Massachusetts Institute of Technology

Optimization of Utilization Rate for a Metal 3D Printer Through Scheduling, Machine Line Simulation, and Inventory Management

In collaboration with:

Physical Sciences Inc.

by Alexander Brush, Matthew Groll, Kanglin Kong, and Yong Ng

2.854 Introduction to Manufacturing Systems

Prof. Brian Anthony

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Abstract

Roughly one year after purchase and implementation, Physical Sciences Inc. (PSI) seeks to improve the utilization rate of a metal 3D printer. Here, utilization rate is defined as the fraction of time spent printing over time spent powered on. The current utilization rate is estimated to be 15-20%. Due to mandatory setup and cleaning time between prints, it is noted that 100% utilization is structurally impossible. We provide an outline for reliably achieving 50% utilization without an increase in long-term labor hours, allowing PSI to improve their turnaround time and serviceable volume for metal prints at minimal cost increase. To achieve this, we have analysed provided data through three core manufacturing strategies: (1) scheduling of jobs, (2) a machine line simulation, focused on buffers, and (3) inventory management. We first developed a scheduling tool in Python and found an earliest-due-date approach, with additional priority to reflect print completion during work hours, to offer the best utilization gains. With our existing simulated conditions, we expect 50% reduction in tardiness and 15% savings in total print time. A scheduling tool with sample data, based on historic metal print times, shows ideal utilization rates in the range of 60-70%. We estimate with changeover time and real world discrepancies, a 50% utilization is a reasonable target. We do note that real results will depend heavily on the nature of company assigned deadlines and nature of print times, but we have worked with PSI to set up a reasonable starting estimate. Through a machine line simulation, we then derived a recommended build plate buffer in the range of 10-15 plates per material. And lastly, historical inventory review leads us to recommend a change to an up-to-level inventory strategy which suggests a 25% increase in service and 18% decrease in cost. We also offer suggestions towards improving data collection and provide user-friendly spreadsheet templates for doing so. Alongside this paper, we will provide code and other materials which PSI may use and modify as their collected data improves and evolves, further maximizing printer utilization.

Introduction

Physical Sciences Inc. (PSI) is a research and development firm in Andover, Massachusetts that specializes in a wide array of engineering concentrations including optics, propulsion, and advanced materials. Much of their work involves prototyping and low rate production, and as a result, the firm purchased a Nikon SLM metal 3D printer to bolster their internal manufacturing capabilities. This decision was made to save time and money over contracting another company for a high quantity of unique, complex metal components. The benefits of this decision have become even more apparent with their growing need for exotic materials such as Inconel and other custom metal alloys.

Our team is composed of four students in MIT's Master of Engineering program in Advanced Manufacturing and Design Innovation within the Mechanical Engineering department: Alexander Brush, Matthew Groll, Kanglin Kong, and Yong Ng. This paper has been created as part of class 2.854, Introduction to Manufacturing Systems taught by Prof. Brian Anthony. This team has worked with Sanja Kirova, Senior Engineer at Physical Sciences Inc. to analyse, diagnose, and propose a plan for improving the utilization rate of PSI's metal 3D printer.

Problem Statement

The key problem faced by PSI today is low and inconsistent utilization of their metal 3D printer, burdened further by a growing demand for its usage. Utilization rate is a useful benchmark to quickly assess overall performance of a machine's operation, and it is the guiding metric used in this study. Our team and PSI define the relevant utilization rate to be that of time spent printing divided by time of the machine spent powered on. While the exact utilization rate of the printer has not been measured exactly, PSI's best approximation is in the range of 15-20%. At times, this rate may increase depending on the demands of ongoing programs, but this comes at the cost of increased labor hours and stresses on employee schedules. We provide an approach to sustainably manage an increased utilization rate to roughly 50% by examining a handful of strategies in manufacturing theory. These include job scheduling, machine line simulation, and inventory management.

While the results we have collected are specifically sourced for PSI's metal 3D printer, this approach can be generalized. To start with, the inputs for our study can be modified to change numerical results, whether due to new information or an assumption that needs to be modified. Beyond this, we believe that the methods used can apply to essentially any simple machine line especially those not incorporated into a fully operational factory or production facility. Many R&D firms face a challenging balance between internal production and external payment. One of the steepest barriers can be implementing consistent and steady production line thinking into an otherwise highly dynamic work environment. We provide this analysis both as specific support to improving printer utilization, and as a broad strategy for introducing manufacturing practices into the field of prototyping and research.

During the initial discussion with PSI, the team discussed various topics from the course to determine what work would benefit PSI the most. During these talks, the following question arose multiple times: what is the minimum amount of build plates that PSI should own to always be able to fulfill demand? This question is useful for PSI to know because they aim to rapidly increase utilization and they do not want to be limited by material resources. This question is closely aligned with course content because it can be answered with a stochastic simulation. Build plates need to be post processed, meaning that their use cycle can be modeled as a system of unreliable machines with buffers between them. This is more complex than the simulations run in class, however, because three different types of build plates need to be tracked simultaneously.

One of the other key problems the team addressed for PSI was optimizing SLM inventory management. Currently, no automated system exists to schedule orders for consumables used in SLM printing, such as metal powder, filters, and base plates. This challenge exists due to challenges in demand forecasting and managing multiple types of consumables. The project aligns closely with course topics, including inventory management and MRP optimization, offering solutions to streamline PSI's printing and ordering processes, enhance service levels, and minimize financial losses from inefficient ordering. While the project stayed largely true to the original proposal, the team adapted its scope due to time constraints and the limited dataset provided by PSI. As a result, the focus narrowed to developing a metal powder ordering system, designed to be adaptable for other consumables with parameter adjustment.

Another item of immediate impact would be implementing a consistent, automated strategy for scheduling a batch of print jobs. A balance in assessing priority, overall efficiency, and adjusting as new jobs arrived, was agreed upon as a very useful area of improvement. Our analysis will begin with a review on PSI's current job scheduling and suggested changes to this process.

Job Scheduling:

The Nikon SLM can be left on its own, unsupervised, once a print is started. However, once a print is completed, the machine must be reconfigured and cleaned by hand before another print can begin. For SLM printing in particular, this changeover time can be roughly an hour or more per print, costing not only print time, but employee time as well. For this reason, we recommend maximizing build plate allocation, merging parts into a small number of jobs. Selective Laser Melting printing has unique demands in terms of support and slicing, and because of how complex the problem becomes by doing so, we will not review the arrangement of individual parts. Instead, we will assume prints to be packed to the best of the printer's ability. However, we do want to emphasize that reducing job count by manipulating individual parts across prints can be a very effective action and optimized well beyond general human intuition. This requires conditions to be met from material, slicer, and build plate volume, and is a great potential area for future review.

To improve the scheduling approach we will first summarize PSI's current practices. PSI shared that they use an approximate "First Come First Serve" (FCFS) schedule, with some high priority prints pushed to the top of the list. It is worth noting that outside of these urgent prints, others do not have a strictly assigned due date. At the start of roughly every week, a team member will manually configure a schedule that blends these high priority prints along with the existing print order, and to the best of their ability, aim to have prints end during the work day. As PSI operates on core hours of 8 AM to 4 PM, it is essential that prints end during this time range. If a print were to end in the middle of the night, this can result in many hours of dead time and will be a significant detractor to the utilization rate. Depending on interruptions during the week, this schedule may need to be tuned, but will be used as a guiding target until it is re-built.

Our first suggestion is to mandate a due date on any print that enters the system. This will enable a much more robust scheduling approach, and provide future assessment on the performance of a given scheduling strategy. If a due date is not provided for a given print, we suggest assigning a default such as 30 days. It is important that, internally, such a due date system is not abused. Due dates should not be provided on when is most convenient, but instead on when a print is needed to fulfill their respective program schedules. For uniformity, this date should not include any buffer or safety time. It is instead an assumption for all due dates that this is the last possible date before a schedule slip.

Once equipped with a due date system, we can now compare scheduling approaches and weigh their effectiveness numerically. This can be done by assigning a "tardiness" value which measures time of completion past the deadline, and seeking to minimize it. A simulation was developed that used historic ranges from PSI's print durations of 10 to 48 hours, and an approximate due date range of 1 day to 5 weeks pulled from discussion with PSI. 100 randomly generated job batches at 30 jobs each were created, and then simulated for total time taken and cumulative tardiness. To further refine the simulation, we aimed to incorporate the reality of working hour availability. We adjusted our simulation to account for “core hours” of 8 AM to 4 PM, Monday through Friday, and “quiet hours” at all other times, in which prints cannot be started.

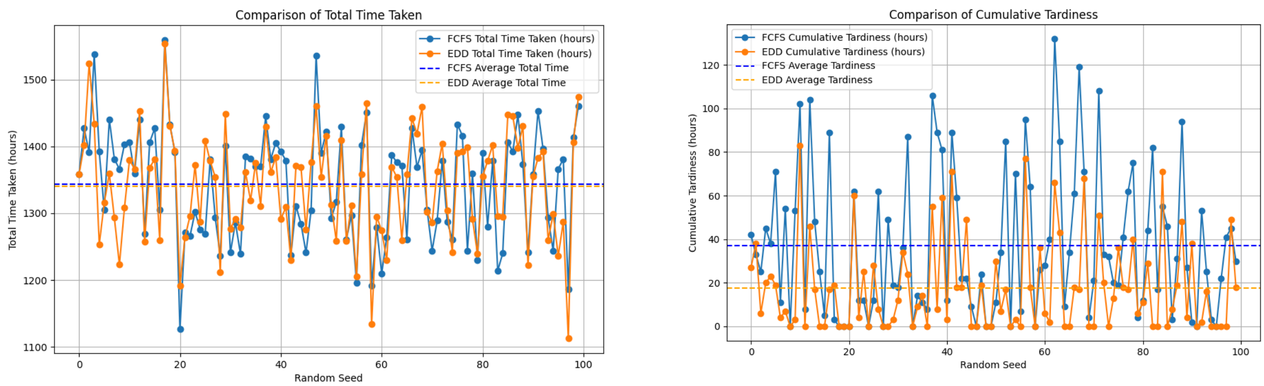

Figure 1 and 2: Simulated Total Time Taken and Cumulative Tardiness

We found the total time taken to be roughly equivalent through both methods and an approximate 20 hour saving in tardiness through an EDD strategy. We added a third approach that minimized total time taken, as well, which became more impactful with these new conditions.

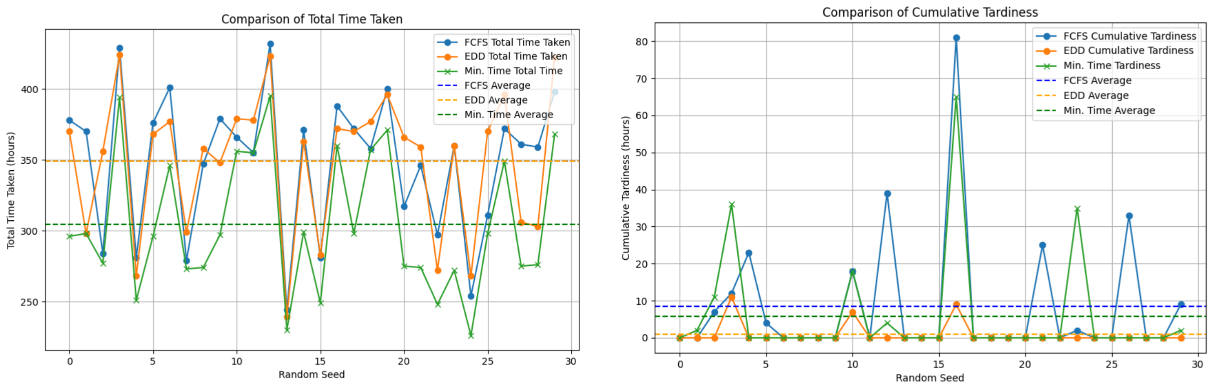

Figure 3 and 4: Simulated Time and Tardiness with MTT added

While we find EDD to continue as the lowest average tardiness score, there are instances where EDD ties with what we call a minimal time taken (MTT) approach, often when both have zero tardiness. In these cases, it makes sense to opt for MTT for the sake of utilization, as nothing is lost in regards to tardiness. We therefore recommend a strategy that first prioritizes EDD, and may convert to MTT if tardiness is tied for both options.

<u>Machine Line Simulation:</u>

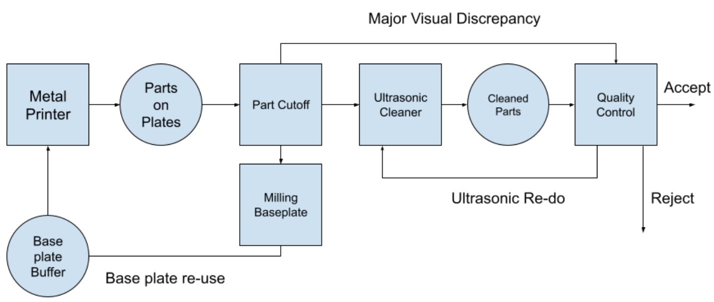

Figure 5: PSI’s metal 3D printer post-processing system

In the post-processing system for the Nikon SLM 125, parts undergo a series of finishing operations after being printed on a build plate. This system consists of three machines for processing the build plates, as shown in Figure 5: the selective laser melting (SLM) printer, the band saw, and the milling machine. PSI's current system includes two buffers for the build plates, placed between the printer and the band saw, and between the milling machine and the printer. After a part is printed, the build plate is removed from the SLM printer and placed in the buffer before being processed by the band saw, where the part is separated from the build plate. Next, the build plate is moved to the milling machine for surface leveling to restore its flatness, preparing it for reuse in subsequent prints. Buffers help handle variations in machine availability and processing times, preventing delays caused by downtime or capacity issues. By effectively managing these buffers, the system aims to maximize the utilization of all machines and streamline the overall production process.

Beginning the characterization of the data, the team was supplied with a print tracker spreadsheet and a build plate tracker spreadsheet. The print tracker spreadsheet included data about previous prints, recording their date, print time, and administrative information for PSI's internal documentation. The build plate tracker was limiting, however, because it only tracked the height of current build plates. The team required more data than was given, and therefore developed a new spreadsheet which combined the two given spreadsheets and introduced additional columns for necessary information. This new spreadsheet tracked prints with higher resolution and also tracked which build plates were used for each print, using this information to calculate build plate life as well as general machine characteristics. Tracking the build plate per print was an important addition to the spreadsheet because it provided insight into how frequently each of the three print materials were used. SLM 3D printing is a long process, and therefore the team filled in the new spreadsheet with both real and fabricated data to ensure that it was working. The fabricated data was also used in the following simulations to ensure that they work properly.

To determine the minimum amount of build plates needed to account for demand at full utilization, the team looked into various methods to model buffers for an unreliable machine, eventually settling on a python simulation. This simulation may have been easier if it were done using simulation software, but a python simulation was selected because it could seamlessly integrate with the spreadsheet created by the team, resulting in the best user experience for PSI. The python simulation was written to simulate the use-cycle of a build plate as it is printed on and post-processed. To begin, the system of PSI is modeled. Within this system, the printer, band saw, and mill are all modeled as unreliable machines. The parameters used to model the machines are calculated from the updated spreadsheet and shown in table 1:

Table 1: Calculated Machine Characteristics

Ave ALU Life	4	Prints
% ALU Used	42.86%	
Ave SS Life	2	Prints
% SS Used	35.71%	
Ave IN Life	2	Prints
% IN Used	21.43%	
Average Print Time	27.1	Hours
Minimum Print Time	7.0	Hours
Maximum Print Time	74.5	Hours
Average Print Frequency	147.2	Hours
SLM MTTF	324.67	Hours
SLM MTTR	10.00	Hours
Band Saw Availability	78.57%	
Band Saw Wait Time	1	Hours
Mill Availability	57.14%	
Mill Wait Time	1	Hours

In this table, the average life of each type of build plate is calculated, along with how frequently each type of material is used. The python code uses the material frequency to randomly select what build plate material is used next in the simulation. To model the machines, the python code requires mean time to fail (MTTF) and mean time to repair (MTTR). For the SLM printer, these are calculated as the time between failed prints and how long the failed prints take to complete, respectively. For the band saw and mill, however, the calculation is a bit different. Within PSI, the machine shop is not exclusively used for the SLM printer, and therefore the band saw and mill are used in other projects and not always available. Because of this, the MTTF is not calculated as the time the machine is not working, but rather the time that the machines are not available for use with build plates. The PSI technicians working on the printer are unable to track the use of these machines outside of their work with them, so therefore MTTR is estimated as the average amount of time that a build plate needs to wait before it is processed by the machine. During the ramp up, little to no buffers are expected, and therefore this is a reasonable approximation. The build plates do not always have to wait, and therefore a percentage of machine availability is calculated. From these parameters, MTTF is estimated using the following equation.

$$MTTF \; = \; \frac{Average\ Wait\ Time}{1 - Machine\ Availability}$$

Equation 1: The formula for estimating mean time to fail

The simulation finally requires the process times from each machine. For the SLM printer, this is calculated by averaging all the print times from the spreadsheet. A similar process can be used for the band saw and mill, but the team decided that this would make tracking the process too tedious for PSI, and therefore used realistic assumed values. For the band saw, the code assumes that the process time is a random variable that is uniformly distributed between 45 and 60 minutes. Similarly, for the mill the code assumes a random variable uniformly distributed between 60 and 90 minutes. These values are overestimated to provide a factor of safety to the assumption and to account for any machine setup that needs to occur such as switching tool heads or blades.

Inventory Management:

Using pre-processed data on machine utilization and input from a PSI engineer, the team established parameters for the inventory management model with several realistic assumptions. Key parameters included material longevity, lead time, demand, and associated costs. Focusing on AlSi10Mg, a primary powder used by PSI, it was determined that each 5 kg bottle typically lasts for four prints, accounting for average part consumption, powder recycling, and 10% waste per print. Lead time was set at an average of six weeks, based on a typical range of 4 - 8 weeks. Demand was modeled as a normal distribution with 52 data points (representing weekly demand over a year), using the average print time to estimate weekly prints at a 50% utilization goal. Standard deviation was derived from average print frequency. Print demand was then converted into powder bottle demand by dividing it by the material's average longevity.Cost parameters included purchasing cost (C) based on supplier pricing from Additive+, holding cost (C_e) calculated for a $1000 SLM powder storage unit with a 90L capacity, and shortage cost (C_s), which incorporated a $25 premium shipping fee and $25 hourly labor cost for delays caused by powder shortages. The service level target was set at 95%.Data availability was a challenge, as PSI lacked detailed inventory records. Improved tracking would greatly enhance forecasting accuracy and model development. A summary of parameters is provided in Table 2.

Table 2: Parameter Settings for inventory management

Parameters		unit
Average Powder lasting time	4	prints per unit
Powder Lead Time	6	week
Minimum Order Quantity	N/A	units
Demand (assume 50%)	3.105	print/week
Demand STD	2	
Powder Purchase Cost (C)	244	$ per unit (5kg)
Powder Order Cost (C_t)	25	$ per order
Powder Hold Cost (C_e)	0.5	$ per unit per week
Powder Shortage Cost (C_s)	225.463	$ per unit per week
Desired Service Level	0.95	percent
Review Time	4	weeks

To simulate the inventory scenario, the team initially built the model using Excel and MATLAB, running simulations 1,000 times to validate its accuracy and repeatability. The goal was to design a solution that PSI could easily implement, streamline the ordering process, and adapt to demand uncertainties. The chosen approach was an ‘up-to-level’ policy, focusing on individual powder orders, which can be extended to other consumables by adjusting parameters. Demand was simulated using a normal distribution with mean and standard deviation derived from weekly print data, converted to weekly consumption rates. Inventory levels were updated weekly by deducting demand from the previous week's inventory unless an order was placed. The optimal order quantity was calculated using the equation:

$$R^* = \overline{Demand} * (Lead\ Time + Review\ Time) + \sqrt{Lead\ Time + Review\ Time} * \sigma_{demand} * \phi^{-1}(desired\ service\ level)$$

Equation 2: The formula for optimal amount to order of up-to-level policy

Using this strategy, PSI would place orders every four weeks to replenish AlSi10Mg powder up to the target inventory level (R*), accounting for the difference between R* and current inventory. A MATLAB script was developed for PSI, enabling parameter adjustments and running 1,000 simulations to assess average costs and service rates under varying demand. The original ‘fixed-quantity’ ordering method, where stock is replenished only when nearly depleted, was also simulated and compared to the new approach. Different fixed order quantities (ranging from 1 to 100 units) were tested to evaluate performance against the optimal solution. Other methods, such as Silver-Meal and Wagner-Whitin, were deemed unsuitable due to demand variability and constraints related to lead time and review periods. Although an optimization model using Gurobi was attempted, it did not yield optimal results.

Results

Our job scheduling analysis indicates immediate value in assigning due dates to all incoming prints, and once implemented, savings in the range of 20 hours of total tardiness for a month of simulation when switching from FCFS to EDD. We also observe roughly 50 hours of total monthly time saving from the MTT approach with expanded details regarding core working hours. EDD continues to have the least tardiness, but in the second simulation we note a high number of tied times, with many at zero tardiness. While the average savings are lower in this simulation, there also exists the avoidance of significant outliers in the range of as much as 80 hours of tardiness. A hybrid approach prioritizing EDD, with a switch to MTT when tardiness is equivalent. We combine the average shifts of the simulation and estimate approximately 50% reduction in tardiness by prioritizing this system, and 15% reduction in total print time.

A job scheduler has been created in Python using the findings from this approach to recommend specific job schedules. This system ensures jobs are run exclusively during the Monday to Friday 8 AM - 4 PM core hours, and blends the EDD and MTT approaches. Utilization rates from the sample data settled on with PSI is in the range of 60-70%, depending slightly on the random seed. These numbers exist only as an estimate and will depend greatly on real deadline requirements, but they should be largely representative of the maximum capability of the system given the structural constraints on print times.

An additional deliverable developed by the team is an updated print tracker spreadsheet which improves upon the existing data acquisition system of PSI. This tracker served as the foundation for understanding the workflow dynamics of the system. Table 3 showcases the print tracker, which was adapted from their existing spreadsheet. The “Argon Used” column was pulled directly from the provided sheet and does not work because it was linked to another spreadsheet which was not provided to the team. This column was added to the updated sheet and will work when given to PSI.

Table 3: Print Tracker

Print Tracker

Traveller #	File Creation Date	Charge Numbers			Materials	Material Estimate (kg)	Print Start		Print End		Print Status	Print Time		Labor Hours					Pressure	Argon Used	
		Program 1	Program 2	Program 3										AM	BS	BD	RD	SK		(cu. in.)	# Bottles
	Date print file was created.	Assume equal split unless otherwise noted. Operator time and material costs will be billed against these programs.			Note all materials	Estimate using linked calculator. If doing a transition print, include contaminated waste.	Date build started	Time build started (24:00)	Date build finished	Time build finished (24:00)	Status of print after machine finished	Estimated print time from slicer (hr)	Actual print time from build info screen on MCS (hr)						Difference between initial and final pressure reading on the inlet of the tank rack	Calculations based on Argon tanks at 336 cu. in. at 2,500 psi.	
24-1001																				#REF!	#REF!
24-1002																				#REF!	#REF!
24-1003																				#REF!	#REF!
24-1004																				#REF!	#REF!
24-1005																				#REF!	#REF!
24-1006																				#REF!	#REF!
24-1007																				#REF!	#REF!
24-1008																				#REF!	#REF!
24-1009																				#REF!	#REF!
24-1010	2024/8/2																			#REF!	#REF!
24-1011	2024/8/9																			#REF!	#REF!
24-1012	2024/8/15	190009.000.001	171025.000.003		IN625		2024/8/15		2024/8/17		Pass									#REF!	#REF!
24-1013	2024/8/28	110024	110010		IN625/HX	3	2024/8/30		2024/8/30		Pass									#REF!	#REF!

Alongside the print tracker is a build plate tracker which is filled out simultaneously to track which build plate was used for each print. This data was not provided to the team, and therefore the data shown in Table 4 below is fabricated based on reasonable estimates.

Table 4: Build Plate Tracker

Build Plate Tracker

Traveller #	Build Plate #	Material	Number	Dimensions	Height	Band Saw Wait		Mill Wait		Notes
				(mm x mm)						
	Material and engraved number (i.e. IN1, SS2, ALU4). If using the reduced build plate size, include "R" (i.e. IN1R...).				Height of build plate after print (retire once 17mm tall)	Was the band saw immediately available?	Wait time (hr)	Was the mill immediately available?	Wait time (hr)	
24-1001	ALU1	Aluminum	1	(123x123)	20	Yes		Yes		
24-1002	ALU2	Aluminum	2	(123x123)	20	No	1	Yes		
24-1003	SS1	Stainless Steel	1	(123x123)	20	Yes		No	0.5	
24-1004	ALU1	Aluminum	1	(123x123)	18.6	Yes		No	0.5	
24-1005	ALU1	Aluminum	1	(123x123)	17.8	No	1.5	No	1.5	
24-1006	ALU1	Aluminum	1	(123x123)	16.2	Yes		Yes		
24-1007	IN1	Inconel	1	(123x123)	20	Yes		No	2	
24-1008	ALU3	Aluminum	3	(123x123)	20	Yes		Yes		
24-1009	SS1	Stainless Steel	1	(123x123)	16.9	Yes		Yes		

The final section of the spreadsheet draws from the build plate tracker to actively track the status of each build plate. After a build plate has been milled to a height below 17 millimeters, it is considered to be retired and it is taken out of use. This build plate life tracker is shown below in Table 5.

Table 5: Build Plate Life

Build Plate Life

Build Plate	Status	Life	Build Plate	Status	Life	Build Plate	Status	Life
	In Use Retired			In Use Retired			In Use Retired	
Aluminum			Stainless Steel			Inconel		
ALU1		4	SS1		2	IN1		2
ALU2		1	SS2		1	IN2		1
ALU3		1	SS3		1			
			SS4		1			

Using the fabricated data in the spreadsheet showcased above, the python simulation calculated graphs for each buffer. The simulation modeled the buffer between the SLM machine and the band saw as well as the buffer between the band saw and the mill. The python code simulates the machine line running for three thousand hours which provides insight into how large the buffers get.

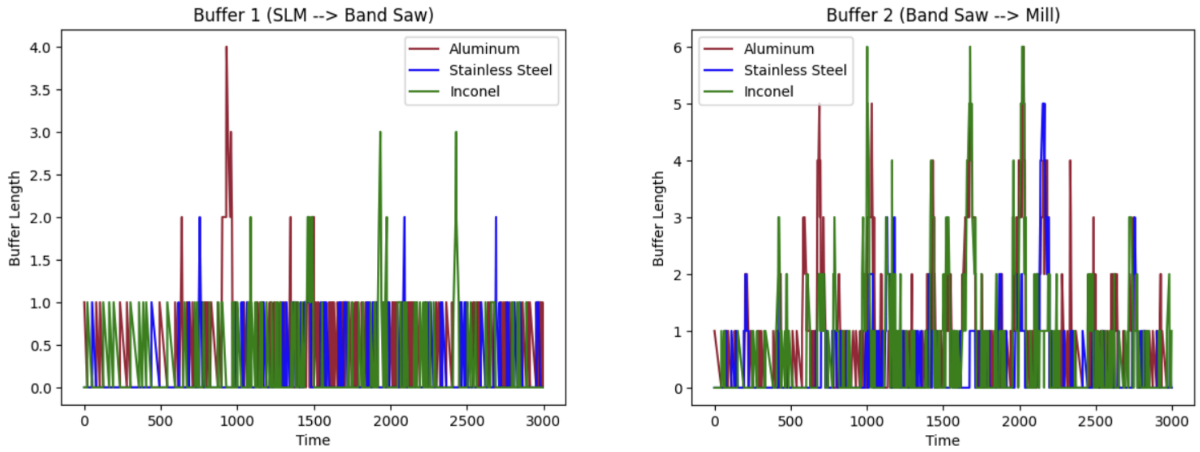

Figure 6 and 7: Build Plate Buffer Sizes Over 3000 Simulated Hours

Figure 6 shows the first buffer, between the SLM printer and the band saw. As expected, the majority of the time this buffer holds zero or one unit. The process time for the printer and band saw are so different, that even with a large MTTF due to the band saw being used for other projects, it is rare that the printer finishes a print before the band saw has had time to process the previous build plate. There are instances, however, where buffers build, but they never grow especially large.

Figure 7 shows the buffer between the band saw and the mill. This buffer has many more spikes because the process time for the mill is longer than the process time for the band saw. Using this information, the minimum number of build plates is calculated by the program by adding the highest peak within each buffer. To overestimate slightly, 3 additional plates are added on to this recommended maximum to account for a build plate being in each of the machines while the buffers exist. The results from the fabricated data are shown below.

```
Recommended # of aluminum build plates:  13
Recommended # of stainless steel build plates:  10
Recommended # of inconel build plates:  12
```

The simulation results for PSI's inventory management methods provide valuable insights. For the original fixed-amount method, 1,000 simulations were run with a reorder threshold of 20% and a fixed order quantity of 10 units, reflecting PSI's current practice. The average total cost was approximately \$11,830, with a minimum service rate of 67%, shown in figures 8 and 9. The variability in demand caused fluctuations in inventory levels, resulting in inconsistent order timing. The sharp decline observed at the end of the average plot was due to an order placed before week 52 that did not arrive within the simulation time frame.

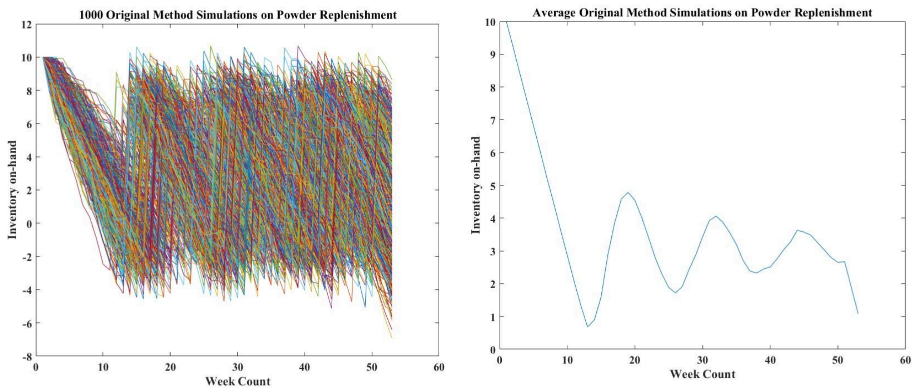

Figure 8 and 9: Plots showing the simulations for the original method used (fixed-quantity)

In contrast, the new up-to-level policy performed significantly better. Under this approach, the optimal order size was determined to be 10 units. For instance, if the inventory level at the start of a review period was 3 units, a 7-unit order would be placed, arriving after five weeks (including the order week). Simulations clearly showed consistent inventory replenishment patterns, with levels dropping and returning to the target point, demonstrating the policy's adaptability to demand fluctuations. The average total cost was approximately $9,711, and the minimum service rate improved to 92%, representing an 18% cost reduction and a substantial improvement in reliability compared to the original method. Detailed plots are shown below.

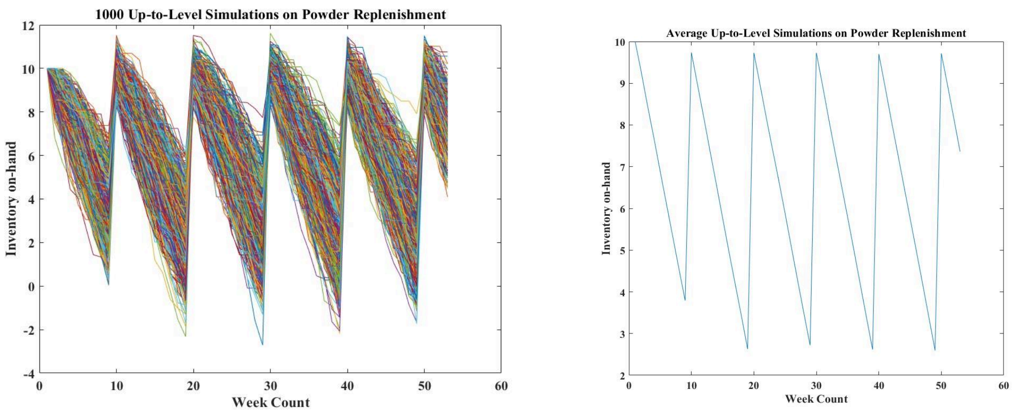

Figure 10 and 11: Plots showing the simulations for up-to-level method used

The two methods were also compared in figures 12 and 13 across various order quantities under the fixed-order approach. While an order size of around 33 units achieved a similar cost to the up-to-level policy, it resulted in a lower service rate. This outcome highlights the impact of PSI's relatively low holding costs but also underscores the potential for increased storage and maintenance expenses with larger inventories. In conclusion, the up-to-level policy offers a robust solution for PSI’s SLM consumables inventory management. By leveraging the new policy and simulation script, PSI can streamline its processes, reduce uncertainties, lower costs, and maintain a high utilization rate of the SLM machine.

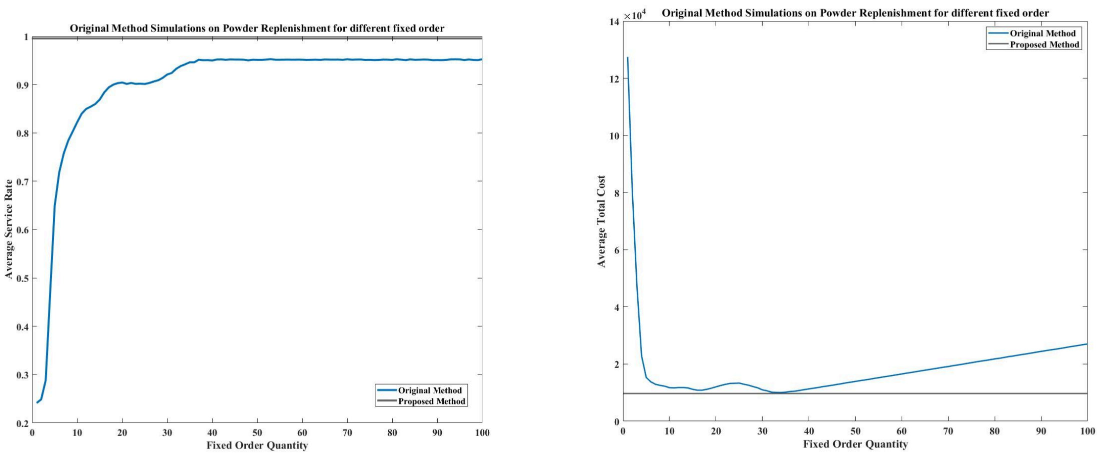

Figure 12 and 13: Plots showing the simulations for different quantity fixed-order scenarios

Discussions and Conclusion

An important caveat to much of our analysis is the importance of integrating additional real data and updating models over time to account for drifting behavior. While the job scheduler, for example, may indicate a percent savings of 15% in total print time, and utilization around 65%, this will depend significantly on the combination of print times and deadlines. If deadlines become shorter, time savings will likely decrease with reduced flexibility. Meanwhile, if print times decrease, savings may increase as more potential combinations for ideal arrangements emerge. This tool at minimum provides a consistent approach to reducing overhead time spent scheduling, and allows for a quick overview on printing strategies and tradeoffs.

The machine line simulation provides information to determine the minimum number of build plates that PSI should own to always be able to meet demand. Due to how variables are calculated, the simulation provides a good estimate for machine characteristics, however it is not perfect. To perfect the simulation, much more data would need to be recorded but that is not feasible for the technicians at PSI. PSI already owns enough build plates to meet current demand, and therefore as they get more data the simulation will be able to provide a more accurate number which accounts for increased utilization of the SLM printer.

The comparison between the up-to-level policy and PSI's current fixed-amount method highlights several key differences. While the fixed-amount method performed poorly in handling demand variability and required significant manual adjustments, the up-to-level policy demonstrated greater adaptability and efficiency. Additionally, the fixed-amount method's inability to respond dynamically to changes in demand limited its effectiveness, resulting in higher costs and lower service rates. These findings suggest that the up-to-level policy offers a more practical and cost-effective solution for PSI's inventory management needs.

To support PSI's implementation of the proposed improvements, we have included a Standard Operating Procedure (SOP) (Appendix A) along with the code we developed during the project. The SOP provides step-by-step instructions for using the tools and simulations, ensuring that the methodology can be easily adopted and executed by PSI's team. It includes guidance on collecting data, running the Python and Matlab scripts, interpreting the outputs, and customizing the models for future use. By integrating the SOp with the provided code, PSI can efficiently manage their post-processing system, optimize build plate and SLM utilization, and refine their inventory management strategies as more data becomes available.

Future improvements should focus on enhancing the precision of demand modeling, especially given PSI's increasing production needs. More accurate demand forecasts and refined parameter inputs, including holding and shortage costs, could further optimize the model's performance. For the fixed-amount method, adjusting the reorder threshold based on precise forecasts could improve its service rate and reduce costs, though its inherent inflexibility remains a limitation. Exploring the use of Gurobi optimization is another important avenue for future work. Refining this approach could enable PSI to achieve optimal ordering decisions consistently. Additionally, extending the savings to the design process by equipping engineers with data on cost variations across different SLM materials could support more informed decision-making. Testing the model in diverse scenarios and collecting more real-world data will further validate and enhance its utility for PSI and similar manufacturing systems.

Overall this project utilized course content to suggest methods to improve PSI's machine utilization through job scheduling, build plate quantity, and reordering. The information within this report has been presented to PSI, and the team will continue to work with them to implement the suggested strategies.

Appendix A: Standard Operating Procedure (SOP)

Standard Operating Procedure

Title	**Optimizing Utilization Rate of Nikon SLM 125**
Purpose	The purpose is to maximize the utilization rate of PSI's Nikon SLM 125 by ensuring efficient, cost-effective production while addressing scheduling, build plate availability and powder inventory management.
Scope	The SOP applies to the operation and maintenance of the Nikon SLM 125 production line for Physical Sciences, Inc.
Responsibility	The person responsible for this SOP is the Manufacturing Engineer.
Procedure	

1. Schedule Optimization

1.1. Develop a daily or weekly print schedule based on job complexity and expected print times with due dates.

1.2. Use **Python's "Main Job Scheduler For Use by PSI.py"** to obtain an updated optimized schedule.

1.3. Continuously update the schedule based on real-time machine status and print completion reports.

2. Manage Build Plates

2.1. Use **Python's "Buffer Simulation.ipynb"** to simulate and visualize workflows.

2.2. Input updated data from **Print Traveler Tracker** and **Build Plate Tracker** into the simulation. Record availability and wait time of band saw and mill.

2.3. Ensure sufficient buffer space between the **Metal 3D Printer**, **Band Saw**, and **Milling Machine** based on buffer length estimates from the simulation.

2.4. Regularly reassess buffer space requirements as part complexities or machine availability changes.

2.5. Compare the recommended number of build plates for each material with current inventory.

2.6. If simulation highlights shortages, initiate an immediate order for additional build plates. ***3. Powder Material Management*** 3.1. Use **Matlab's "Inventory.m"** script to simulate powder inventory flow. 3.2. Input recent demand, lead times, and reorder thresholds to optimize review cycles. 3.3. Assess flow of the graph to get an optimum review time. 3.4. Use the review time to establish regular monitoring intervals.	
Revision and Updates	Review this SOP quarterly to incorporate feedback, data-driven insights, and technological advancements.