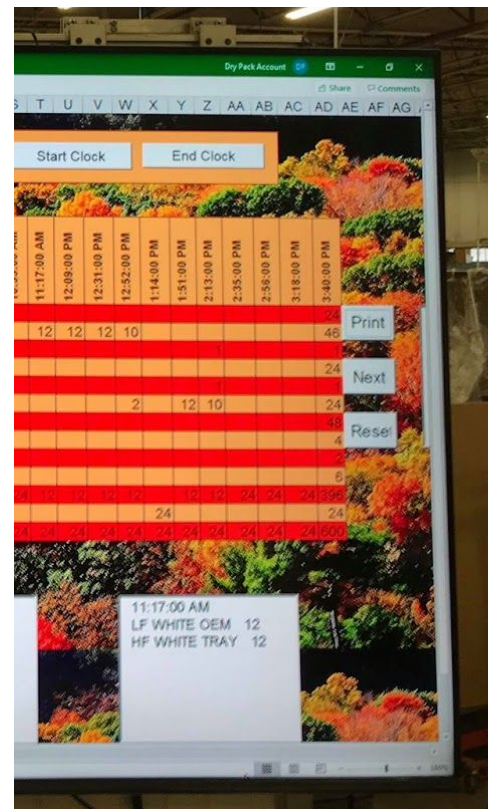




Developing a Program to Automate the Heijunka Board Process on the AMV Line at Thetford Co.



Presented by: Automation Solutions

Automation Solutions thanks Thetford for the opportunity and the instructors for IOE 424: Practicum in Production and Service Systems at the University of Michigan in developing our solution.

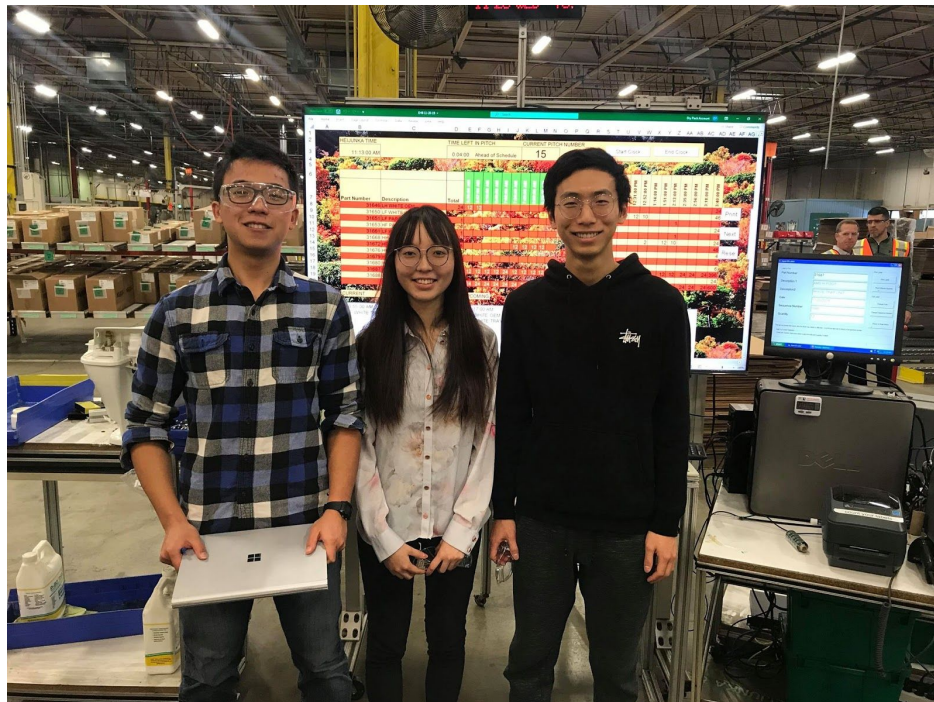
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Team Biography

Jason Bian studies industrial and operations engineering at the University of Michigan and is graduating in December 2019. He is interested in ranting about random Industrial Engineering topics to people who are not interested.

Yizhou Cao studies industrial and operations engineering at the University of Michigan and is graduating in May 2020. He is also pursuing a Computer Science minor. After graduation, Daniel will be attending graduate school and further his education in the subject of industrial engineering and operations research.

Cindy Xuan studies industrial and operations engineering at the University of Michigan and is graduating in December 2019. She also enjoys art, so much so that she got an Art major along with her Industrial Engineering degree.



Executive Summary

Problem Statement

Assist Thetford Corp. in developing an electronic Heijunka board in place of the current system in order to reduce operating time on the AMV line.

Findings

Time studies and interviews conducted onsite have generated the following findings:

1. Inventory calculations took over 30 minutes a day for the group leader.
2. 125.83 minutes were spent operating the Heijunka board each pitch.
3. Errors in the Heijunka board would cause downtime for the entire line
4. Different products have different difficulty levels

Conclusions

Based on the above findings, Automation Solutions focused development on the following three categories for the Heijunka Board:

1. Automation: Reducing redundant steps during Heijunka board operations
2. Error-Proofing: Reducing the chance for errors in Heijunka board operation
3. Line-Balancing: Generating and pre-populating schedules that balance the production difficulty

Deliverables

After evaluation, Automation Solutions has implemented the following products as deliverables.

1. An auto-generating Excel electronic Heijunka board program to be displayed.
2. A Python scheduler program to generate the quantity to be produced for each part.
3. A new hardware setup to run and display the electronic Heijunka board.

Introduction

Client Overview

Headquartered in Ann Arbor, Michigan, Thetford markets its products through various national and international distribution systems, including Original Equipment Manufacturers (OEMs), Wholesale Distributors (WDs) and a range of national retail outlets. The customer base is located in North America, Europe, and Australia.

A popular product sold to both distributors and individual customers is Aqua Magic V (AMV). AMV is a lightweight all-plastic RV toilet that is easy to install and service. It can be categorized into hand flush and foot flush with the choice of water saver, heights, and different color configurations.

Process Overview

The line currently holds a manual Heijunka board to help keep track of the manufacturing process. The plant layout is shown in Figure 1 and Process 1 shows the current process map of the AMV production line.

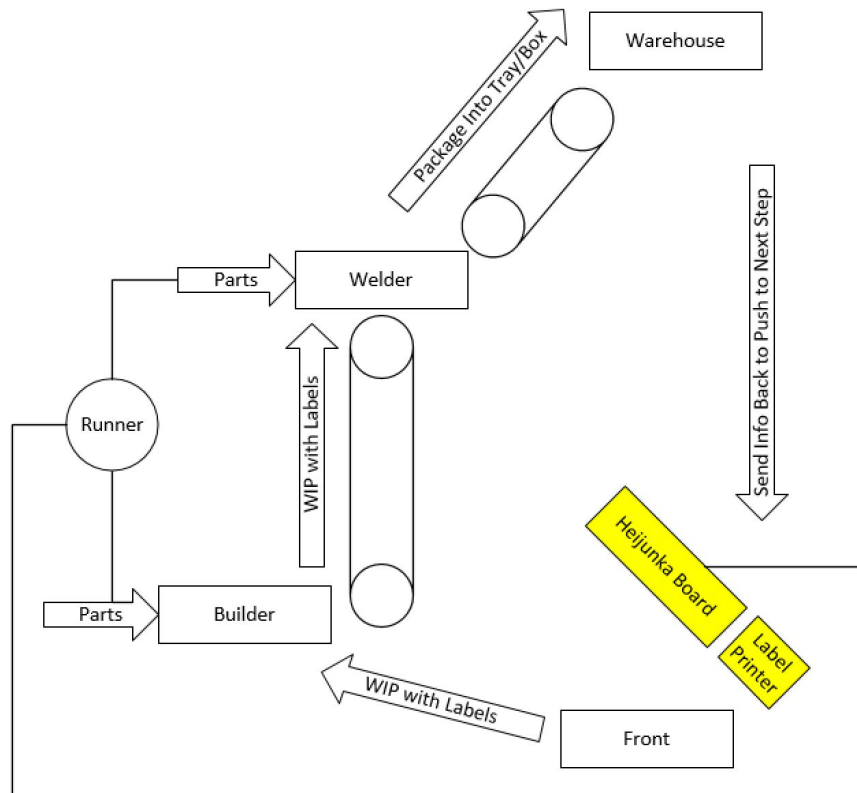


Figure 1: Physical plant layout for the AMV line

Process 1

1. Gather Inventory and Demand pdf from ERP (Group Leader)
 2. Create Production Checklist (Group Leader)
 3. Setup Heijunka Board (Group Leader)
 4. **While** shift != 0
 - If** time < pitch_rate **then**
 - 4.0 Rebalance line (Group Leader, Manufacturing Supervisor)
 - else**
 - If** Raw products > 0 **then**
 - 4.1 Pull orange card (Operator)
 - 4.2 Manual entry of orange card to printer (Operator)
 - 4.3 Print product labels (Operator)
 - 4.4 Scan product labels to print warranty labels (Operator)
 - 4.5 Send printed labels to tray (Operator)
 - 4.6 Grab first Raw product for pitch (Operator)
 - 4.7 Push all toilets down the line (Operator)
 - 4.8 Receipt blue card (Operator)
 - else**
 - 4.9 Gather Raw products (Runner)
 - end**
 5. Prime the line for next day to start line during Heijunka setup (Group Leader)
-

Problem Overview

The current Heijunka process consists of many manual tasks which incur both financial and time costs. As a result, Thetford has asked Automation Solution to build an electronic Heijunka board to improve this process.

Project Scope

The project scope is limited to processes used for Heijunka scheduling and does not include the manufacturing lines controlled by the board. The meetings with Thetford confirmed that the following objectives should be achieved:

- Reduce the amount of time and cost spent each year on manual scheduling and adjusting
- Reduce the error caused by the mismatch between actual orders and Heijunka cards
- Develop and implement a visual display system to display the program
- Develop a program that is replicable for other production lines

Data Collection and Methods

Time Studies

Three initial time studies were conducted to measure the current process. Those time studies were then used to identify areas of improvement. After installation, two validation time studies were then conducted. A list of all the studies conducted is shown in Table 1:

Table 1: List of studies conducted

Initial Time Studies	Number of plant visits	Data points collected	Validation Time Studies	Number of plant visits	Data points collected
Setup Time	1	1	Setup Time	1	1
Operation Time	4	9	Operation Time	3	9
Production Time	3	6			

Time studies were conducted using clipboards and watch timers. For the time study documenting setup time, the group leader was asked to setup the board as how he normally would. The observer then recorded each step in the process and documented the time stamps.

For the time study documenting operation time, steps 4.0 to 4.9 in algorithm one was broken into discrete events for an observer to document. The observer then recorded the timestamp for when each step occurred into a time study sheet during the plant visit. A total of 9 heijunka uses cases were observed over the course of 4 plant visits.

For the time study documenting production time, it was confirmed that hand configurations are easy for front operators and welders and tray items are easier for the packing stage. We also found that while it usually took front operators 60 seconds to 80 seconds to finish one unit, it only took the welding station around 50 seconds, meaning that the bottleneck is within the front operators.. Therefore, sometimes one of the two welders would leave his station to help the other parts of the line.

After performing the setup and operational time studies, it was estimated that 125.83 minutes were spent per day on setting up and using the Heijunka board. Operators need to pull the receipts from the Heijunka board after a pitch finishes and print out the labels for the next pitch, resulting in 2.25 Heijunka touches per pitch on average. The study parameters were summarized in Table 2 and the estimated downtime is presented in Table 3.

Table 2. Summary of Time Study Parameters of the Current Process

Study Parameters	Result
Avg. Heijunka Board Setup Time (min)	41.07
Total Use of Heijunka Board	9

Total Pitches Observed	4
Average Uses/Pitch	2.25
Average Time/Use (s)	83.56 (mean) 25.77 (std.)
Time spent on Heijunka/Pitch (s)	188
Average Debugging/Use (s)	27.33

Table 3. Current Estimated Downtime Related to Heijunka Board Per Day

Estimated Time / Day	Time (min)
Average Time Spent	105.33
Average Total Time Spent on debugging	20.50
Heijunka related Line Downtime	15.00
Total time Loss/Day	125.83
Total Line Downtime/Day	15.00

A Pareto breakdown of setup time is shown in Figure 2, where the operator was found to spend equal amounts of time in scheduling decision making and board setup with a total time of 41 minutes per day. Many of the discrete steps were automatable and there was also considerable potential in error proofing the Heijunka setup steps to prevent problems during line operation.

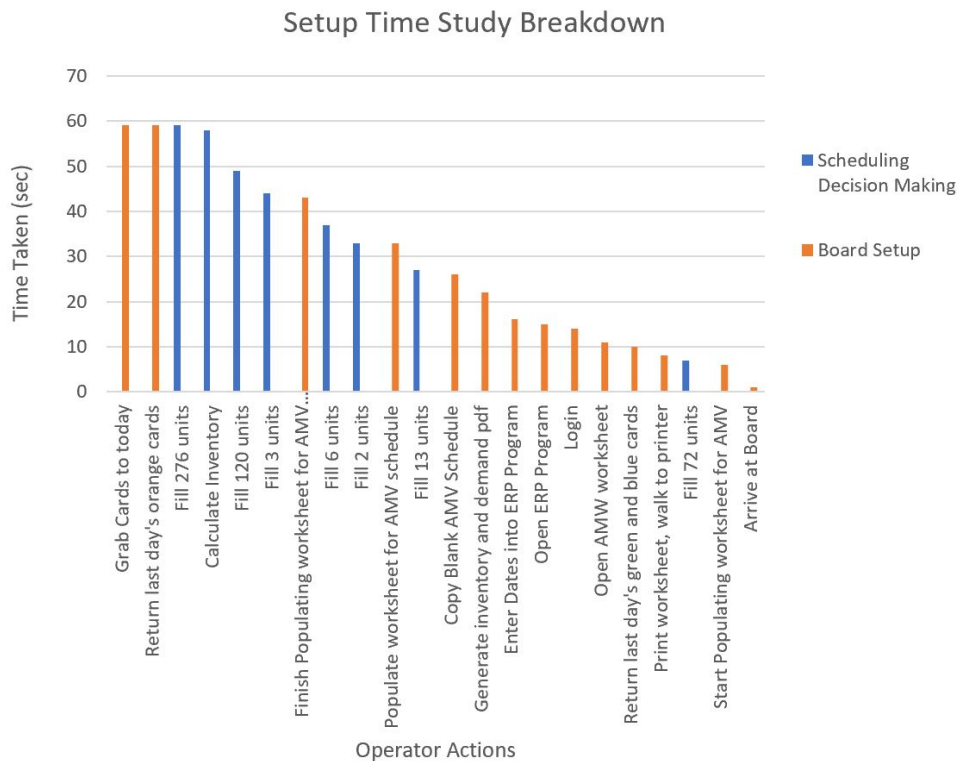


Figure 2: Pareto breakdown of setup time

A breakdown of operational time is shown in Figure 3, with the average time for each operational step of two studies marked in two colors. Most of the time was spent on scanning the product labels and sending printed product labels to the tray. Time taken for pulling the orange card and manual entry of the orange card could easily be automated and subject to error proofing. An electronic Heijunka board could also automate the printer process and prevent the time taken in the scanning of product labels. Migrating scanning would also reduce the ergonomic load on the operator. Since changing plant layout was outside the scope of our project, we did not consider reducing the amount of time to send printed labels to the front of the line, an action that signals production.

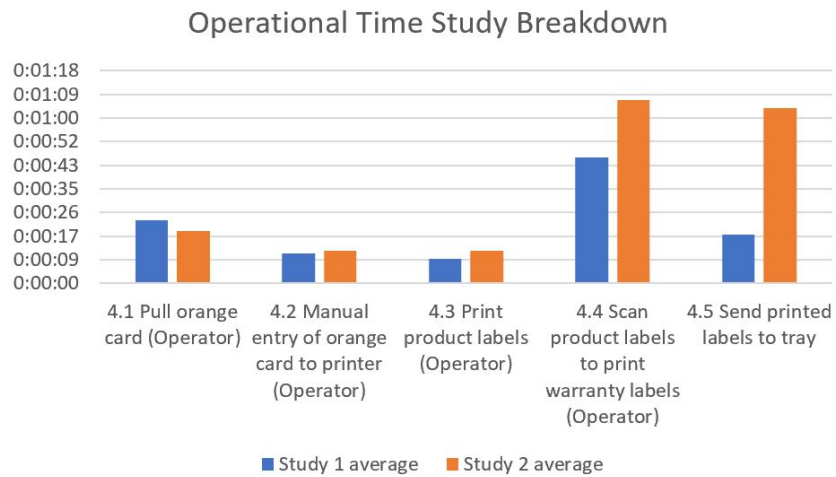


Figure 3: Breakdown of operational time

Interviews

We conducted specific interviews to gain qualitative data from the AMV line. During the interview, we asked questions about how he took error-proofing methods, what specific worksheets he used, how busy the AMV line typically was. These interview answers were essential for us to develop our Python scheduler program and Electronic Heijunka program. The group leader was also interviewed on how he scheduled the AMV line as the products could be categorized into Hand/Foot, with/without water saver, Tray/Box, which have different packing requirements and average producing time. It was found that OEM products of the following day need to be done today so that they could be sent to shipping on time while CP, Tray, and European products could be scheduled on the same day of their due date. Meanwhile, if different schedules could be made, the optimal one would be the one that balances the number of Hand/Foot and Tray/Box. During the first interview, the AMV line had a low inventory level which means the daily output could only satisfy the shortage of the same day or at most 3 days ahead. During the second interview, in contrast, the AMV line had a high inventory level which means the daily output was aimed for the upcoming three days and the remaining capacity after

fulfilling the three days was allocated mainly to high-volume products such as #31687 (HF White Tray) and #31688 (HF Parch Tray).

Literature Review

The output rate variation (ORV) problem^[1] is a popularly researched field in multi-level production systems. In our project, we encountered a version of mixed model level scheduling in which Hand/Foot, with/without water saver, Tray/Box configurations should be better spaced out in daily production. The goal is to have operators experience a consistent level of difficulty to reduce line downtime and the risk of defects. Therefore, we researched ORV methodologies to better understand the optimal balance between production difficulty and output.

Findings and Conclusions

The findings from the time studies, interviews and literature review can be summarized into three improvement areas.

1. Automation: Reducing redundant steps during Heijunka board operations
2. Error-Proofing: Reducing the chance for errors in Heijunka board operation
3. Line-Balancing: Generating and pre-populating schedules that balance the production difficulty

These three improvement areas will reduce the overall time spent on the Heijunka board, reduce line downtime due to the Heijunka board, and generate effective schedules with balanced manufacturing load.

Implementation

We implemented the Heijunka project automation by running the Python Scheduler and Electronic Heijunka Board on a workstation supplied by IT. The programs were then displayed on a new monitor in the plant.

Hardware

Thetford purchased a 65'' 4K monitor based on Automation Solutions' suggestion and installed it on the original location of the Heijunka board as shown in Figure 4.

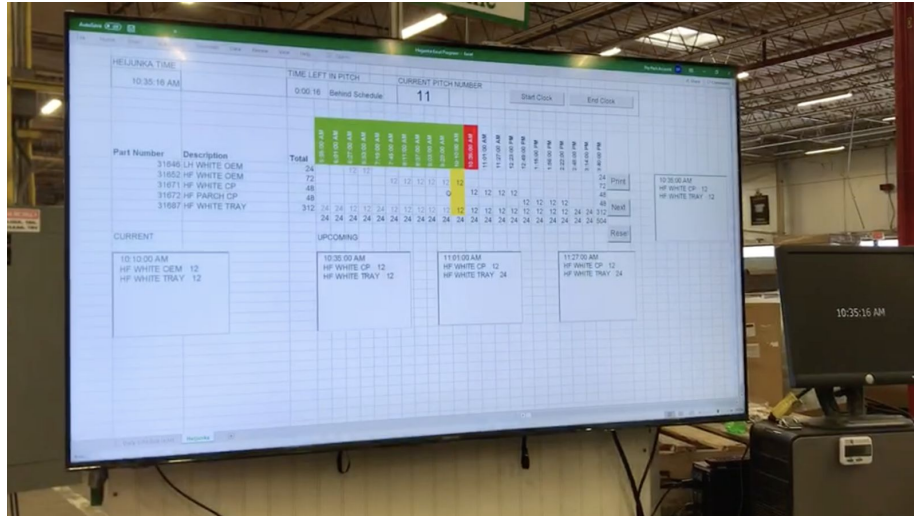


Figure 4: Installed hardware on site

Python Scheduler

There are several functions used by the scheduling program to create a reasonable output:

Reading the Inventory File and Inventory Deviation Table

The program locates today's folder with the hierarchy of EHB - year - month - day, reads into the inventory .pdf file downloaded from the ERP system and the inventory deviation table provided by the group leader as the ERP system may have deviations from the actual storage. If there are no .pdf under today's folder, an error message will pop up: "No PDF detected. Make sure the inventory file is in today's folder and then run the program again." Otherwise, the program will proceed: subtract the inventory from the demand of each item to calculate the shortage for today, the upcoming three days and the upcoming six days, respectively.

Inputting and Error Checking

The program will prompt for user input by displaying "What is the hour of production today?" and "What is the number of workers today?". Depending on the hour and number of workers from user input, it will read the AMV_GOAL.xlsx to find the total production unit. It will compare the total production unit with the shortage, and determine the schedule. If the input is not a number, the program will require the user to input again.

Scheduling

There are four possible scenarios and each is addressed as follows:

- Capacity < Today's demand
 - Exit and display "Unable to satisfy the demand with the given capacity. Please use your own decision rule for the schedule."
- Today's demand <= Capacity < 3 days' demands

Look into the following days (day 2 and 3) by these criteria:

- o Round up built-to-order items until they add up to a multiple of 12
- o Round up supermarket items to the nearest 24
- o Round up tray items to the nearest 12
- o If there is remaining capacity, add units to the current schedule following the requirement: supermarket items add 24 units each loop, tray items add 12 units each loop. Built-to-orders are the least important to consider except that #31650 usually has a high demand and can produce more ahead of time. The program breaks the loop when the capacity matches the schedule.
 - o Display “Able to look ahead for 3 days.”
- 3 days’ demand \leq Capacity \leq 6days’ demands
 - o Look into the following days (days 4, 5, 6) until the sum of units match with today’s capacity. The criteria are the same as the above scenario.
 - o Display “Able to look ahead for the whole week.”
- Capacity > 6 days’ demands
 - o Suggest a scheduler using the above scenario for all of the items in the upcoming 6 days.
 - o Display “Current goal larger than whole week demand so add QTY to produce based on your judgment.”

Outputting to Worksheet

Once a viable schedule is generated, it is outputted to “Schedule.xlsx” under today’s folder. Column QTY is the suggested schedule with built-to-order items highlighted in red so the group leader can easily find how those non-12s items can be aggregated to a pitch. Additional columns Actual_shortage, Upcoming3, Upcoming6 are also provided so that if the group leader decides to change the schedule, he can look at these shortages and make reasonable adjustments quickly. It is evident that the QTY column should be at least larger than Actual_shortage, which is the orders due today. Figure 5 shows a sample output of the current scheduler program based on 2019/9/18 inventory files.

PRODUCT	Deviation	Category	Note	Type	QTY	Actual_Shortage	upcoming3	upcoming6
31646	-1	24s	OEM	Hand				22
31647	-11		OEM	Hand	10	5	8	18
31648	0		OEM	Hand	22	18	44	64
31649	0		OEM	Hand				
31650	-17		OEM	Foot				36
31651	-1		OEM	Foot				
31652	0	24s	OEM	Foot				151
31653	0	24s	OEM	Foot			16	16
31657	0		OEM	Hand				2
31658	-2		OEM	Hand				6
31659	0		OEM	Hand				
31661	0		OEM	Foot				
31662	0		OEM	Foot				1
31663	0		OEM	Foot				
31664	0		OEM	Foot				
31667	0	24s	CP	Hand			6	51
31668	0	24s	CP	Hand	24	9	29	62
31671	0	24s	CP	Foot			15	65
31672	0	24s	CP	Foot				50
31675	0		CP	Hand				5
31676	-3		CP	Hand				7
31679	0		CP	Foot	4		15	25
31680	0		CP	Foot				4
31681	0	12s	TRAY	Hand				35
31682	0	12s	TRAY	Hand				
31683	0	12s	TRAY	Hand				
31684	0	12s	TRAY	Hand				
31685	0	12s	TRAY	Foot	12	12	12	12
31686	0	12s	TRAY	Foot				
31687	0	12s	TRAY	Foot	240		306	978
31688	0	12s	TRAY	Foot				111
31733	0		EUROPEAN	Hand				
31734	0		EUROPEAN	Hand				
31735	0		EUROPEAN					
31736	0		EUROPEAN					

Figure 5: 2019/09/18 Test Case of Python Scheduler Output

Electronic Heijunka Board

We created an electronic Heijunka board program that reads into the start time, end time, break time and production units. It then creates a time bar showing the start time of each pitch which is highlighted in green when on schedule and red when behind schedule. The program automatically refreshes every second so all operators and the group leader will be able to see the current Heijunka time and the time left for the current pitch. Each time a pitch is finished, the operator will hit the “Print” button and the following pitch will replace the current pitch and every pitch behind will move one step ahead accordingly. It will also be pushed to the SQL database which is connected to the new Printer Program to release all the labels for the next pitch. The current interface is shown in Figure 6. Figure 7 shows the shift of timeline and change in time color when the “Print” or “Next” button is clicked.

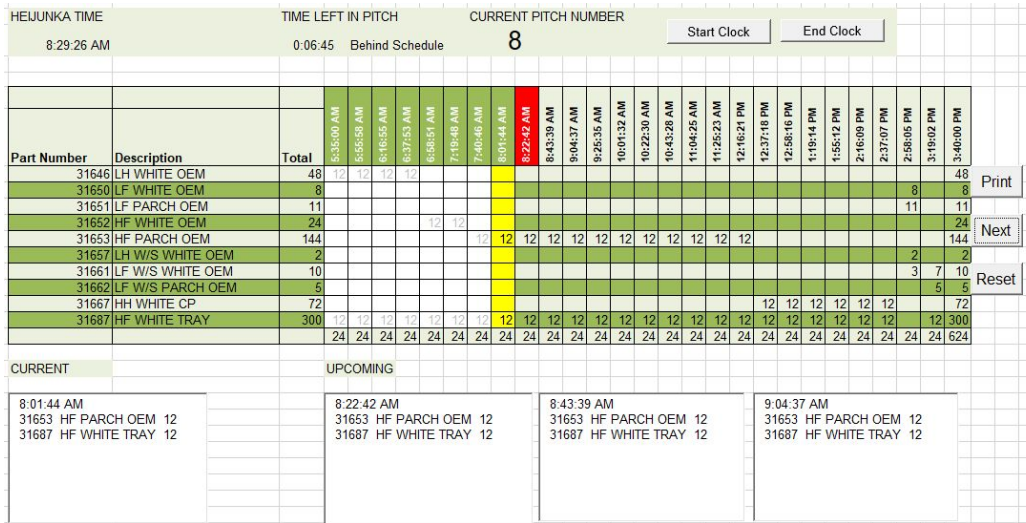


Figure 6: Electronic Heijunka Board

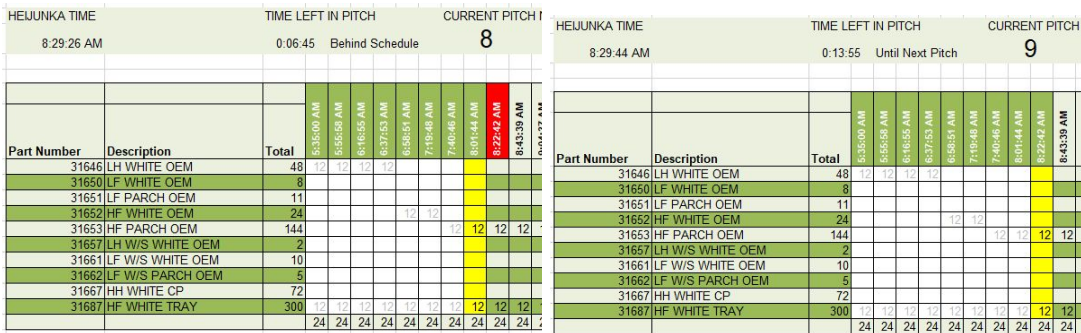


Figure 7: Behind Schedule vs. Ahead of Schedule

Enter Today's Production Information and Error Proofing

To create the Heijunka Board, the user can copy the output from the pdf reader to the daily schedule sheet, shown in Figure 8. Then the user will need to enter the start time, end time, pitch size, first break start, first break end, lunch start, lunch end, second break start, and second break end times. These cells are all error proofed so a wrong variable type cannot be entered in those cells. For example, the system will send an error message if a whole number is entered in the start time cell. Additionally, operators can select and customize the colors used in the Heijunka board. Finally, the user can click "Finalize" to generate the electronic Heijunka board with the correct pitch timeline.

Current Time	11:21:49 AM	Finalize	First Break Start	9:30:00 AM
Difference			First Break End	9:45:00 AM
Heijunka Time	11:21:49 AM		Lunch Start	11:30:00 AM
Start Time	5:35:00 AM		Lunch End	12:00:00 PM
Pitch Size	24.00		Second Break Start	1:30:00 PM
End Time	3:40:00 PM		Second Break End	1:45:00 PM
Calculated Pitch Time	20.96			

10/9/2019	AMV SCHEDULE	624	Difficulty	Type	Interior Color	
48 days	Part #	DESCRIPTION	Level	e		
24's	31646	LH WHITE OEM	Crystal M	48	moderate	BOX
SUPER PITCH	31647	LH PARCH OEM	Angie		moderate	S
	31648	HH WHITE OEM	Tonyetta		moderate	S
24's	31649	HH PARCH OEM	Tommy		moderate	BOX
SUPER PITCH	31650	LF WHITE OEM	Linda	8	hard	S
	31651	LF PARCH OEM	Tobias	11	hard	S
24's	31652	HF WHITE OEM	Tamy	24	hard	BOX
SUPER PITCH						
						Alternate Color

Figure 8: Screenshot of Daily Schedule

Heijunka Creation and Production Algorithm

Depending on the number of parts to be produced and the time given on the day, an electronic Heijunka board will be generated with the correct relative size after the Finalize button is pressed. The VBA code for populating the Heijunka board cells will also be initiated. There are three proposed ways to populate a Heijunka board:

- A. Depending on the difficulties of each part and the number of each part to be produced, the code will assign the number of each part to be produced in each pitch depending on the following heuristic:
 - If there are special orders that do not have number of parts as multiples of 12, assemble them to pitches of 24s. If there are order with multiples of 12 but not 24, assemble them to pitches of 24s.
 - Rotate between easy/moderate with hard parts of pitches of 24s as only multiples of 24 are left.
 - Assign the European parts as the last pitches.

- B. In AMV lines, 12 boxes and 12 trays are usually combined into a pitch and the following heuristic follows this tradition:
 - Select 12 boxes from a box order and select 12 trays from a tray order and combine them into a pitch.
 - If all tray orders are finished, produce 24 boxes each pitch or if all box orders are finished, produce 24 trays each pitch.
 - If there are 12 boxes or trays left, they need to be combined with 12 special orders.

- Finish the remaining special orders and assign the European parts as the last pitches.

C. The output rate variation (ORV) problem is a popularly researched field in multi-level production systems. In our project, we encountered a version of mixed model level scheduling in which hand/foot, tray/box and with/without water saver configurations must be spaced out in daily production. The goal is to have operators experience a consistent level of difficulty to reduce line downtime and the risk of defects. Therefore, we proposed an optimization model below to find the optimal balance between production difficulty and output shown in Figure 9. This program is currently non-linear, but the square term could be removed in Z_n to linearize the program for future implementation.

$\min \sum_n (Z_n + rP_n + sQ_n)$		r, s : weighting of each decision variable, can be adjusted above or below 1 based on their importance or by conducting sensitivity analysis
$s. t. Z_n = \left(\sum_m X_{mn} A_m - T \right)^2 \quad \forall n \in N$		X_{mn} : number of model m in pitch n T : scheduled pitch time, e.g. 26 mins per pitch
$avg_a = \left(\frac{\sum_m h_m}{N} \right) \quad \in N$		N : total number of orders today Z_n : variation between time of pitch n and scheduled pitch time
$avg_b = \left(\frac{\sum_m b_m}{N} \right) \quad \in N$		A_m : average time to produce one model m d_m : demand of model m today
$\sum_n X_{mn} = d_m \quad \forall m \in M$		w_m : binary variable, i.e. 1 if model m is water-saver or European and 0 otherwise
$\sum_m X_{mn} = 24 \quad \forall n \in N$		h_m : difficulty level for front operators for model m , e.g. hard=2, moderate=1, easy=0
$X_{m1} \leq M w_m \quad \forall m \in M$		b_m : difficulty level for packing for model m , e.g. hard=2, moderate=1, easy=0
$P_n = \left(\sum_m X_{mn} h_m - avg_a \right)^2 \quad \forall n \in N$		P_n : variation between difficulty level for front operators of pitch n and average difficulty level of all pitches
$Q_n = \left(\sum_m X_{mn} b_m - avg_b \right)^2 \quad \forall n \in N$		Q_n : variation between difficulty level for packing operators of pitch n and average difficulty level of all pitches
		M : big M dummy to make sure water-saver or European orders are not produced at the beginning of a day

Figure 9: Proposed Automated Heijunka Optimization Program

Approach B is used in the current implementation. However, approach A or C may fit other lines better in the future. Approach A requires a rough estimation of the difficulty level of each type while approach C requires an accurate documented production time of each type. Based on the requirements of each line and the data available, Thetford can choose different approaches for different lines to maximize efficiency.

Start Clock, End Clock, Reset, Next, and Push to Print Buttons

There are a total of five buttons on the Heijunka sheet in the excel file. “Start Clock” will start automatically updating cell B3, Heijunka Time. This allows the timeline color to be updated if a pitch time has been passed by the actual time. “End Clock” will end that process. “Reset” needs to be clicked before the Heijunka board can be used. This button will update the textboxes and timeline to the start of the day format. “Next” will move the timeline to the next pitch. This button can be used if the user wants to move the timeline without print any labels. In addition to changing the pitch’s timeline color to green, indicating the pitch has been started, the current pitch’s cells will be highlighted and the completed pitches cells will turn grey. “Push to Print” will do exactly what the “Next” button does and additionally print the serial number and warranty labels of the current pitch parts. The idea is that next and reset can be used to control the board. Actual printing is done by the “Push to Print” button while next and reset can be used to activate the board. The push to print button is pressed, VBA code will call a stored SQL procedure that initiates the printing process.

New Process Map

With the above implementations, the new process map is summarized as follows:

Process 2

1. Gather Inventory and Demand pdf from ERP (Group Leader)
 2. Run Python Scheduler Program (Group Leader)
 3. Adjust schedules according to need and set up electronic Heijunka Board (Group Leader)
 4. **While** shift != 0
 - If** Raw products > 0 **then**
 - 4.1 Hit “Push to print” (Operator)
 - If** printer_state == 0 **then**
 - 4.2 Get product and warranty labels at the same time (Operator)
 - 4.3 Grab first Raw product for pitch (Operator)
 - 4.4 Push all toilets down the line (Operator)
 - else**
 - 4.5 Hit “Reset” and “Next” to the current pitch (Operator)
 - end**
 - else**
 - 4.9 Gather Raw products (Runner)
 - end**
-

The comparison of the new process map and the old one can be found in the appendix.

Validation

We have conducted a second round of time studies to validate the improvements of the electronic Heijunka board. Table 4 shows the comparisons between the amount of time spent on the Heijunka board before and after the implementation. Total operator, group leader, and manufacturing engineer time saved is 77.18 minutes per day on the AMV line after installation. We did not keep track of defect count in our time studies, but we believe our error-proofing methods will reduce Heijunka related manufacturing defects.

Table 4: Comparison of Time Study Results before and after installation

Parameters	Pre-installation	Post-installation
Uses/Pitch	2.250 times	1.125 times
Time spent on Heijunka/Pitch	188.00 s	43.13 s
Setup time/Day	37.12 min	10.90 min
Operation time/Day	78.33 min	17.25 min
Total time/Day	105.33 min	28.15 min

Using an unpaired t-test as shown in Figure 10, the new operation time reveals a significant mean shift of 45.22 seconds with a p value of 0.00248.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2 \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}}$$

$$s^2 = \frac{\sum_{i=1}^{n_1} (x_i - \bar{x}_1)^2 + \sum_{j=1}^{n_2} (x_j - \bar{x}_2)^2}{n_1 + n_2 - 2}$$

Figure 10: Statistical unpaired t-test

Using an F-test as shown in Figure 11, a p value of 0.853 was obtained. There was not a significant change in pre-installation and post-installation variance. The variance of the operation time 25.87 seconds for pre-installation and 27.68 for post-installation.

$$F = \frac{S_X^2}{S_Y^2}$$

$$S_X^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2 \text{ and } S_Y^2 = \frac{1}{m-1} \sum_{i=1}^m (Y_i - \bar{Y})^2$$

Figure 11: Statistical F-test

Our solution is also fully supported by Thetford IT and implementable for additional lines in the plant. This allows our automation to scale to provide additional error-proofing and time savings in the plant. Additionally, when a new group leader is trained, we believe our program is easier to train for than the existing process.

Next Steps

Going forward, the ORV algorithm and the push to print functionality are improvement areas that have not been fully implemented. Thetford IT department will fully automate the printer process in January and enable the push to print functionality to complete the AMV automation. Further studies will be needed to develop the ORV algorithm, including qualifying the effects of uneven operator load on production output. If Thetford decides to bring the Heijunka Automation to additional lines, the Python Scheduler and the Daily Schedule sheet in the Electronic Heijunka Board will need to be adjusted for parameters used for the new line.

References

[1] Nils Boysen, Malte Fliedner, Armin Scholl. Level Scheduling of Mixed-Model Assembly Lines under Storage Constraints. *International Journal of Production Research*, Taylor & Francis, 2009, 47 (10), pp.2669-2684. [ff10.1080/00207540701725067](https://doi.org/10.1080/00207540701725067)ff. Ffhal-00513011f

Appendix