ENPM692
Manufacturing and Automation

Project on:

Process Analysis of Space Hardware Manufacturing

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Table of Contents

Abstract

The manufacturing of space hardware is a very precise and controlled process. Space mechanisms are unique because there is no way of servicing them once they are launched. Because of this limitation, a lot of time and money is spent on making sure the mechanism is robust and the hardware manufactured will work during the separation. This report will focus on the manufacturing process of a small aerospace hardware manufacturer - Planetary Systems Corp (PSC). PSC focuses on building separation systems that will separate small scale satellites from the rocket once they reach orbit. These are mission critical systems that can cost millions of dollars if they do not perform properly. Their manufacturing process is very intricate and there are ways they can improve the existing processes while maintaining their level of confidence in their systems. A manufacturing simulation software is used to identify areas of improvement to optimize their processes. Optimizing these processes will lead to increased volume of production, shorter lead times, lower costs, and greater reliability and repeatability.

Background

Space Hardware Manufacturing

Manufacturing of space hardware must be very tightly controlled in order to perform as designed. Part tolerances are kept low so that parts fit together exactly how they are supposed to. Surface treatments are applied in order to increase the properties of the part such as wear resistance and EMI resistivity. These features make space hardware very difficult to manufacture and leads to high cost and long lead times. With part lead times being so long, program managers must schedule procurement far in advance. It can also lead to long periods of time where assembly is on hold waiting for parts to come in house.

Space applications call for complex and creative projects to solve challenges faced in space. Engineers can design the perfect mechanism for an application but become forced to alter their design in order to be manufacturable. These design alterations could increase the cost and weight of a part while also making them less capable. These design constraints are a large drawback of traditional manufacturing and could be solved by incorporating newer technologies such as additive manufacturing. Some space companies have already started to 3D print space hardware. The Vega rocket is currently testing the abilities of a 3D printed thrust chamber for its M10 engine. By using advanced technologies like these, manufacturing can become cheaper, faster, and more creative.

While not all space hardware is manufactured the same, we can get an idea of some of the difficulties of space hardware manufacturing by looking into one specific company. The company we chose to analyze is a small engineering company where one of our group members is currently employed.

Planetary Systems Corp

Planetary Systems Corp is a small engineering company located in Silver Spring, Maryland. They focus on separation systems for small satellites and cubesats. These mechanisms separate the satellite from the rocket once the rocket gets into orbit. All of their systems use DC brushed motors to separate in less than half a second. Using motors instead of consumables such as pyrotechnics allow the systems to be reset quickly. During the manufacturing process, the systems can be stowed and deployed multiple times to verify they are functioning correctly.

The products produced by PSC are outlined below:

Motorized Lightband

Figure 1: Motorized Lightband

The Motorized Lightband (MLB) is the company's highest selling product. They vary in size from 8" to 38" in diameter to accommodate different sized satellites. One side of the MLB is attached to the launch vehicle, and the other to the space vehicle. It uses two DC motors to lock the two rings into place. When ready, the motors are powered which release the two rings and allow the attached springs to push the space vehicle away from the launch vehicle.

Advanced Lightband

Figure 2: Advanced Lightband

The Advanced Lightband (ALB) is the upgraded version of the Motorized Lightband. The ALB is a product of PSC's years of experience designing, building, and testing the MLB. The ALB has far fewer parts which will aid in the easing of procurement, inventory tracking, inspection, and build.

Canisterized Satellite Dispenser

Figure 3: Canisterized Satellite Dispenser

For customers that require their satellite to be encapsulated, PSC offers the Canisterized Satellite Dispenser (CSD). The CSD is meant to accommodate a special type of satellite called a Cubesat. A Cubesat is a satellite that follows a standardized sizing spec where a U is a standard 10cm^3 area. These "U"s are put together to form different sizes such as a 3U (30cm x 10cm x 10cm) or a 12U (30cm x 20cm x 20 cm). These satellites are loaded into the box and when the time comes, the door opens using the same motor as the MLB. Once the door is open, the satellite is pushed out and into orbit. The CSD shares some parts with the MLB such as screws and washers and will have to be taken into consideration when looking at the inventory of such parts.

The MLB and CSD have achieved a technology readiness level (TRL) 9 rating, meaning it has reached the highest level of technology maturity according to the US government. They have achieved this level of assurance by never failing to separate in orbit.

This success can be attributed to their high standards when manufacturing parts, strict inspection process, and highly controlled assembly procedures.

The Lightband is made up of over 50 different parts making inventory tracking and procurement a difficult problem to handle. With 10 different Lightband sizes, parts unique to each size also add complexity by needing to track more parts. PSC will have to track inventory for all of these parts, including parts that also get used in other builds such as CSD builds. If PSC loses track of inventory or parts are manufactured incorrectly, it could lead to long delivery delays and possibly even customer mission delays. This paper outlines how PSC can alter their current manufacturing process to avoid problems throughout the processes.

Problem

The problem we hope to address during this report is the duration and cost of manufacturing space hardware. We will be identifying where PSC can save time during the manufacturing process and how the cost of building these systems can decrease to save their customers money.

Goal

In a competitive environment, offering a variety of products to meet customer demand is not enough for a manufacturer to achieve a high level of financial performance. In addition, an organization must maintain high performance levels in the management of the flow of materials within the organization from the point of origin to the point of consumption and from raw materials to in-process inventory to finished goods. Achieving such goals requires that a manufacturer define appropriate logistics performance objectives or goals pertaining to procurement, production and distribution processes.

The goal of this project is to reduce lead time, build time and inspection time as well as optimize the sub processes involved, to improve efficiency of the manufacturing processes of various satellite separation systems being manufactured by PSC. By incorporating non-traditional manufacturing processes such as additive manufacturing, using different simulation softwares like Flexsim to keep track of the inventory and simulating various What-If scenarios we anticipate that this goal may be achievable.

Current Process

The parts assembled at PSC are machined and fabricated by vendors maintaining standards set by PSC. These parts are designed, assembled, and tested by Engineers working at PSC. The figure below shows the lifecycle process of parts from being ordered to being used in an assembly. All the tasks associated with procurement, inspection, storage, assembly, testing and shipment are documented by PSC and controlled by inventory management softwares.

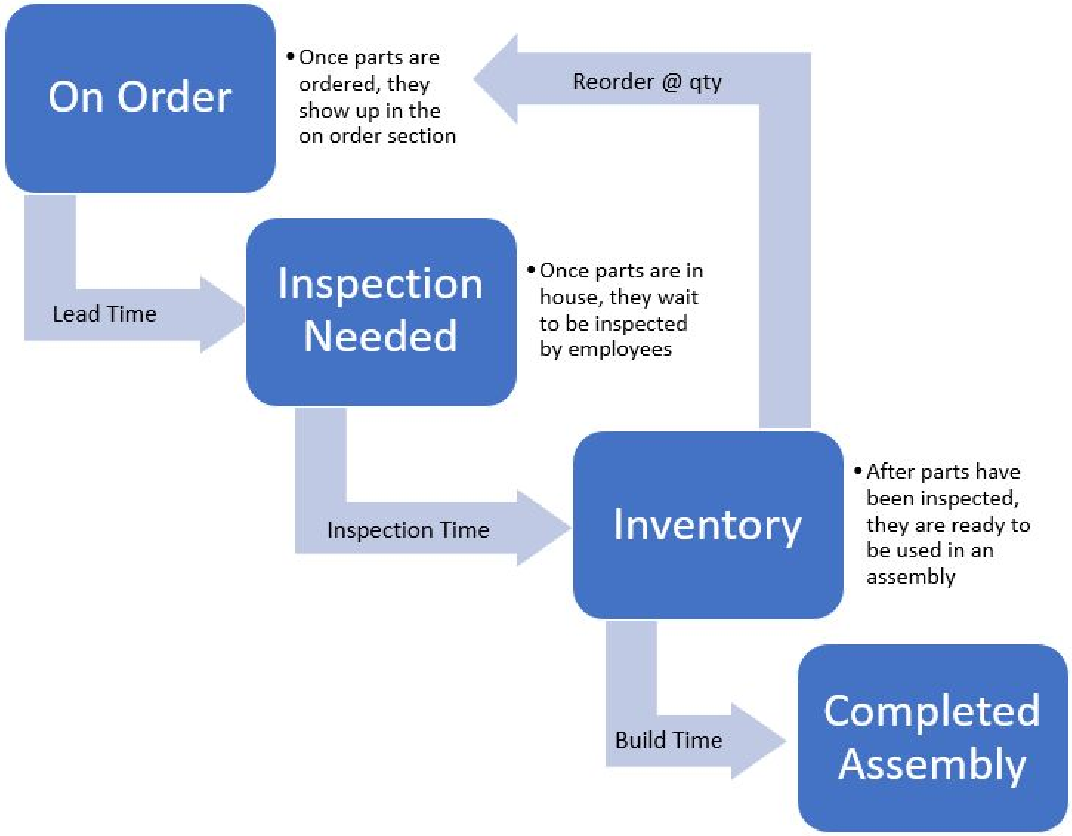


Figure 4: Flowchart of Manufacturing Process

The process starts when parts are placed on order. Once they are placed on order, they take time for the parts to be manufactured. Some parts can take a week to come in, other more complicated parts can take several months. These times are called lead times and should be tracked by the company in order to schedule restocking correctly. Once the parts come in house, they must wait to be inspected before they can be put into inventory. The inspection time can vary based on the complexity of the part and the number of resources available. Once the parts are accepted into inventory, they are available to be used in an assembly. Assemblies must wait for all the required parts and sub-assemblies to become available before beginning build.

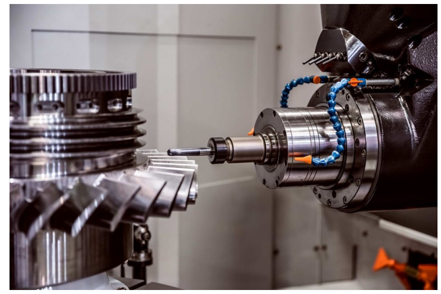
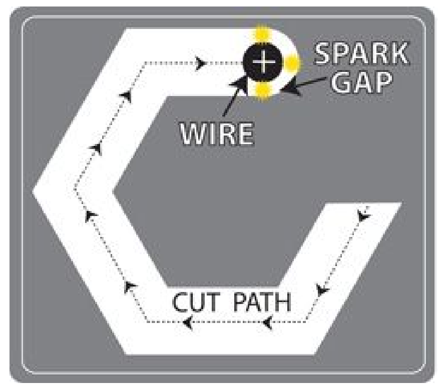
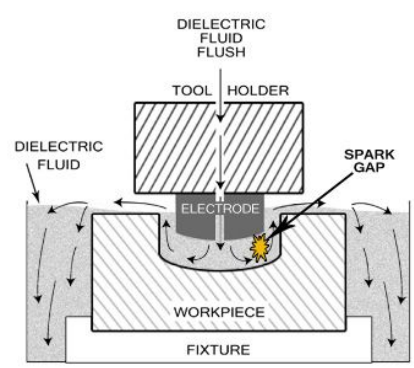
The table below outlines the parameters that must be monitored and adjusted when optimizing the manufacturing process.

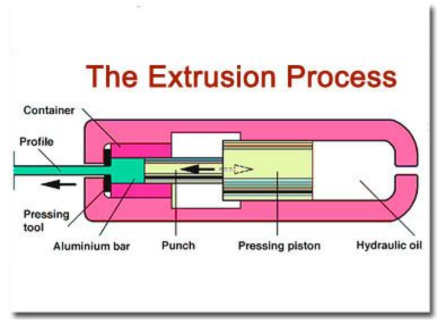
Parameter	Description
Lead Time	How long it takes from parts to come in house after being ordered
Reorder Qty	The quantity of parts ordered at a time
Reorder Trigger	The threshold of inventory that triggers a reorder of a part
Inspection Time	The time it takes to inspect a part before it goes into inventory
Build Time	The time it takes to build an assembly

The main processes we will be analyzing in our report will be the manufacturing and procurement of parts, inspection, and assembly. In order to optimize these processes, we must first understand how they are currently being done.

Manufacturing & Procurement

Vendors manufacture the parts by maintaining the Good Manufacturing Practices (GMP) set by PSC. Engineers at PSC design parts and decide how tight of tolerances these parts need to be in order to function properly. Once the manufacturing drawings are approved, they are sent to the machine shops where the parts will be quoted. Often, the machinist will give their input on the feasibility of a part or offer advice on how to make the part easier to machine. The machinist will also help decide the best process to use to manufacture each part. Some of the processes currently being used are outlined below:

Manufacturing Process	Description	
CNC Milling	Material is cut away from a solid piece of material using various different types of sharp cutters mounted to a spindle. The cutter moves around the part using CNC programming (G code and M code).	
Wire Electrical Discharge Machining	A wire is inserted through a hold in the material and charged. The wire is moved around the part creating a spark between the wire and the part. The spark cuts away material forming shapes inside the material.	
Ram Electrical Discharge Machining	A spark is created between the electrode and the part. The electrode is moved around the part through CNC programming. As the electrode moves around the workpiece, the spark cuts away at the material forming cavities of different shapes.	

Extrusion	Long pieces of metal are heated and forced through a die. The die forms the cross section of the part and then the long piece is divided into smaller pieces to create individual parts.	

Inspection

Inspection is a critical process in the manufacturing process. In order to ensure the parts will function exactly as they are designed, they must be rigorously inspected before being used in assembly. If parts do not meet the tolerances in the drawings provided to the machinists, they will either be rejected or accepted use-as-is by the chief engineer. Currently, inspection is a large bottleneck as multiple parts come in house around the same time. Once the parts get added to the queue of parts waiting to be inspected, it could be weeks or even months until they are ready to be used in assembly. Currently all inspection is done by hand using handheld tools such as micrometers, height gages, and calipers. Cylindrical parts are inspected by putting them through ring gages. Holes are inspected to be the right diameter using very precise gage pins. All of these processes take a lot of time and resources away from other processes. By optimizing and automating the inspection process, resources are freed and parts are ready to use in assembly quicker.

Assembly

The assembly process is very tightly controlled, tracking the torque on each screw and ensuring parts are put together perfectly. Engineers at PSC assemble the systems by hand using tools such as torque measuring screwdrivers and hex drivers, pin presses, and even some custom tools.

Assembly is very resource intensive as many steps require both a technician and a quality assurance engineer to be present. While other industries have introduced robots into their assembly processes, the space industry hasn't quite taken advantage of automation. This is likely due to the high standards set by the space industry that robots in the past have not been able to accommodate.

Inventory Management Software

Tracking parts during assembly has two main functions. The first is to keep traceability of each part in case something goes wrong with that specific part. The second is to know how much inventory is available. Knowing the inventory count is extremely important in our analysis as it can trigger the reordering of parts, let us know what parts are causing slowdowns, and much more.

Currently PSC uses an inventory software system but may not be using it in a way that collects data efficiently. Parts are usually taken out of inventory once build is complete. This could lead to incorrect inventory numbers and ultimately lead to late reordering of parts. Having real time inventory tracking would lead to a more accurate inventory count and a more efficient reordering of parts. One possible way of having real time inventory tracking is by using a barcode scanning system where parts are deducted from the inventory management software as soon as they are used. Assembly times could also be tracked by looking at when inventory is being used and correlating that with what parts are used in each step. This data can also be used while looking for ways to optimize the manufacturing process.

Simulation

A manufacturing process simulation can be an extremely powerful tool. It can show bottlenecks, address resource issues, and track where a company can save the most time and money. Many simulations exist to aid companies optimize their processes.

For this project, we chose a simulation platform called FlexSim. Flexsim is a powerful tool for creating process flows and analyzing the data created in these processes. Processors can be used to simulate a process such as assembly or inspection. Parts can be moved from process to process using task executors. When parts are waiting to be moved to the next process, they can be stored in queues until the process or executor is ready. Once these objects are set up, the process flow must be defined. In FlexSim, parts can be taken through a defined path from start to finish. Parts can be created based on statistical distributions or on a schedule. These are only a few of the incredibly useful tools that can be to simulate a given process.

While being able to simulate the process is useful, the real value of FlexSim is the analysis tools available. FlexSim makes it easy for the company to track different parameters such as how long parts have been in a certain queue, or how utilized a process is. This data can be tracked and recorded several different ways including bar graphs, pie charts, and time varying graphs. We will use these analysis tools to determine how beneficial a change to the process is.

Simulation Model

We created a flexsim model to analyze the current manufacturing process. This model serves as our base model that we can run different what-if scenarios to see how changing certain parameters can improve the process.

Flexsim Model Description

In our model, after parts are placed on order, they are put into the on order queue. Then a task executor will move the parts from the on order queue to the inspection needed queue. The rate at which these task executors move will simulate the different lead times for each part. After they are placed in the inspection needed queues, they wait to be pulled into the inspection processor.

This processor runs at a different speed depending on the part it's inspecting in order to simulate inspection times. After the parts are inspected, they are put into their respective inventory queue where the builder process can pull from. The builder process pulls a different amount of each part based on how many parts that build requires. Build time can also be varied by speeding up or slowing down the processor. Once the processor is complete, a finished product is placed on the rack ready to be shipped.

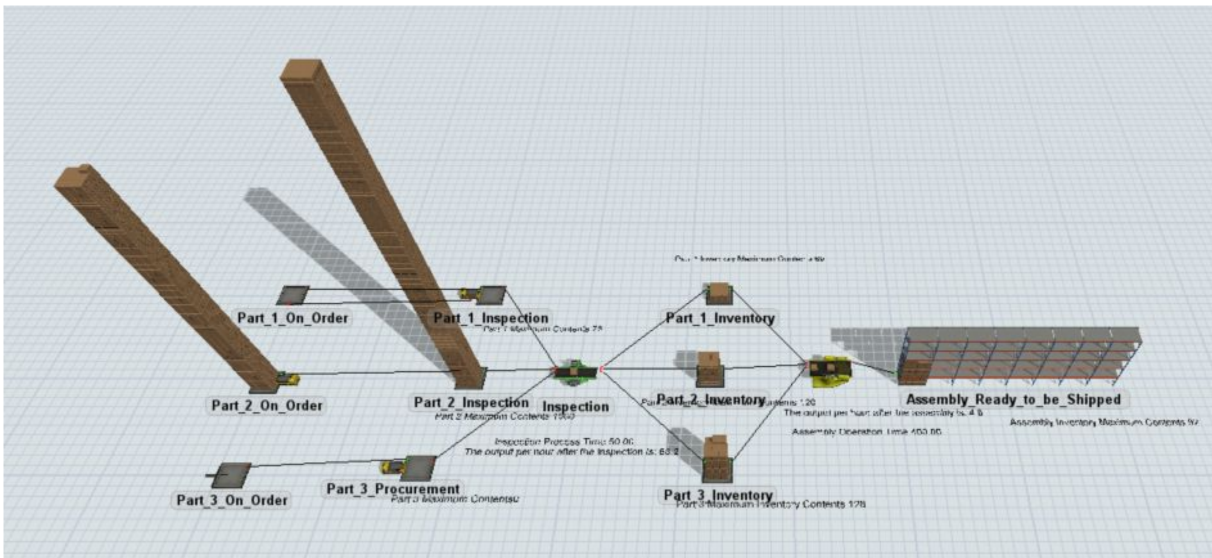


Figure 5 : Simulation of the overall manufacturing process

Model Assumptions

Some assumptions were made in order to simplify our model. They are outlined in the table below along with our justification:

Assumption	Justification
All parts are flawless and pass inspection	For the sake of this model, we will use a best case scenario where all of the parts are flawless. Dealing with rejected parts is out of the scope of this project.
Build always takes the same amount of time	While build doesn't always take the same amount of time due to external factors, we will use an average build time in the simulation.
Design and testing are not part of this simulation	While design precedes the manufacturing process and testing follows, they will be considered outside of the scope of this project.
Only 3 parts in the assembly	While the actual assembly is over 50 parts, we will only be using 3 for this project. By doing so, we will prove the functionality of the software without having to create an in depth model.

What-If Scenarios

A what-if scenario is a way to theoretically alter a process and see the effects that change has on the process. These scenarios can be anything from adding or subtracting resources and processes, changing process speeds, or changing quantities of things. In this section, we have performed some what-if scenarios on our model and analyzed how they have changed the process. While the model can output a lot of useful data, we chose to show what we believed showed the greatest effect the what-if scenario had on the process. The rest of the data can also be analyzed and pulled at any time if requested.

1. Adding a Second Inspector

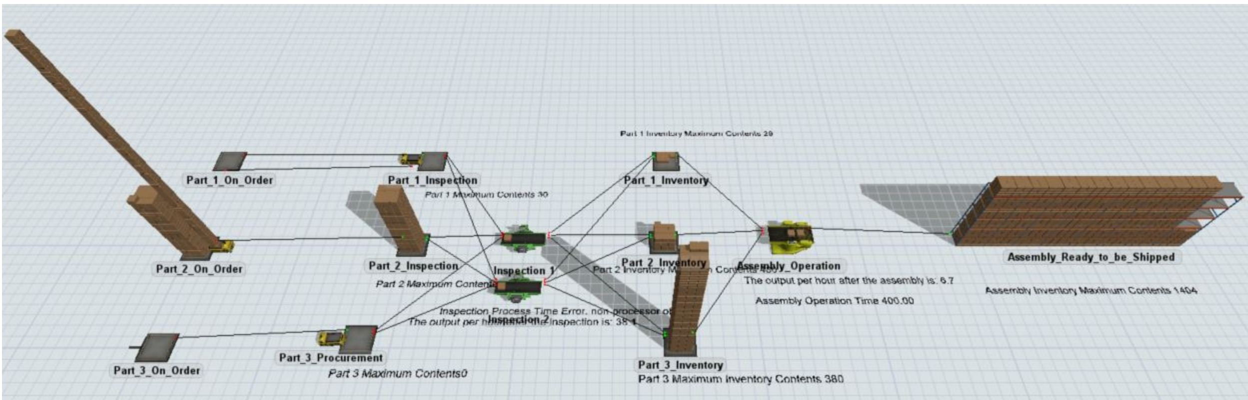


Figure 6: Adding Second Inspector

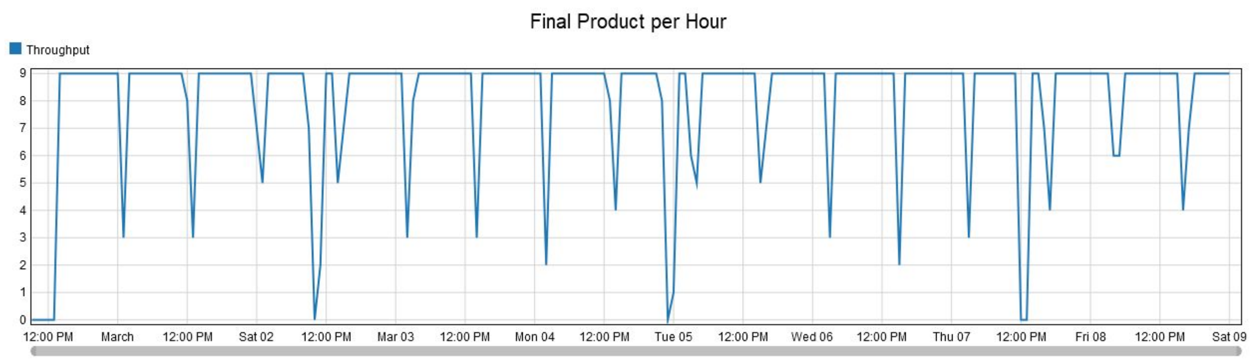


Figure 7: Final Product per Hour With 1 Inspector

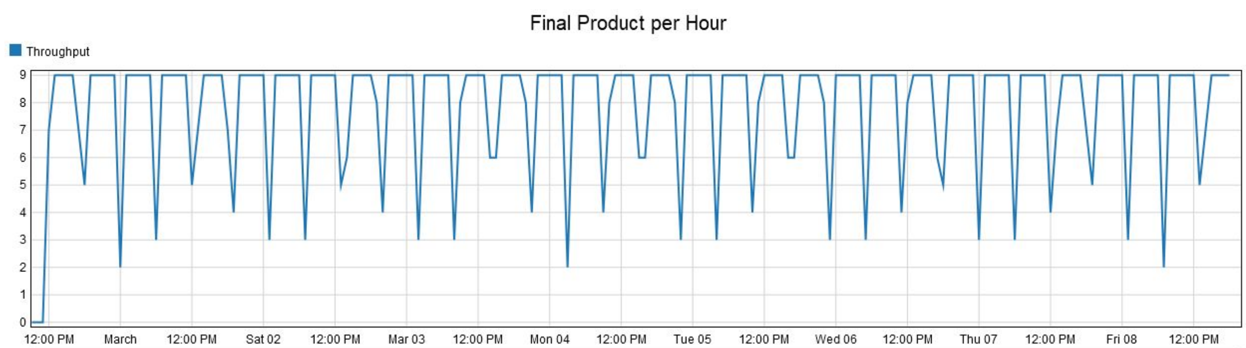


Figure 8: Final Product per Hour With 2 Inspectors

In figure 7, we see that with one inspector, the throughput of products per hour drops down to zero three times. These are times where parts are being held up in inspection rather than in inventory. By adding a second inspector, we eliminate these drops in figure 8 and are always producing final products.

2. Decreasing lead times

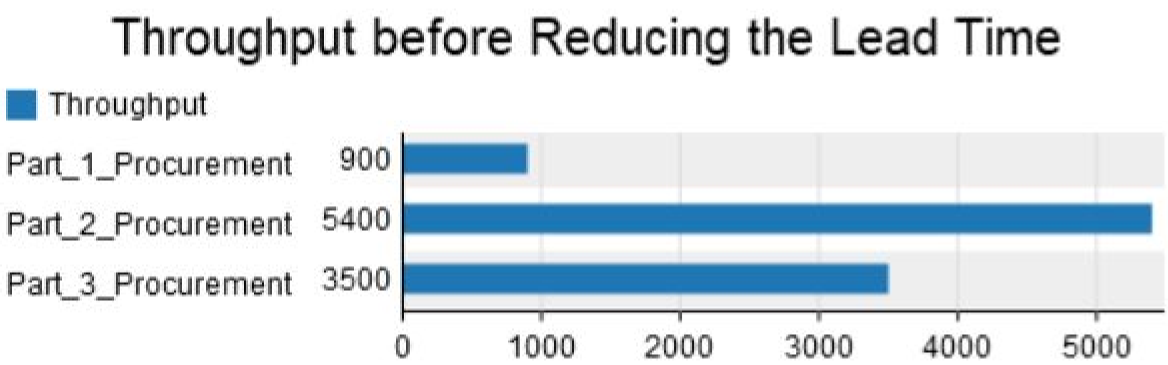


Figure 9: Total Throughput of Parts Procured Before Reducing Lead Time

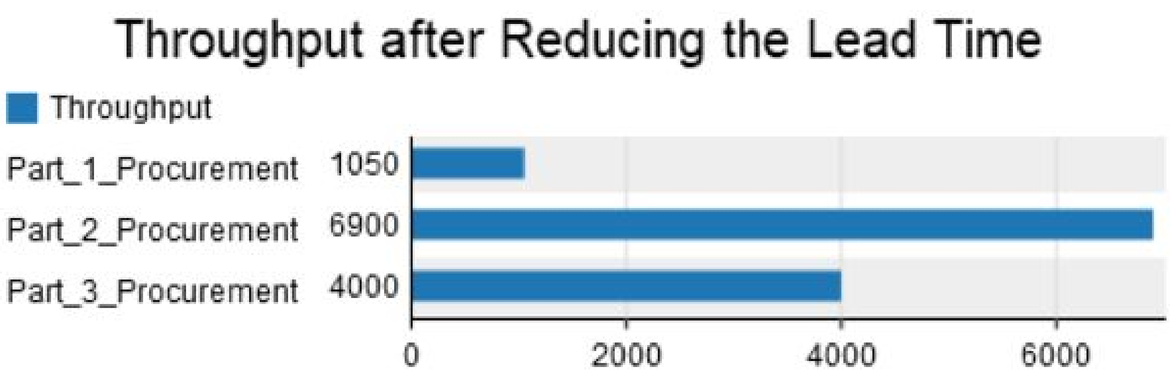


Figure 10: Total Throughput of Parts Procured AfterReducing Lead Time

We can observe that after reducing the lead time, we were able to procure more parts.

3. Adding Second Builder

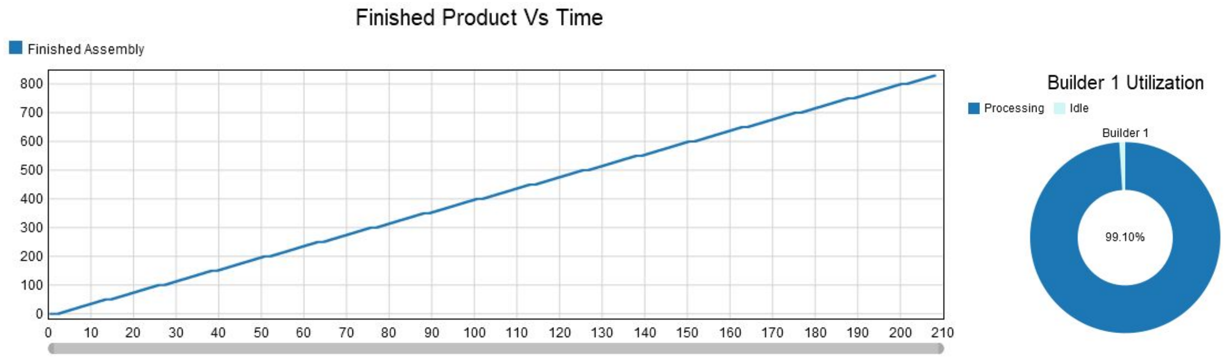


Figure 11: Finished Product vs Time and Utilization of One Builder

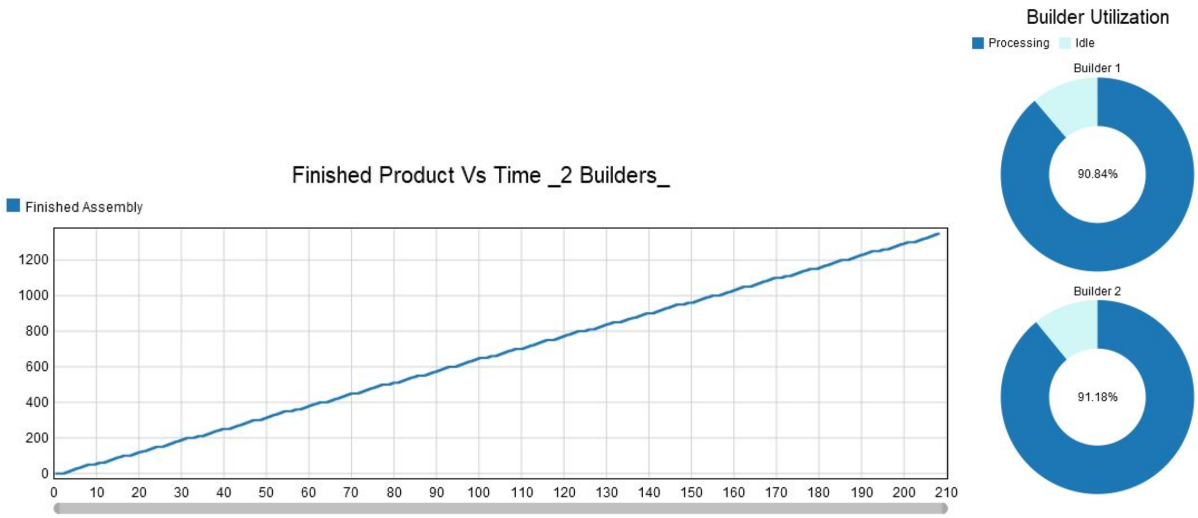


Figure 12: Finished Product vs Time and Utilization of Two Builders

By adding a second builder, we were able to increase the total number or assemblies made by over 70%. The pie charts indicate that with only one builder, the assembly process was being saturated. The builder was being utilized over 99% of the time meaning there were a lot of times where parts were waiting to be assembled but there wasn't a builder available. When there are two builders, they are being utilized around 91% of the time. This shows that they are still being utilized quite a lot but aren't saturated.

4. Optimizing Qty Ordered and Reorder Trigger

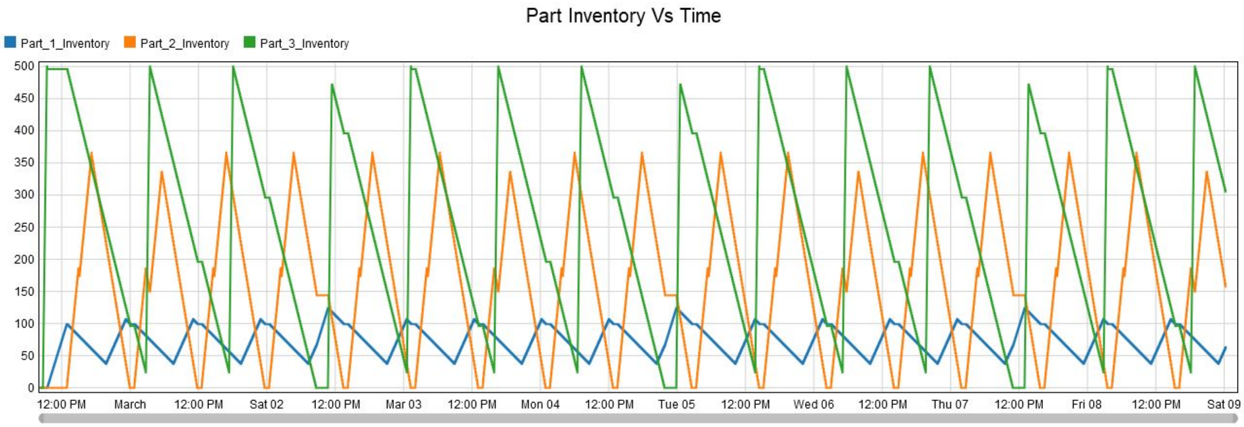


Figure 13: Part Inventory vs Time Before Optimization

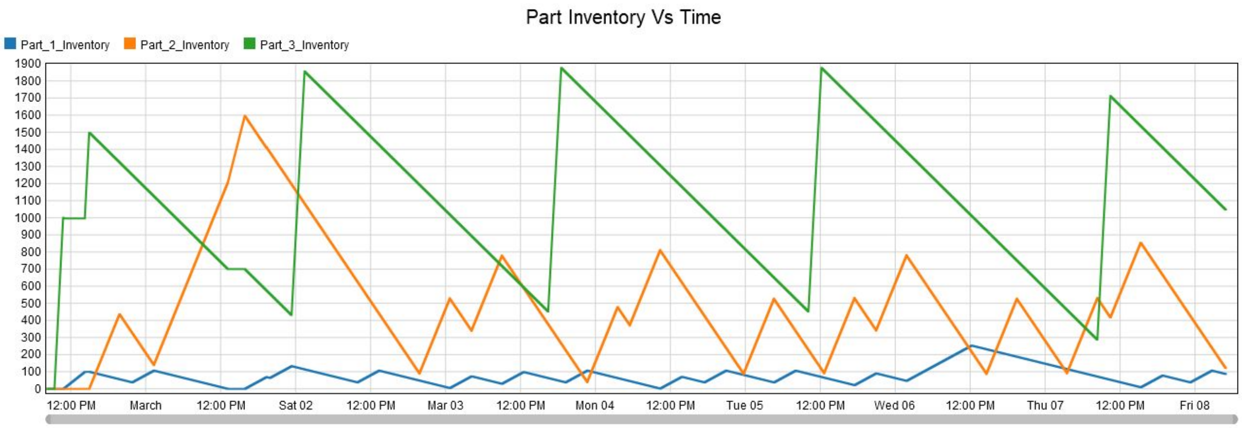


Figure 14: Part Inventory vs Time After Optimization

The figures above show the value of optimizing how much of each part gets reordered at a time and at what inventory levels parts are reordered at. In the first figure, inventory drops to zero before parts are restocked. By adjusting the quantity ordered and reorder triggers, inventory never drops to zero. Keeping inventory from dropping to zero will allow assembly to continue working without being interrupted.

5. Decreasing build time

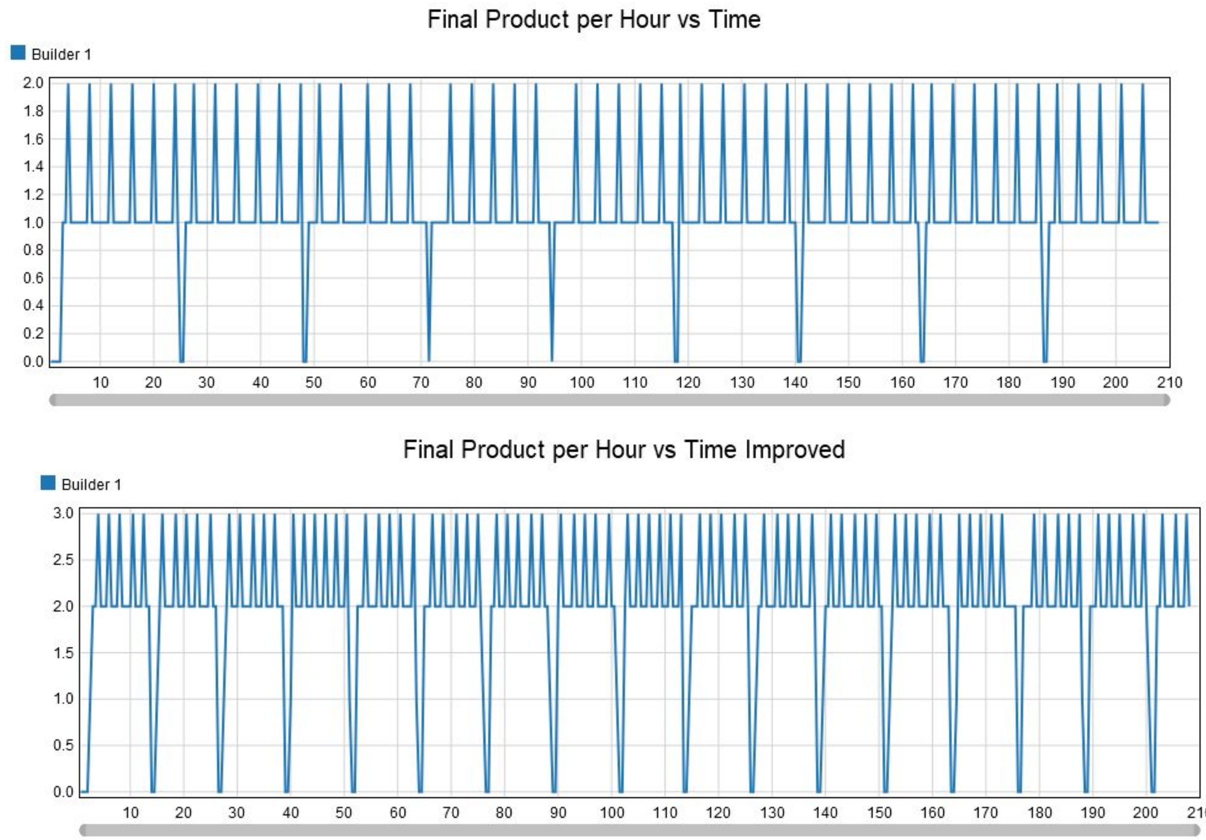


Figure 15: Final Product vs Time Improved Graphical representation

By decreasing build time, we can see that the average product produced per hour increased from ~1.2 to ~2.5. While this result is to be expected, what is also made clear is the number of times the product per hour dropped to 0. By simulating the decreased build time, we are able to predict an inventory issue where parts are being used up quicker than they are being restocked. This leads to extended periods of time where the assembly processors are waiting for parts to come back into stock.

Process improvements

Manufacturing Improvements

The current design for the separation system is fabricated out of aluminum and carbon fibre materials. These two parts are then bolted together to form one big cone ranging in several diameters. Although the current design has 100% success rate, recent calculations have shown that payload adapters fabricated from only carbon fibre provide better efficiency. This new design will improve the system's weight and stiffness which will help increase the rocket's efficiency and investment payback.

Currently, the two parts fabricated from aluminum and carbon are bolted together. But if the payload adapter is fabricated of only one material then PSC can incorporate using "finger joints" which are being used for glued laminate(glulam) construction beams. These joints can be used only when joining similar materials and these joints provide larger contact surfaces and stronger joints.

Figure 16 : Carbon fibre adapter with finger joints

The figure above shows the payload adapter fabricated from carbon fibre with finger joints. Therefore, the two parts are glued together forming “finger joints”, rather than bolting them together.

Though this design has proven to increase efficiency, there are some challenges that PSC might face. This design requires novel water jet cutting techniques as neither milling nor sawing can be used to obtain complex carbon fibre geometries. One huge advantage of the waterjet is that it can cut very thick carbon panels with relative ease.Another major advantage to using a waterjet is the dust containment. One of the main concerns when working with carbon fiber is dust. Carbon fiber dust can find its way into the inner workings of the machines causing parts to grind or wear faster. With a waterjet, all the carbon dust gets blasted into the water tank where it is easier to handle for proper disposal and no expensive dust evacuation systems are required.

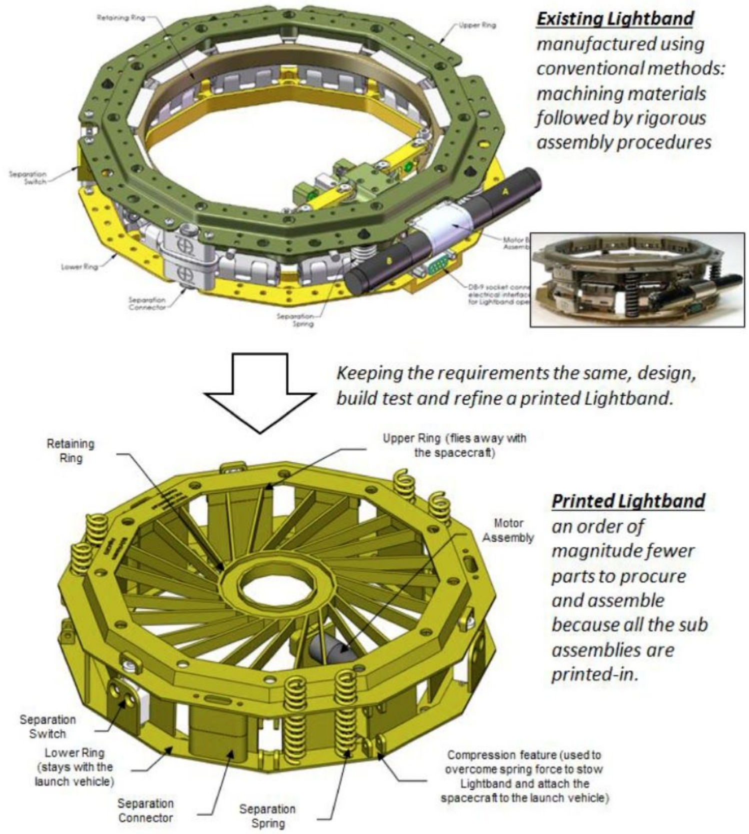


Figure 17: 3D Printed Titanium Lightband

The other process that can be incorporated is utilizing Additive manufacturing techniques to manufacture separation systems for US government and commercial customers. A recent study, carried out by PSC shows that 3D printing the parts will result in 90% reduction in cost and energy.Savings are attained by printing in many of the parts and sub assemblies as one part. This greatly reduces the labor associated with design, procurement, assembly and calibration of mechanisms.

Inspection Improvements

After parts get manufactured, they must be inspected.Parts must meet tight specifications in order to function properly when assembled. Currently at PSC the parts are manually inspected by the engineers.

Manual inspection process results in higher labour costs, ineffective identification of defects and increase in labour fatigue rates. The improvements given below can be implemented to increase inspection speed:

1. **Coordinate Measuring Machine (CMM)** - CMM allows inspection of products for quality by measuring the dimensions and quality of the object.CMM is made up of three axes X, Y and Z and each axis helps to measure the product and further positions them accurately in other precision machines.

Figure 18 : Nikon CMM Machine

The measurement capabilities of a CMM can stretch through many different parts such as:

- Dimensional – The ability to measure multiple axes of an object to get the whole dimension.
- Profile – CMM can capture profile information and the form of both 2D and 3D objects.
- Angle – Angles and orientation of two different points of an object can easily be measured.
- Depth – The ability to map the depth of any object with the use of two stereo images.

2. **Optical Comparators -** Optical Comparators are a type of optical measuring instrument. The measurement principle is similar to that of optical microscopes. The target is placed on the stage and a light is shined on the target from underneath to project the target's shadow on the screen. Optical comparators were originally developed to inspect the outlines of targets.

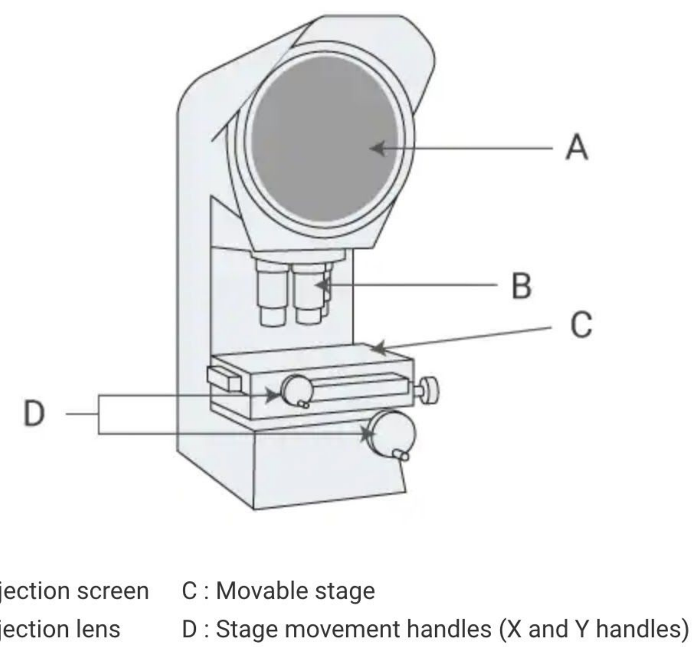


Figure 19 : Optical Comparator

The following are some advantages of optical comparators.

- Non-contact measurement of target.
- Measurement is possible even for targets with small or complicated shapes.
- Unlike measuring microscopes, there is no need to look through an ocular lens, which makes it possible for multiple people to perform observations at the same time.

Assembly Improvements

For manufacturers, the benefits of assembly line production are enormous. An inherent part of the idea of assembly lines is that each item produced from a certain product line is as close to identical as possible. This allows quick and easy assembly throughout the process, and it also means that maintenance and replacement of worn or broken parts is a much simpler task down the road. Currently assembly at PSC is done manually. This results in slower manufacturing of new products. PSC can incorporate the following improvements to expedite the overall assembly process:

1. **Screw Driving Robots** - Screw Driving Robot is an excellent solution for assembly applications that require compact workstations and an extremely fast and accurate robot where no wrist rotation is required.A screw driving robot picks individual screws from a screw feeder and uses a nut runner to drive the screws into four points on a terminal box for assembly. Once all four screws are in place, the terminal opens, the screws fall through and the cycle repeats. This helps display the speed and repeatability of the robot and system.

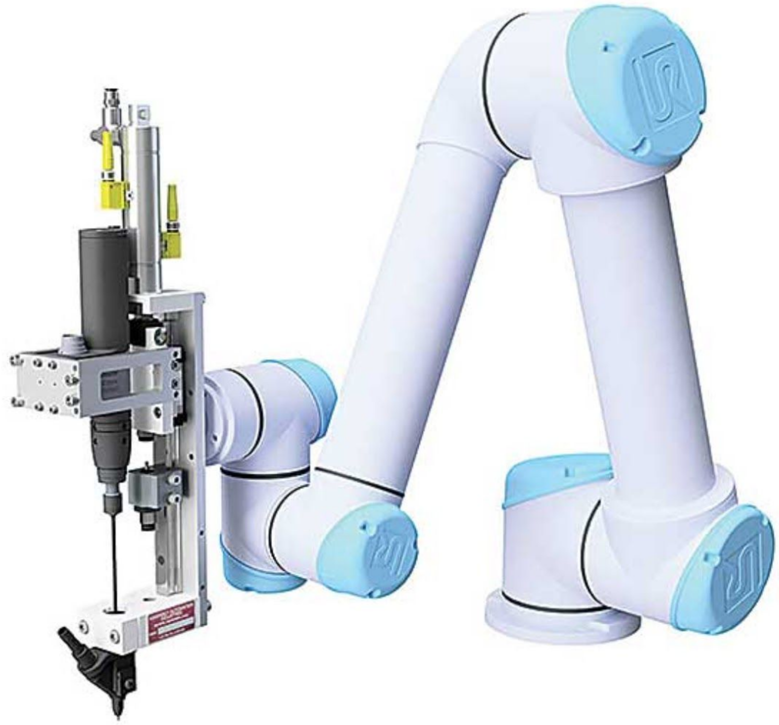


Figure 20: Screw Driving Robot

Some of the advantages of using Screw Driving Robots are:

- They allow a greater degree of consistency than traditional handheld screwdriving systems.
- They do not get tired and they do not take breaks.
- Robots have more flexibility than fixed screwdriving.
- They are more consistent and can be run faster than handheld driving, due to the increased strength and repeatability of the robot.

2. **Adhesive/Grease Dispensing Robot** - Robotic dispensing units can take many forms. Among the most commonly used are desktop or benchtop units, which usually have a work area ranging from 200 mm by 200 mm to 400 mm by 400 mm. Such units are often used to increase productivity without adding labor and these robots improve precision in dispensing.Mobility and adaptability are also advantages to desktop units, which can be moved between stations and programmed to handle new dispenses and products by the day.

Often these systems are mounted with cameras that allow these robots to view and precisely measure the product inorder to carry out accurate dispensing.

Figure 21: Adhesive/Grease Dispensing Robot

3. **Automated Pin Pushing** -The increasing need for flexible and cost effective manufacturing of electronic devices, increased demand of precision in techniques for the insertion of connectors on printed circuit boards (PCBs) and the increased adoption of these automated installation machines in the medical field, is driving the growth of the global automatic pin insertion machines market. Pin insertion machines provide hassle free auto-insertion of pins. These machines are capable of feeding and cutting reel terminals and inserting them into the PCB hole in a precise manner.

Figure 22: Automated Pin Insertion Machine

Some of the advantages of using these machines are as follows:

- Reducing manufacturing costs, thereby increasing profits.
- Improvisation of manufacturing processes and eradicating re-work.
- Convenient placement of pins on the printed circuit boards automatically.
- Compact size allows them to operate in small spaces.

Conclusion

By using this simulation software, PSC can optimize their manufacturing of their satellite separation systems. This simulation can be used to find where bottlenecks occur and where they should be allocating resources. It can also be used to test how making alterations to a subprocess will affect the rest of the process. Being able to simulate what will happen in the future if a parameter in the process is changed can save PSC a lot of time and money.

Optimizing their production process will allow PSC to continue delivering reliable separation systems to their customers but with decreased lead times and at a fraction of the cost. Customers will be more likely to purchase PSC's products because they will gain margin in both their schedule and budget.

The time saved in product manufacturing can also free up employees to work on other projects. These projects could include new and improved products such as the Advanced Lightband. They can also include projects such as automation tasks as described in the process improvements section. These projects would end up improving the manufacturing process and the cycle of becoming an efficient manufacturing company continues.

Future Work

The work done above merely shows the functionality of this software and how it can be useful to PSC. There is still a lot of work to do before it can be directly correlated to the actual PSC manufacturing process.

Due to limitations on the trial version of the FlexSim software, we were limited to 30 objects. In reality, PSC has multiple products and hundreds of different parts to keep track of. There are also subassemblies that need to be built before a final assembly can be built. PSC will need to make a much more detailed version of our model before it can become useful to them.

Environmental testing could also be added to the model to truly encompass the full manufacturing process of the separation system. Factors such as test fixture availability and throughput could be tracked to determine if there are bottlenecks or possible improvements to be made during environmental testing.

PSC's inventory management system could be linked to the simulation to provide real time inventory quantities, on order quantities, and other useful data to the simulation. By doing this, we can essentially create a digital twin of PSC.

References

1. “Water jet technology.” *American Machinist.,* https://www.americanmachinist.com/machining-cutting/media-gallery/21902791/cuttingedge-cutting-becomes-rocket-science
2. “Conventional or RAM EDM (Die Sinker EDM).” *Header Die & Tool Inc.*, www.header.com/capabilities/conventional-edm.
3. “Electrical Discharge Machining: Wire EDM.” *Header Die & Tool Inc.*, www.header.com/capabilities/edm.
4. “Extrusion Process.” *The Metal Casting*, www.themetalcasting.com/extrusion-process.html.
5. “Coordinate Measuring Machines.” *Hexagon.,* https://www.hexagonmi.com/products/coordinate-measuring-machines
6. Corner B. (1984) Automated Pin Insertion. In: Riley F. (eds) The Electronics Assembly Handbook. Springer, Berlin, Heidelberg
7. “Adhesive Dispensing Machine.” *Dispenser works Ins.,* http://dispenseworks.com/
8. “Dispensing Robots.” *Nordson.,* https://www.nordson.com/en/products/dispense-robots?ps=all&page=1
9. “Robotic Screw Driving System with Screw Inspection for Automated Assembly.” *FANUC America Corporation.,* https://www.fanucamerica.com/solutions/applications/assembly-robots
10. “Optical Comparator.” *Wikipedia.,* https://en.wikipedia.org/wiki/Optical_comparator
11. “Robotics and Automation in fluid and adhesive dispensing.” *Gluespec.,* https://www.gluespec.com/blog/robotics-and-automation-in-fluid-and-adhesives-dispensing
12. “Advance Lightband User Manual.” *Planetary Systems Corporation.,* https://www.planetarysystemscorp.com/wp-content/uploads/2019/07/2003336-Advanced-Lightband-Users-Manual.pdf
13. “Printed Spacecraft Separation System.” *Oak Ridge National Laboratory.,* https://info.ornl.gov/sites/publications/files/Pub70260.pdf