used and easily understood by customers.

The outputs from this simulation are graphically displayed on the user interface, seen in Figure 11 below. The visualization includes all of the customer requirements and a summary of the top four product recommendations. Also, the chart contains a line representing the cost of not automating the process, and instead fastening the product manually.

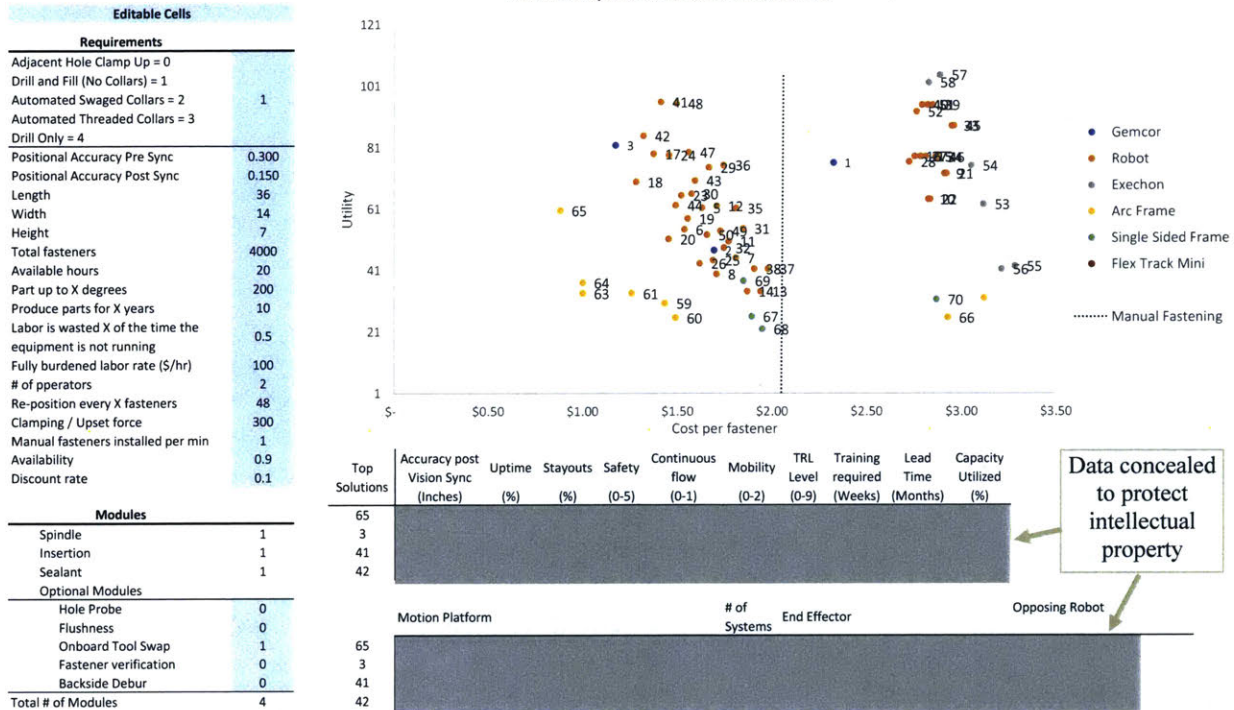


Figure 11: Product Selection Tool Output and User Interface

The interface displaying the graph is dynamic, allowing the customer to adjust their requirements and preferences in real time, run the simulation, and visualize the sensitivity or risk of the recommended solution based on their specific requirements.

3.8 Results

For the application depicted in the simulation results above, Figure 11, solutions 65, 3, 41 and 42 are considered to be the preferred options. They provide the highest utility to the customer at the lowest cost. However, it is important to note that the model does not conclude that any one solution is the favorite; instead, it provides the entire tradespace of possible solutions.

According to the model, Solution 41, a Fanuc robot on an AGV, has the highest utility, however solution 65, an Arc Frame motion platform, has the lowest cost. The tool provides a

starting point from which Ascent can work with their customer to determine which attributes are most important and which are worth sacrificing. This product selection framework is in complete contrast with the current method in which Ascent recommends products to their customers. Rather than an individual seller writing a detailed proposal with a single product option, Ascent can instead have a data-driven conversation with their customers to review multiple solutions and discover which is most applicable for their business.

3.9 Summary

The Product Selection Tool utilizes 29 application-specific variables and 24 product-specific variables to generate the tradespace. This solution space plots Ascent's 71 different product offerings onto a single graph of customer utility versus cost per fastener. This new approach empowers the people at Ascent to work closely with their customers to generate a data-driven solution, identify areas of concern early on in the product selection process, and introduce cost effective technology that provides an increased benefit to the customer. Ascent should eventually reduce the number of variables used in this model. Eliminating variables that have little effect on the model will simplify the amount of data Ascent needs from their customers.

4 Technology Provisioning

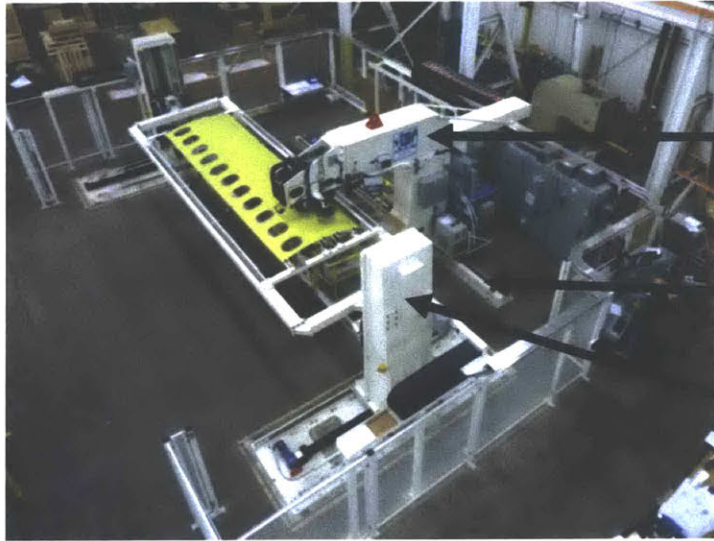
The product selection tool enables Ascent to explore gaps in the product tradespace of utility versus cost and explore possible technology improvement to fill these gaps. However, there is significant risk in recommending a product to a customer that is not tested in a production environment, or developing a product that was not directly requested by the customer.

4.1 Current Ascent Aerospace Technology

A typical lens used to view the different drilling and fastening products is based on whether they are considered a monument or a flexible system. Monuments are thought of as reliable, fast, and immovable platforms, whereas flexible systems are associated with robotics and autonomous vehicles.

4.1.1 Monument Automation Solutions

Gemcor has three primary drilling and fastening systems, the G12, G86, and G2000, which are all considered monument-based platforms. The G12 is smallest of the three configurations and is designed for components such as engine nacelles and small fuselage panels. The platform has rails bolted to the floor that a C-Frame traverses on, and CNC positioners to adjust the orientation of the part. For some applications of the G12, a robot is used to hold the part instead of the CNC positioners.



C-Frame: OML MFEE mounted on top and IML End Effector mounted on bottom

Linear rails to move C-Frame

CNC positioners to move part

Figure 12: Gemcor G12 Motion Platform

The outer mold line (OML) process head is mounted on the top half of the C-Frame, and the inner mold line (IML) opposing process head is mounted to the bottom half of the C-Frame. The C-Frame configuration maintains alignment between the OML and IML end effectors, and provides a rigid structure to react the force of compressing large rivets. The linear rails and CNC positioners enable accurate alignment of the process head to the part and allow the equipment to have a large coverage area. This ultimately reduces the number of *stayout* fasteners due to the equipment configuration.

The G12 motion platform, shown in Figure 12 above, is small enough that—in most cases—it does not require a foundation to be installed in the factory floor. A typical foundation requires a concrete footprint six to ten feet deep, reinforced with rebar. A foundation is expensive to install and locks the equipment into a specific location and orientation in the factory.

The Gemcor G86 motion platform, shown in Figure 13 below, requires a foundation be installed under the linear rails and CNC positioners. The G86 motion platform is significantly larger than the G12, and therefore can accommodate larger aerospace structures.

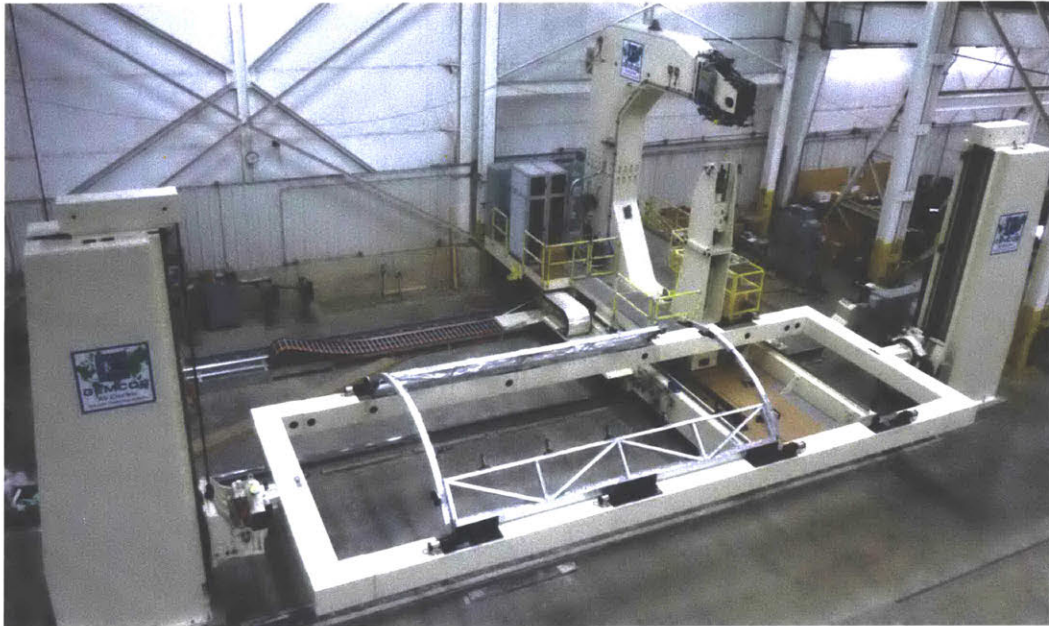


Figure 13: Gemcor G86 Motion Platform

The third and final motion platform variant offered by Gemcor is the G2000, shown in Figure 14 below. This motion platform has two C-Frames, one within the other. The inner C-Frame can rotate 180°, allows the motion platform to reach the far side of large fuselage panels, such as those found on the Boeing 747 and 777 airplanes.



Figure 14: Gemcor G2000 Motion Platform

These three Gemcor configurations enable the equipment to maintain high levels of accuracy, precision, and speed, over large distances.

The Brown business unit has a different approach to motion platforms. They take a series of off-the-shelf components and assemble them based on the requirements of the customer. This provides the Brown team with a much larger solution set to choose from. The lack of standardization, however, has led to each solution being implemented only a few times, so lessons learned are not transferred to the newer generations as seamlessly as they are at Gemcor.

The motion platforms offered by the Brown division that most closely overlaps with the Gemcor series are the Arc Frame, shown in Figure 1 above, and the Single Sided Frame, shown in Figure 15 below. The primary difference for these platforms is that they do not have a C-Frame to enable access to the inner mold line (IML) of the part. Instead, a separate motion platform is required to access the IML. This additional motion platform is necessary if internal clamp-up pressure, a rivet bucking bar, or fastener collaring are required.



Figure 15: Brown Single Sided Motion Platform

4.1.2 Flexible Automation Solutions

For applications where more flexibility is required, the Brown unit offers a robotic arm as the motion platform. The robotic arm holds the process head and can simply be bolted to the floor for small scale applications, or mounted to a series of linear rails to provide greater reach. Optional secondary encoders can be installed on the robotic joints to increase the robot's accuracy.

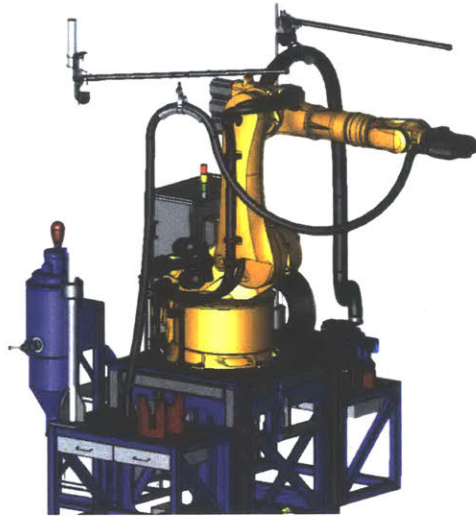


Figure 16: Brown robotic motion platform

For applications that require even greater flexibility, the robotic arm can be mounted on an autonomously guided vehicle (AGV) (see Figure 3). The AGV eliminates the need for any permanent fastening to the factory floor; however, this configuration adds significant complexity to the motion platform. This complexity stems from maintaining a safe environment, transferring the necessary utilities to the robotic arm, and accurately positioning the AGV.

Robotic arms do not satisfy customers that have extremely tight accuracy requirements. For these applications, the Brown team offers a parallel kinematic system. The parallel kinematic system is more rigid than a robot, but offers a much smaller range of travel[17].

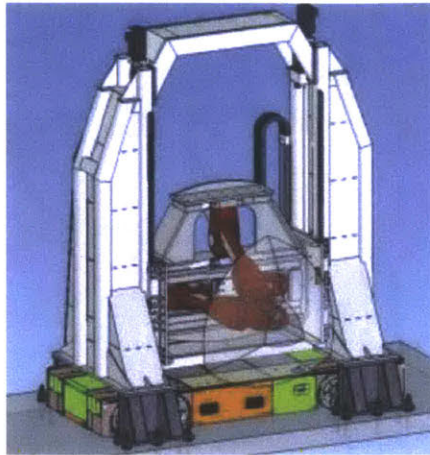


Figure 17: Exechon Parallel Kinematic Motion Platform[17]

4.2 Gaps in Product Tradespace and Future Product Improvements

The simulation results shown in Figure 11 above are configured for Customer A. We call this customer, “Customer A” to conceal their intellectual property. Customer A requested Ascent to propose a drilling and fastening product that meets a series of requirements and aligns with the goals of their production system. A simple glance at the product tradespace shows a clear tradeoff of cost and utility between the top contenders.

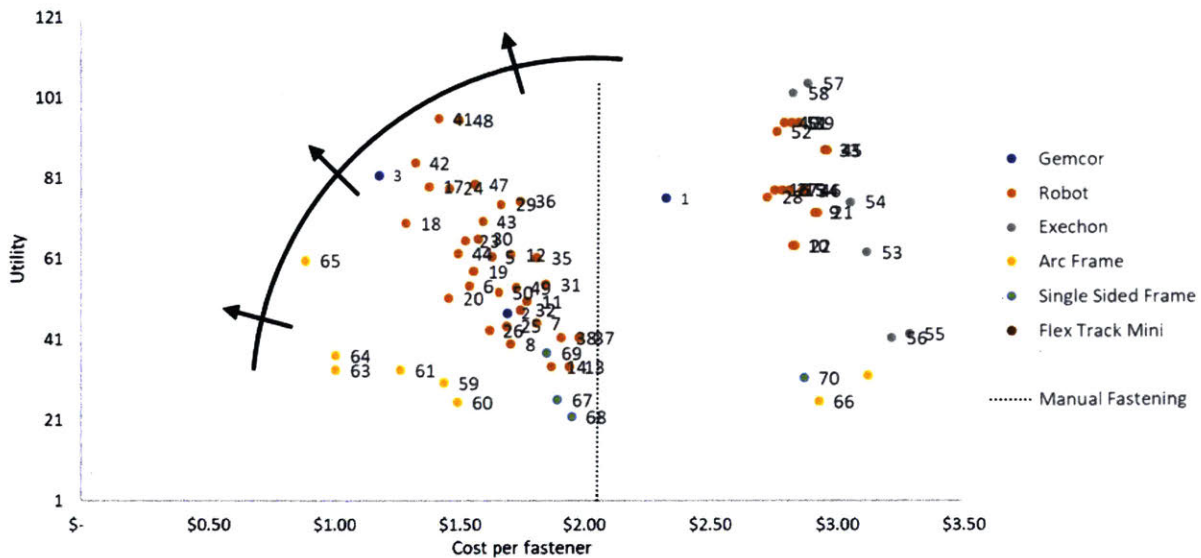


Figure 18: Tradeoff between potential product solutions

Ascent can propose a flexible robotic based solution, such as Solution 41, a monument-based solution from the Gemcor team, such as Solution 3, or a monument-based solution from the Brown team, such as Solution 65. However, this scenario presents a great opportunity for the entire Ascent team to look at weak points in these products and investigate ways to reduce cost and increase utility.

Two separate opportunities are reviewed in this chapter; the first is to increase the speed of Solution 41, and the second is to increase the mobility and enable continuous flow for Solution 3. Increasing the speed of Solution 41 can be accomplished through a series of improvements to the existing system. These improvements range from using a stiffer robot and process head, to fine tuning all of the parameters that control the system.

The Gemcor-based solutions are significantly faster than Brown's robot-based solutions, because the Gemcor machines are much stiffer, and the parameters have been tuned over the past 40 years. The Gemcor G2000, Solution 3, can operate between 12 to 16 fasteners per minute, where the Brown robot based motion platform can operate up to two fasteners per minute. Assuming the Ascent team is able to increase the speed of Solution 3 to just three fasteners per minute, the utility versus cost tradespace would adjust to the following:

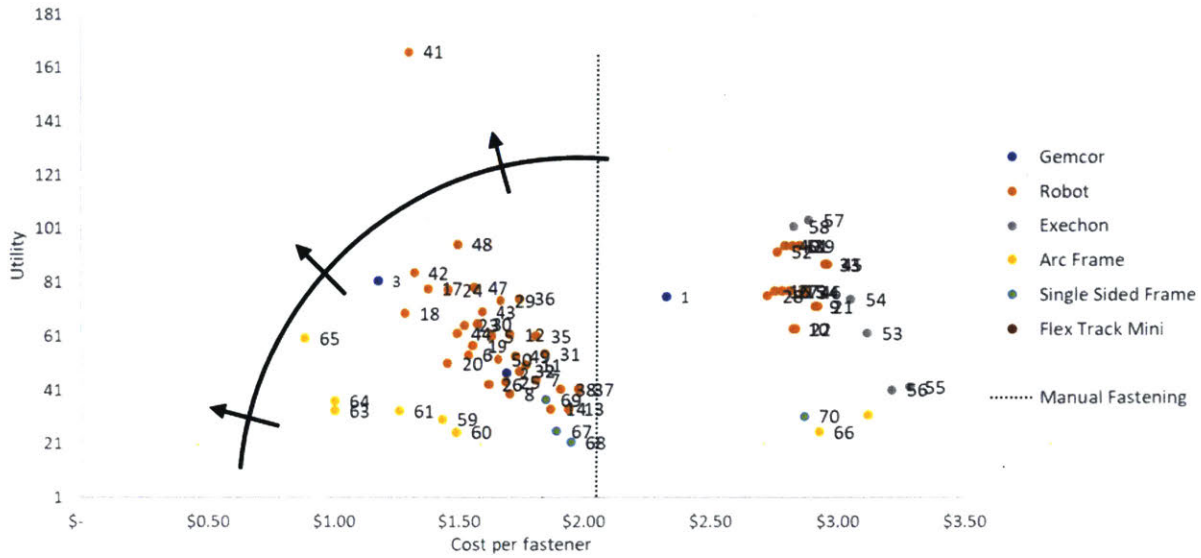


Figure 19: Speed improvements to solution 41

Increasing the mobility and enabling continuous flow of Solution 3 was also explored.

The Gemcor design team investigated reducing the size of the motion platform, thereby reducing the accuracy of the system but also eliminating the need for a foundation in the factory floor.

This new design concept, which cannot be displayed to protect Ascent’s intellectual property, is named Solution 4, and can be seen in Figure 20, below.

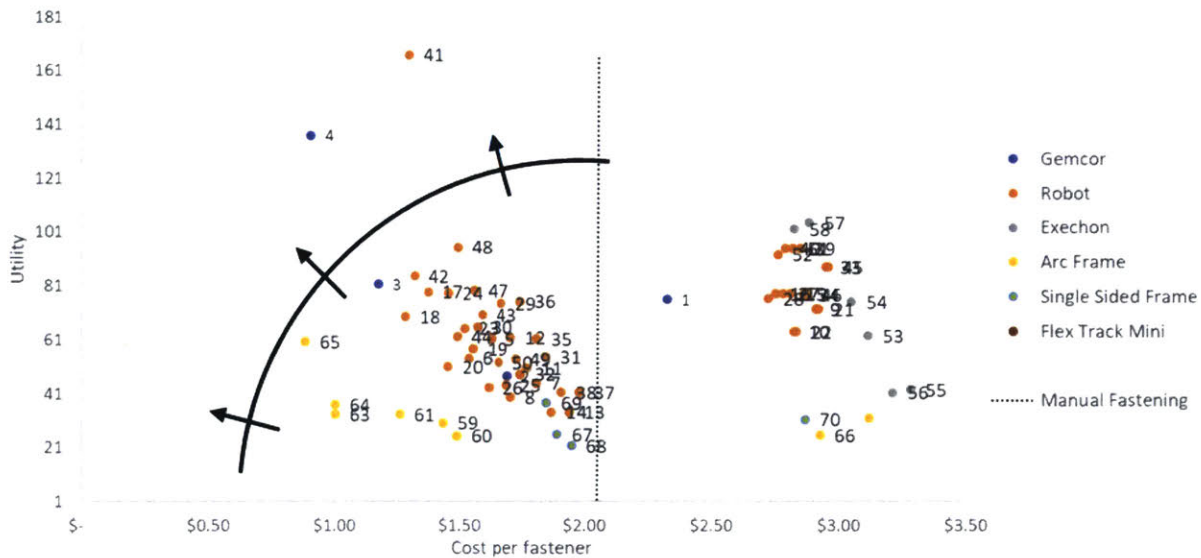


Figure 20: Increasing mobility to solution 3, results in new solution 4

Both the improved Solution 41 and the new Solution 3 show significant improvements in total utility. The cost that is not captured in the product selection tool is the significant investment Ascent will need to make in both of these products if they are to make them available to the customer.

4.3 Appetite for Unproven Technology

The risk a company undertakes when selecting an unproven product is the compression of the development phase with the test phase. Typically, the development phase has a much longer time duration and allows any major technical challenges to be solved prior to building the final product. Optimism and excitement can be detrimental to the successful implementation of an unproven product, in that it may overshadow the significant engineering challenges that must be overcome.

4.3.1 Historical Unproven Automation Technology Introduction

Between 2012 and 2017, robot-based motion platforms were considered the next generation technology in aerospace manufacturing. Two of the leading aerospace equipment manufacturers had assembled and begun the implementation of their Mobile Robotic Platforms (MRPs).

Electroimpact built and delivered five MRPs to Boeing South Carolina in 2016[18]. Electroimpact had been developing robot base drilling and fastening since 2001[19]. The configuration placed the MRP and process head on the outside of the fuselage and utilized humans on the inside of the fuselage to install a collar on the fastener. This product implementation was successful, however, significant development time was invested in the technology.

Concurrently, a different aerospace equipment manufacturer, Kuka, was contracted to implement a MRP system for the 777 fuselage in Everett, WA (see Figure 5 in Section 2.4.1). The leadership team admitted that the system proved more difficult to set up than expected, and the ramp up phase took longer than expected[10]. Kuka did not have a decade of experience in developing these systems, and instead purchased off-the-shelf components from other manufacturers. Where the Electroimpact system could be characterized as TRL 8 prior to implementation, the Kuka system was only TRL 7.

After struggling through the implementation of the Kuka system, Boeing is now looking to implement technology that is proven in a production environment, TRL 9. This either restricts their suppliers from offering potentially superior, yet unproven, solutions, or puts the burden on the supplier to invest heavily in development costs to increase the TRL of their products.

4.3.2 Technology Development Prior to Customer Proposal Request

The new Solution 4 concept is assigned a TRL of 7. This means that the subsystems have been proven in a production environment, however the product as a whole has not even seen a lab environment. That means that if Ascent offers Solution 4 to a customer, Ascent and the customer will take on an immense amount of risk. Ascent's preliminary analysis might not have uncovered all issues with the system. For example, if the natural frequency of the finished product matches the hammer modules frequency, the system could become unstable and not meet the required cycle time.

If Ascent invests in the development of Solution 4 prior to a contract from a customer, they might begin developing a product that the customer does not actually want. Even if Ascent can prove the increased utility from Solution 4, by the time the technology is at a TRL of 9, and the customer is ready to purchase new equipment, the customer's preferences may have shifted.

The product selection tool is a great opportunity to discuss the discrete benefits of these new products and develop a plan to share the risk and development burden. Ascent could work with their customers' research teams to develop these products, without the pressure of production schedules. This will require a high level of trust, as well as a clear delineation of intellectual property rights.

4.4 Summary

The product selection tool has shown a clear opportunity for Ascent to advance their monument and flexible drilling and fastening automation products. Developing these new products, at their own risk, could differentiate Ascent among their competitors and increase the probability that they will win future contracts. The challenge will be whether to proceed with investing in these new concepts, or to wait for customers to show interest and submit contracts.

5 Applying the Product Selection Tool

The Product selection tool has two key use cases beyond identifying gaps in Ascent's product offerings. The first is for Ascent's Sales organization to use the Product Selection Tool to better educate their customers and prove that Ascent's automation technology is superior to their existing manual processes. The second is for Ascent's Proposal team to base their response to a customer's request on the data output from the Product Selection tool.

5.1 Sales Team Adoption

The drilling and fastening products come from two different legacy divisions, Gemcor and Brown. This resulted in the merging of two distinct sales organizations. The employees originating from the Gemcor Sales team are familiar with the Gemcor equipment and the employees originating from the Brown Sales team are familiar with the Brown product offerings. By viewing the attributes of the various products in a single medium, with a common denominator, the teams are better able to integrate and learn the positive and negatives attributes of every product. They are also able to intelligently speak to the different advantages and disadvantages of each product with their customers.

Additionally, most customers of Ascent do not have experience with Ascent's drilling and fastening products. During the sales process, this tool reduces the cognitive load on the customers in decoding the equipment's capabilities at a granular level.

5.1.1 Differentiation Among Competitors

One common question that arises when the Sales team interacts with the Product Selection Tool is 'How do competitors' drilling and fastening equipment compare to Ascent's drilling and fastening equipment?' Incorporating competitor's equipment into the model is a clear next step that will increase the capability and usefulness of the Product Selection Tool. The

primary reason this data is not included in the model is that the data is not publicly available. Although the Design Variable Inputs are available, the Design Variable Outputs are not publicly known.

The Product Selection Tool is designed to emphasize the quantitative differences, and deemphasize the qualitative differences, to remove any innate customer biases. Yet, a qualitative comparison could be made between Ascent's products and their competitor's products using publicly available data. Future research should be undertaken to include quantitative estimates of competitor's equipment, however, caution should be used in showing this data to customers, as it may be inaccurate or misleading.

5.2 Proposal Team Adoption

The Proposal team at Ascent is the intended user of the Product Selection Tool, yet their adoption might prove more challenging than the Sales team. While the Sales team is seeking more information about the products they sell, the Proposals team is intimately familiar with the equipment and how it can be used. Rather than relying on institutional knowledge, if the Proposal team adopts the Product Selection Tool they will have a much easier time onboarding new team members, converting proposals into signed contracts, and even convincing fellow coworkers of their ideas. They can also use the Product Selection Tool to provide customers with a sensitivity analysis around the product they recommend.

5.2.1 Sensitivity Analysis

Currently the model is configured to conduct a sensitivity analysis manually. While holding all variables constant, one can manually change a single variable to see how it impacts the results. Examples of variables that could easily be different in a real production environment, versus what the customer estimates them to be today, include: the number of modules needed on

the process head, the desire to automate the collaring of fasteners, the number of fasteners actually needed to be automated, and the efficiency of the factory the equipment is operating in.

For the results depicted in Figure 11 above, changing the number of fasteners required from 4,000 to 3,000 changed the top four recommended solutions from 65, 3, 41, and 42 to 41, 42, 17, and 18. Where the first set of solutions contained both monument and flexible motion platforms, the later set of solutions only included flexible, robot-based motion platforms.

Future research could investigate methods of incorporating an algorithm to automate the sensitivity analysis. This additional feature, similar to a shadow price in an optimization model, could provide the Proposal team with the most critical attributes and how much they can be adjusted before the customer takes on additional risk.

6 Conclusion and Future Work

Ascent is well positioned to maintain a strong market share in the drilling and fastening aerospace industry. Looking forward, Ascent should focus on both near term improvements both in their product line and in their interactions with customers. Furthermore, Ascent should utilize a data driven approach as they look for new technologies that might disrupt the automated drilling and fastening market.

6.1 One Year Plan

Ascent's drilling and fastening product portfolio covers a wide range of customer applications, and there is not a clear overlap between different products offering the same utility at the same cost. Additionally, the manufacturing of these products is based on a pull system from Ascent's customers. A pull system implies that the product will only be constructed if it is requested by a customer. Therefore, Ascent incurs minimal cost in retaining these 71 different product configurations as an option for their customers.

Ascent's near-term plan should be to focus on the two improvements detailed in section 4.2 above. These changes would differentiate Ascent's next generation products, a key selling point when attempting to integrate into their customer's next generation production systems. Customers are currently seeking efficiency improvements with minimal risk. Maintaining the product's overall Technology Readiness Level (TRL), while making modifications at a component level, will provide a competitive advantage over companies either selling a legacy product or trying to sell brand new technologies.

6.2 Five Year Plan

Looking into the future, Ascent should look to partner with their customers on emerging technologies. Although today's leading aerospace structure joining technology is drilling and fastening, other technologies such as adhesives and composite welding are on the horizon. These disruptive technologies are still 10 to 20 years away from being viable at a large scale, however small proofs-of-concept have already been successfully implemented[4]. Incorporating adhesive and welding products into the Product Selection Tool will reveal the advantages and disadvantages of pursuing the research and development required.

Partnering with Ascent's customers in advancing this technology will maintain Ascent's status as a technology leader in the Aerospace tooling and equipment market. A partnership will also limit Ascent's financial risk, as they will share the financial burden with a customer. The main concern with this approach is not retaining the intellectual property if any new technology developed under the partnership. The retention of intellectual property should be weighed against risk of falling behind their competition.

6.3 Summary

The Product Selection Tool provides a common framework for the entire company to make data-driven decisions. Using this tool regularly will improve communications between the Sales and Proposal teams and reinforce the attributes that drive value for the customer. This framework can also apply to other areas of Ascent's business, and even beyond the aerospace tooling and equipment industry all together. The value versus cost tradespace is an ideal lens in which to view any current or future product a company offers their customer.

7 Bibliography

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