Final Scientific/Technical Report

Date of Report: December 5, 2016

Federal Agency/ Organization Element	DOE/EERE/ Office of Advanced Manufacturing Program (AMO)
Award Number	DE-EE0006025
Project Title	Assisting the Tooling and Machining Industry to Become Energy Efficient
Project Period	01/01/2013 to 6/30/2016
Recipient Organization	Arizona Commerce Authority 333 N. Central Ave. STE 1900 Phoenix, AZ 85004
Principal Investigator	Bennett Curry Vice President Business Development Arizona Commerce Authority

Executive Summary

The Arizona Commerce Authority (ACA) conducted an Innovation in Advanced Manufacturing Grant Competition to support and grow southern and central Arizona's Aerospace and Defense (A&D) industry and its supply chain.

The problem statement for this grant challenge was that many A&D machining processes utilize older generation CNC machine tool technologies that can result an inefficient use of resources – energy, time and materials – compared to the latest state-of-the-art CNC machines.

Competitive awards funded projects to develop innovative new tools and technologies that reduce energy consumption for older generation machine tools and foster working relationships between industry small to medium-sized manufacturing enterprises and third-party solution providers.

During the 42-month term of this grant, 12 competitive awards were made. Final reports have been included with this submission.

<u>January 2014</u>

- The University of Arizona and [Sargent Aerospace & Defense] partnered to develop a ***Machine Tool Coolant & Energy Consumption Monitoring*** technology for remote sensing and control of coolant concentration, contamination, and energy consumption via Apple/Android based apps including the automatic shutdown of the machine when critical thresholds are exceeded. Grant request of $75,000 with additional leveraged funds of $61,178. **Total value - $136,178**.

- The University of Arizona and Sargent Aerospace & Defense partnered to develop a ***Simulation-Based Optimization of Plant Equipment Starting, Stopping & Idle Time*** analysis tool to guide the scheduling of complex multi-step setup and machine tool processes to reduce electricity costs during peak/spike energy consumption times. Grant request of $75,000 with additional leveraged funds of $57,178. **Total value - $132,178**.
- **Blackerby Associates, Inc.** partnering with Accuwright Industries to develop an ***Integrated Lean and Green Kaizen Process***. This project includes development of a new value stream mapping approach that includes measurement of energy use and greenhouse gas emissions at each operation in addition to standard lean flow data. Grant request of $39,402 with additional leveraged funds of $13,134. **Total value - $52,536**.

December 2014

- **Interlink Engineering** partnering with Chandler based, Pilgrim Screw for design & integration of bolt-on automation tooling to improve productivity (cycle time) & repeatability (heating variance) on one hot forging process. Grant request of $72,575 with additional leveraged funds of $21,090. **Total value - $93,665**.
- **Lean Advisors** partnering with Tucson based, Industrial Tool Die & Engineering (ITDE) for improving energy efficiency with a 7-phase approach focused on the use of Energy Value Stream Mapping and Energy Kaizen Events in order to identify and quantify energy efficient process improvement solutions on the shop floor. Grant request of $42,540 with additional leveraged funds of $17,500. **Total value - $60,040.**
- **University of Arizona** partnering with Tucson-based Sargent Aerospace to estimate energy consumption under given machining parameters & maximize energy efficiency as well as productivity of a CNC machine. Grant request of $75,000 with additional leveraged funds of $66,500. **Total value - $141,500**.
- **University of Arizona** partnering with Tucson-based Sargent Aerospace to evaluate lean manufacturing tools & generate optimal production schedules to reduce electricity cost & improve the productivity via simulation-based optimization & value stream mapping. Grant request of $75,000 with additional leveraged funds of $66,500. **Total value - $141,500**.

October 2015

- **Interlink Engineering** partnering with Chandler based, Pilgrim Screw for design & integration of a bolt-on redesigned induction-heating coil. Grant request of $72,390 with additional leveraged funds of $28,390. **Total value - $100,780**.
- **Lean Advisors** partnering with Tucson based, Industrial Tool Die & Engineering (ITDE) for improving energy efficiency with Yellow Belt training for 12 members of ITDE team members. Grant request of $35,000 with additional leveraged funds of $12,500. **Total value - $47,500.**
- **University of Arizona** partnering with Tucson-based Sargent Aerospace to develop a knowledge based optimization module of machining parameters to maximize energy efficiency, as well as productivity of a CNC machine. Grant request of $75,000 with additional leveraged funds of $67,016. **Total value - $142,016**.
- **University of Arizona** partnering with Tucson-based Sargent Aerospace to predict and notify potential production bottlenecks and unexpected production disruptions (e.g. tool

failure) via simulation and dashboard. Grant request of $75,000 with additional leveraged funds of $67,016. **Total value - $142,016**.

February 2016 – One Competitive Award (Energy Reduction Mini-Challenge)

- **Rugo Machine Shop Services** replaced less energy efficient lighting and fans in their production facility. Grant request of $10,000 with additional leveraged funds of $6,845. **Total Value - $16,845.**

Knowledge Gained

- The A&D industry recipients (Sargent, Accuwright, Industrial Tool Design Engineering and Pilgrim Screw) responded positively to the outcomes of the projects.
- It is unclear if the University of Arizona (Arizona Board of Regents) will patent and commercialize the results of their work with Sargent.
- Those receiving lean training (Accuwright and Industrial Tool Design Engineering) were pleased with the outcomes.

4. Goals v. Actual
   - We exceeded our initial goal of ten competitive awards with an actual of 12.
   - The award was fulfilled on time and within budget.

5. Summary of Project Activities
   - Rebranded the grant competition from an "Energy Reduction Grant" to the 2014 Innovation in Advanced Manufacturing Challenge Grant for wider appeal. No changes in scopes of work and target audience.

6. Products
   - Publications, Conference Papers, and Presentations: Dr. Son of the University of Arizona presented his Sargent research projects at the June 4, 2014 meeting of the National Defense Industrial Association's (NDIA) Manufacturing Division in Washington, DC.
   - Inventions, Patent applications, and/or licenses: None
   - Website(s) or other Internet site(s): http://www.azcommerce.com/programs/innovation-in-advanced-manufacturing-grant-competition?referrerId=1313 (Page was taken down at end of program)
   - http://www.azcommerce.com/small-business/business-insights/10-ways-to-reduce-energy-consumption

7. Not applicable to this project.

Project Final Report: Integrated Energy Reduction and Productivity Enhancement of Machine Shop Operations via Smart and Remote Monitoring and Control

Project Period: January 16, 2014~July 15, 2014

July 28, 2014

Submitted to: Arizona Commerce Authority

Southern & Central Arizona Aerospace & Defense Region 2013 Energy Reduction Challenge

Grant Competition Program

Submitted by: Dr. Young-Jun Son

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SME Partner:

Sargent Controls & Aerospace

THE UNIVERSITY OF ARIZONA. | Arizona's First University.

1. Goals

The first goal of this project is to develop smart sensing and control, and software-enabled technologies, which will make older generation, energy-intensive machine tools smarter. This smart feature will allow us to achieve significant energy reduction as well as productivity enhancement of machine shop operations. The particular list of features and technologies that will be developed in this project include 1) remote monitoring of coolant concentrations/contaminations and energy consumptions via in-line refractometer, power-meter, and iPad/smartphone apps, 2) warning notifications via iPad/smartphone apps, 3) automatic shutdown of the machine when critical thresholds (of concentration/contamination levels or energy consumption) are exceeded, and 4) dynamic control of machining parameters (e.g. cutting speed, depth of cut, feed) based on the current coolant concentration considering expected tool life, energy consumption, and cycle time.

The second goal of this project is to establish optimum starting, stopping, and idle times of older generation, energy-intensive machine tools to reduce electricity cost without sacrificing productivity via a flexible, data driven simulation-based optimization system. Under a demand response program (e.g. Sargent is participating in a program provided by Tucson Electric Power) where the price of electricity depends on different time of the day and peak consumption levels, it is imperative to avoid peak/spike consumption and schedule machining vs. setup works such a way to reduce electricity cost. In particular, three major problems will be addressed in this project. First, instead of starting up all pieces of equipment within a short time window 1) at the beginning of each shift or periodic maintenance work or 2) immediately after power outage (that machine shops such as Sargent experience numerous times especially during the summer), the desire is to sequence powering ups to reduce the peak energy consumption. Second, we will compare the energy consumption (and corresponding electricity cost) between keeping the equipment on (during the gaps of jobs), vs. 2) turning off and on again. Third, we will study the impact when service equipment (or set-up activities) is scheduled during non-peak production hours to store energy for use in peak hours.

2. Achievement Summary

Dr. Son's team and Sargent have made the following achievements towards the goals of the project:

- Machine shop layout and equipment specification data collected
- Power meter installed in OKUMA "Twin Star" CNC machine at Sargent
- Refractometer system developed to automatically monitor the coolant concentration
- MySQL Database and communication server program developed to store energy consumption and coolant concentration data, as well as communicate with mobile applications.
- Mobile application (Android and iOS) developed to monitor the energy consumption and coolant concentration statuses.
- Shop operation simulation model developed to optimize the operation schedule and machine turn-on sequence for controlling the shop operations.
- Simulation experiments conducted to demonstrate energy cost saving by adopting optimized operation schedule and machine turn-on sequence.

The following sections explain the aforementioned achievements in detail.

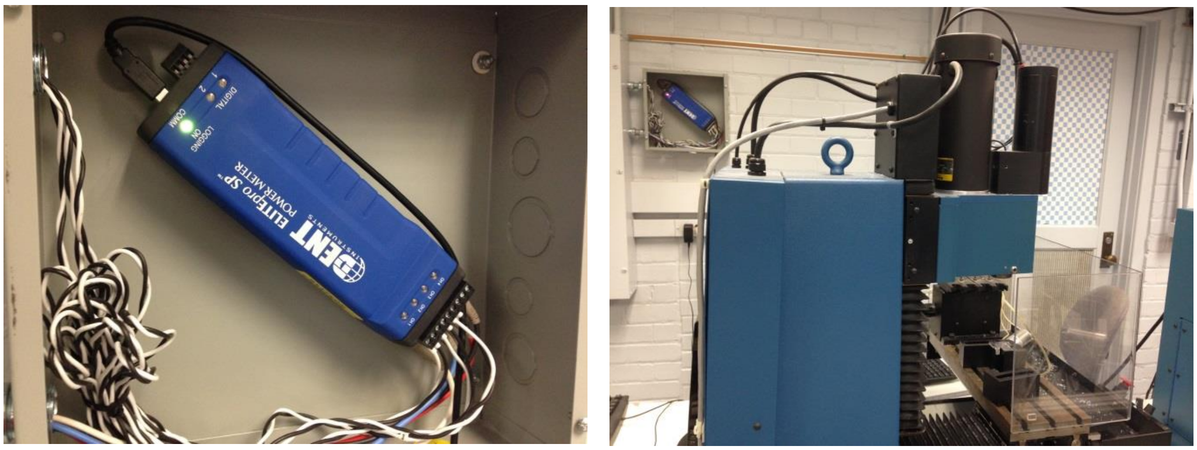
3. Data Collection

Dr. Son's team has been working closely with Sargent in order to develop the remote monitoring system. Sargent has provided onsite working place for Dr. Son's team and major data such as Sargent facility and historical utility bill. To be specific, the following data has been collected for system development:

- Equipment information (e.g. equipment ID, equipment type, and power) for simulation model development
- Monthly utility bill since 2007 for analyzing the energy consumption pattern
- Machining parameters
- Coolant information and samples for developing the refractometer system

4. Power Meter System Testing and Installation

For testing purpose, the power meter system has been first implemented in the CIMS lab at the University of Arizona. As shown in Figures 1, Dent ELITEpro SP^{tm} power meter (similar model that is installed at Sargent) has been purchased and installed in the CNC milling machine as a testbed.



(a) Power meter installed (b) testbed with power meter

Figures 1. Power meter system implemented in CIMS lab at the University of Arizona

The power meter has been set up to automatically log the energy consumption of the manufacturing facility (see Figure 2), and the data is available for the database/communication server program (see Section 6).

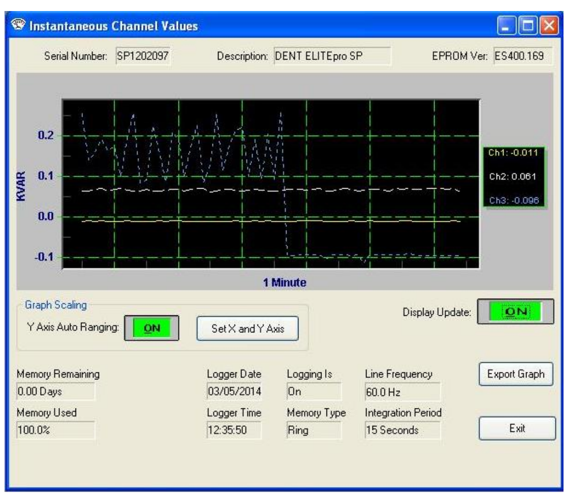


Figure 2. Real-time energy consumption monitoring

The energy consumption data is logged into both .dat and .csv files. Sample data is provided in Table 1.

Table 1. Sample data from power meter

Number	Date	End Time	Min. Volt	Min. Time	Max. Volt	Max. Time	Avg. Volt	Min. Amp	Min. Time	Max. Amp
1	2/16/2014	15:33:15	119.1	15:33:02	119.4	15:33:08	119.3	2.7	15:33:12	3.93
2	2/16/2014	15:33:30	119.2	15:33:22	119.4	15:33:17	119.3	2.7	15:33:20	3.93
3	2/16/2014	15:33:45	119.2	15:33:37	119.4	15:33:30	119.3	2.71	15:33:30	3.96
4	2/16/2014	15:34:00	119.2	15:33:48	119.4	15:33:58	119.3	2.7	15:33:45	3.33
5	2/16/2014	15:34:15	119.3	15:34:08	119.4	15:34:04	119.3	2.69	15:34:04	3.67
6	2/16/2014	15:34:30	119.2	15:34:22	119.4	15:34:15	119.3	2.68	15:34:15	4.16
7	2/16/2014	15:34:45	119.2	15:34:41	119.4	15:34:30	119.3	2.68	15:34:41	3.24
8	2/16/2014	15:35:00	119.3	15:34:45	119.4	15:34:53	119.3	2.69	15:34:51	3.62
9	2/16/2014	15:35:15	119.2	15:35:04	119.4	15:35:11	119.3	2.73	15:35:13	3.88
10	2/16/2014	15:35:30	118.4	15:35:25	119.4	15:35:24	119.3	2.73	15:35:19	3.79

Since the power meter does not provide API for connecting the developed database (See Section 6), Dr. Son's team has developed executable file (.exe) to periodically transferring the energy consumption data from .csv files to the developed database. The same system has been installed at Sargent south facility as shown in Figure 3. Figure 4 shows one instant data collected by the installed power meter.

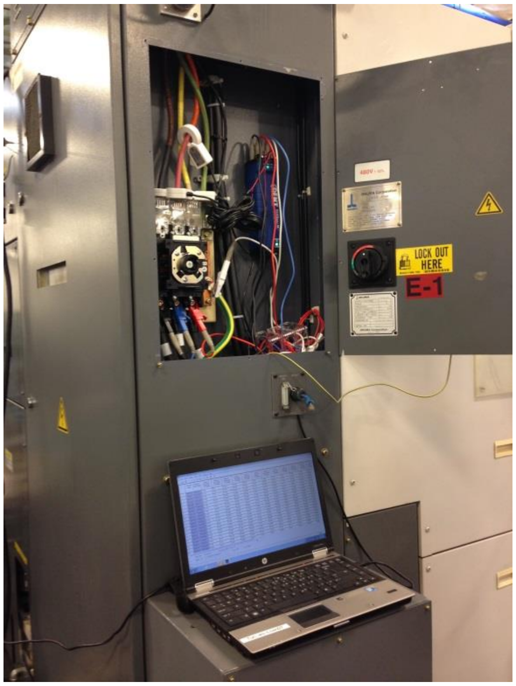


Figure 3. Power meter installed in OKUMA "Twin Star" CNC machine

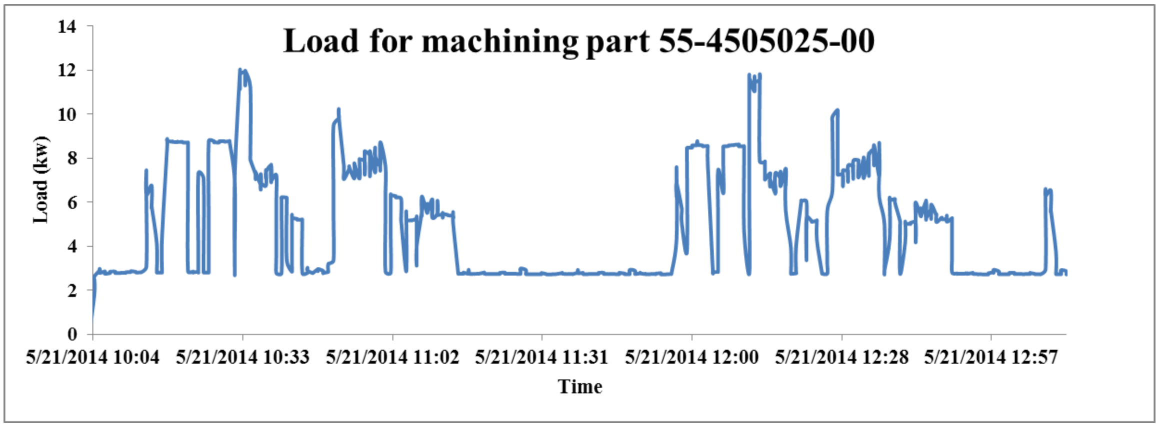


Figure 4. Instant load data collected for processing part 55-4505025-00

5. Refractometer System Development

For real-time monitoring of coolant concentration, Dr. Son's team has implemented computer vision and clustering techniques into a handhold refractometer based platform. Although there exist multiple models of inline refractometer on the market (e.g., Cole-Parmer® PR-111 in-line refractometer) to support real time monitoring of coolant concentration, its high cost (e.g., more than $5,000/unit) is not feasible for small or medium size companies. Thus, a handhold refractometer (about $120/unit) that is being used at Sargent has been utilized with an auto focus web camera and a computer vision based coolant concentration detection algorithm (see Figure 5) to achieve similar performance as commercial inline refractometers.

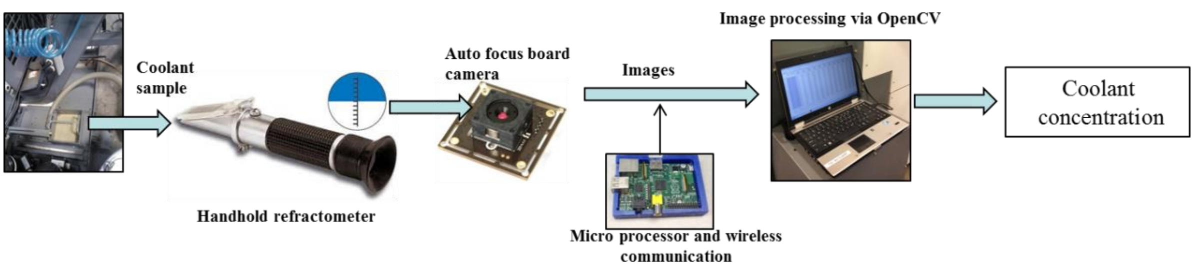


Figure 5. Refractometer system structure

As shown in Figure 5, the coolant is continuously dripped on to the lens of the handhold refractometer. Then the web camera takes the reading view as digital image that is transmitted to the computer vision based detection algorithm. Dr. Son's team has developed two versions of refractometer system: (1) wired version and (2) wireless version based on how the digital image is transmitted. In the wired system, digital images are transmitted to a local computer (where the database is located) via USB cable. This version is appropriate for monitoring the coolant in open space area. On the other hand, the wireless system uses microcomputer (e.g. Raspberry Pi) to connect with the web camera and processes the digital images via the embedded detection algorithm. Then it transmits the coolant concentration data to the local computer wirelessly (e.g. WiFi). Due to the wireless transmission function, it can be installed inside of machine. But, it requires additional power supply for long time operation. To detect the coolant concentration according to the digital images, the coolant concentration detection algorithm program is installed in the microcomputer (wireless version) or the local computer (wired version). Figure 6 illustrates the proposed detection algorithm in detail.

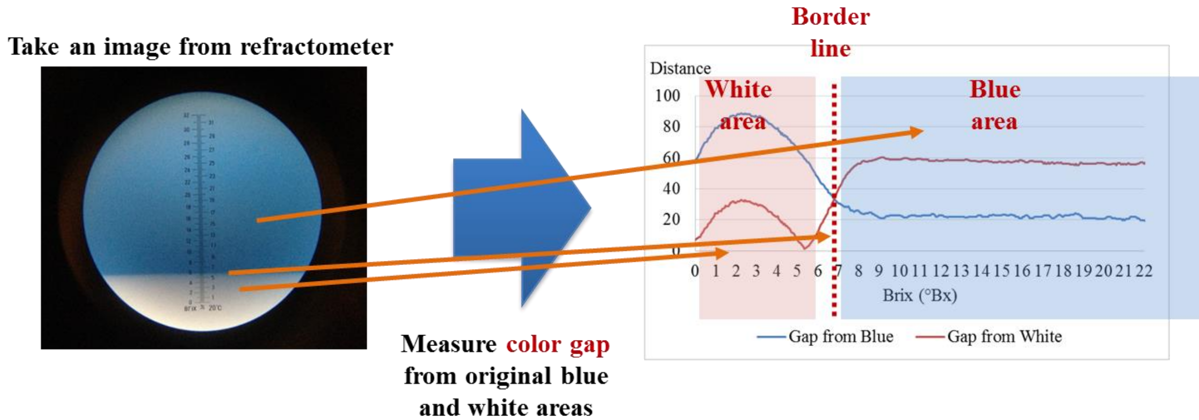
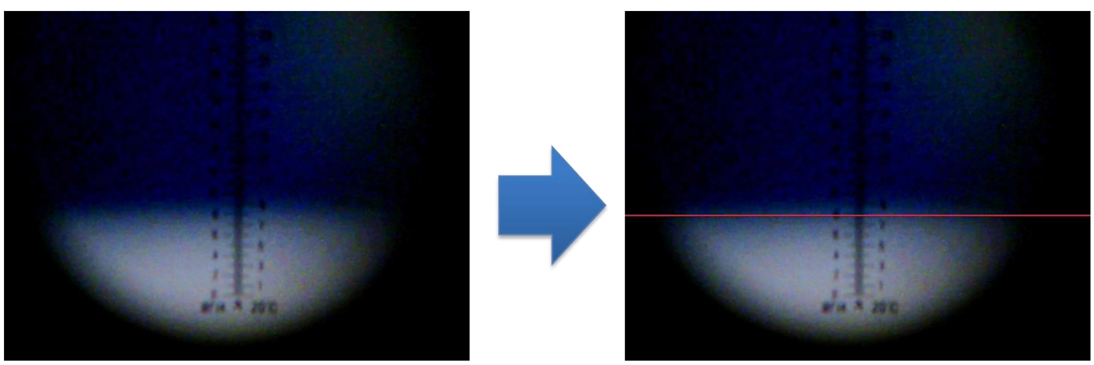


Figure 6. Procedure of a computer vision based detection algorithm

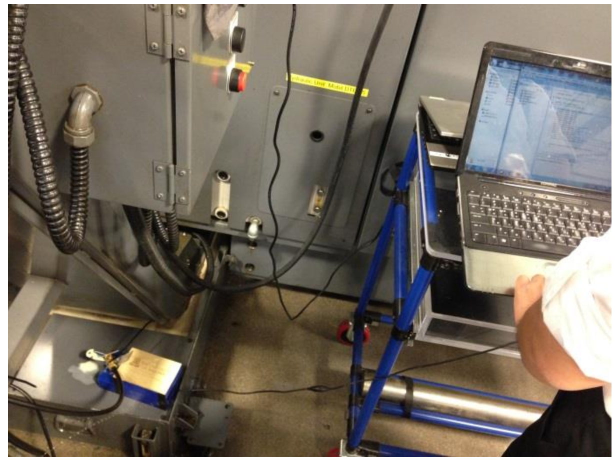
In Figure 6, the original refractometer reading image is decomposed into two different areas (i.e., blue and white) in order to detect the corresponding concentration value. RGB information of the image has been used for the clustering and Manhattan distance has been used to compute the gap between the blue and the white areas. Since the metric value (i.e. concentration value) and its location in the handhold refractometer are already known, the program gives the concentration value once a border between two areas is detected. Based on this approach, Figure 7 shows a sample image obtained by the refractometer system. The red line on Figure 7 (b) is the detected border and the concentration value is 8.1875 °Bx. By taking an image with specified sampling interval (e.g., 1 minute for this experiment), the refractometer system automatically provides the coolant concentration data. Figure 8 shows the implement of wired refractometer system at Sargent and the wireless refractometer system developed.



(a) An original image (b) A processed image

Figure 7. A sample image from the refractometer system

(a) Wired refractometer system implemented



(b) Coolant concentration data collection

(c) Wireless refractometer system

(d) Raspberry Pi for wireless refratometer system

Figure 8. Refractometer systems

6. Database and Communication Server Program Development

A database and a communication server program have been developed in the CIMS lab to help users to access the status information (e.g. energy consumption and coolant concentration) of equipment in the testbed and warning messages (when abnormality occurs) via a smartphone application (see Section 5). Figure 9 shows the schema of the developed database. There are six tables designed, including '*Users*', '*ActionLogInfo*', '*Sensors*', '*Equipment*', '*Energy*', and '*Coolant*'. '*Users*' table includes users' information on account ID, first name, last name, e-mail address, phone number, and cell phone number. '*ActionLogInfo*' table records actions of users such as login/logout or sending a command to control equipment. '*Sensors*' table includes sensor ID, location of sensor (i.e., equipment ID), status (i.e., on or off), and description of a sensor (e.g., vender or specification). Those two tables are updated by a database administrator. '*Equipment*' table includes equipment ID, equipment type, status of equipment (i.e., on/off), and description of an equipment. '*Energy*' table is about energy consumption status information given by power meter sensors. It includes record number, updated time, sensor ID, status of KW, time of KW status. Table 2 shows an example of '*Energy*' table.

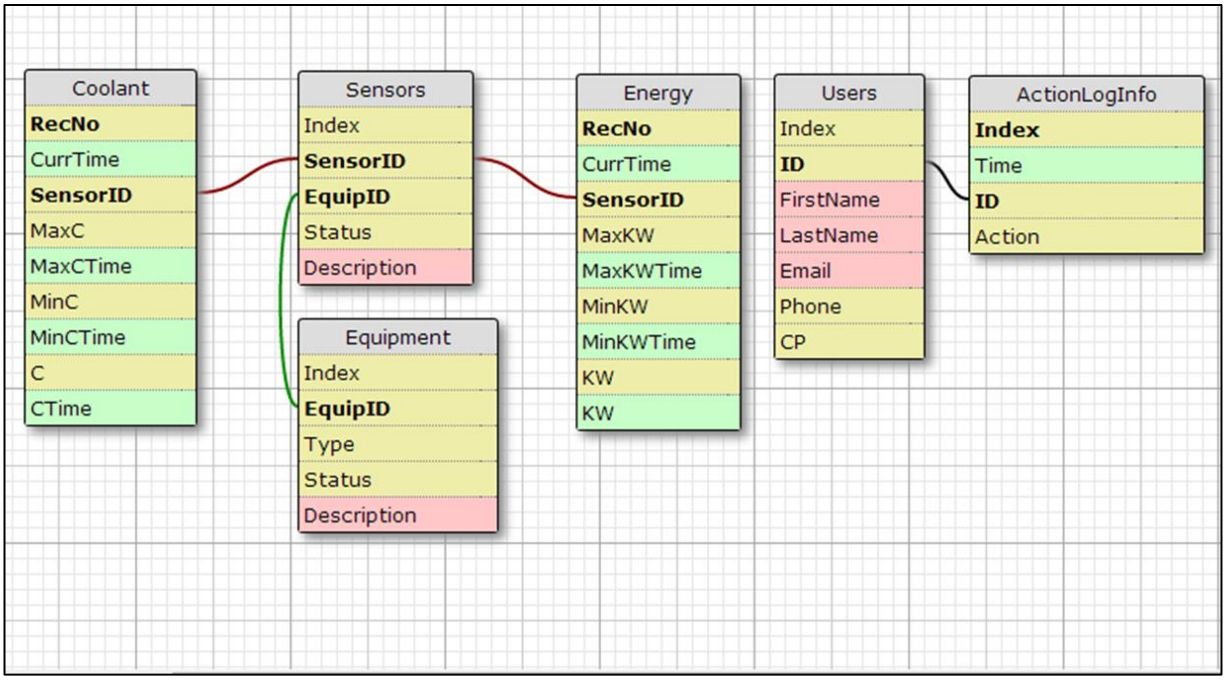


Figure 9. Database schema

Table 2. Example of '*Energy*' table

RecNo	CurrTime	SensorID	MaxKW	MaxKW Time	MinKW	MinKW Time	KW	KW Time
1	2014-05-13 13:09:00	1	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.532	2014-05-13 13:09:00
2	2014-05-13 13:09:15	1	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.542	2014-05-13 13:09:15
3	2014-05-13 13:09:30	1	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.541	2014-05-13 13:09:30
4	2014-05-13 13:09:35	1	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.548	2014-05-13 13:09:35

Similar to '*Energy*' table, the '*Coolant*' table (Table 3) records coolant concentration status involving record number, updated time, sensor ID, status of coolant (*C* represents coolant), time of coolant status. Table 3 shows an example of '*Coolant*' table.

Table 3. Example of '*Coolant*' table

RecNo	CurrTime	SensorID	MaxC	MaxC Time	MinC	MinC Time	C	C Time
1	2014-05-13 13:09:00	1	85	2014-05-13 13:07:15	70	2014-05-13 12:06:00	75	2014-05-13 13:09:00
2	2014-05-13 13:09:15	1	85	2014-05-13 13:07:15	70	2014-05-13 12:06:00	78	2014-05-13 13:09:15
3	2014-05-13 13:09:30	1	84	2014-05-13 13:08:30	68	2014-05-13 12:06:15	73	2014-05-13 13:09:30
4	2014-05-13 13:09:35	1	84	2014-05-13 13:08:30	68	2014-05-13 12:06:15	71	2014-05-13 13:09:35

The status tables (i.e., '*Energy*' and '*Coolant*') are updated by the data from sensors (i.e. power meter and refractometer). In this case, the proposed system uses real-time update client software in microcomputer or local computer connected to sensors. Thus, the real-time update client changes the original sensed data's format to the status tables' formats. For example, the energy consumption data given by power meters (see Table 1) is sent to the communication server program according to the format of '*Energy*' table shown in Table 2. As a result, the communication server program receives the status data of energy consumption and coolant concentration in real time.

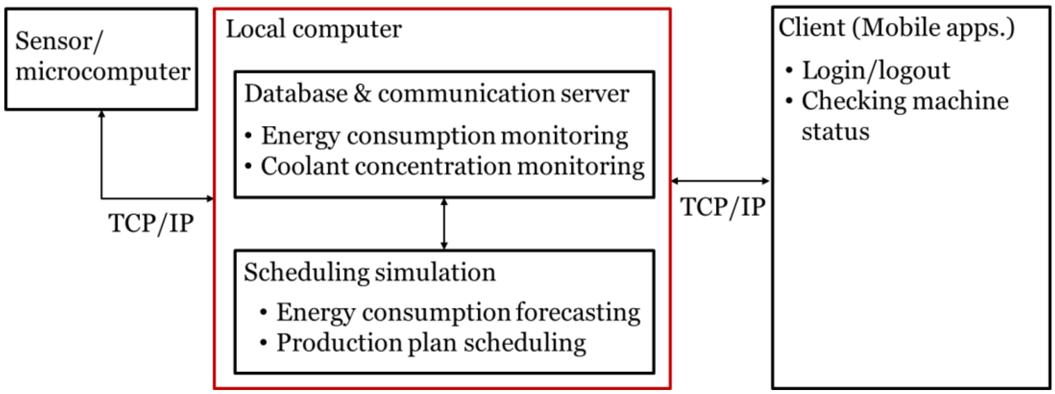


Figure 10. Architecture of automatic monitoring system

As illustrated in Figure 10, the proposed automatic monitoring system consists of five major components such as the refractometer/power meter, microcomputer, local computer (communication server with database), and smart phone (mobile application). In the system, the communication server program populates the database with the latest status information given by sensors (refractometer/power meter) and provides monitoring and warning services to clients (i.e., smartphone application). In the developed server program, MySQL workbench 6.0 has been used for developing the database. The server program executes MySQL queries to provide its services. As a result, users can get status information of coolant or energy consumption via smartphone application.

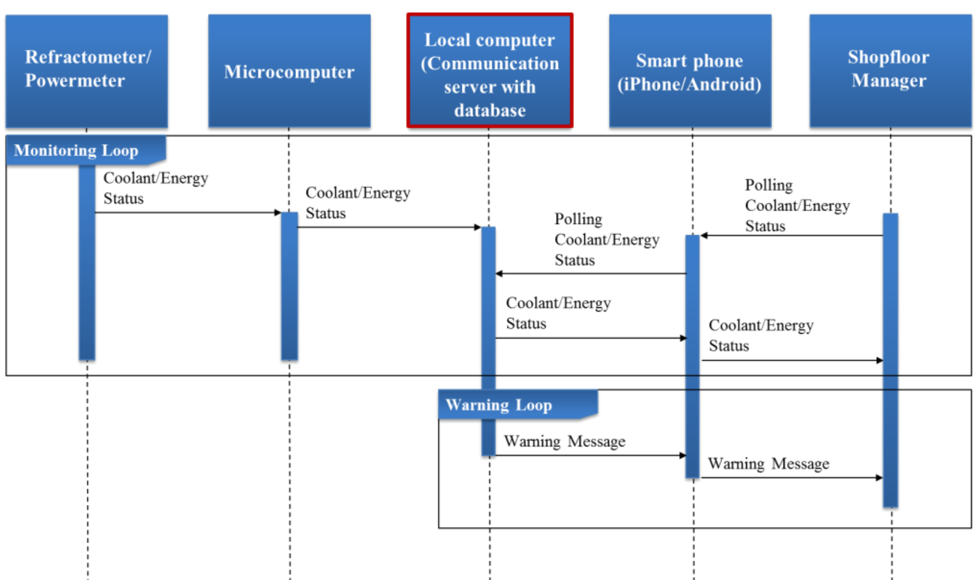


Figure 11. Sequence diagram of monitoring and warning services

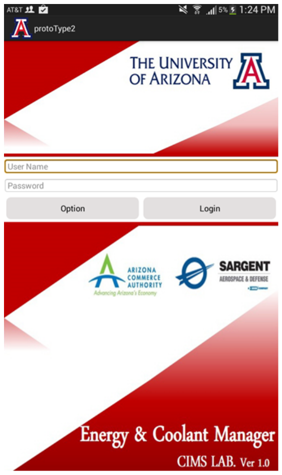
Figure 11 uses sequence diagram to demonstrate the two major services provided by the server program: (1) monitoring the status of sensors (e.g., refractometer and power meter) and (2) warning the users when abnormality is detected. First, the monitoring service has been developed to include updating database with latest status information from sensors and providing the status information. To be specific, the server program initially receives real time status information from multiple sensors under given updating frequencies via microcomputer. Then, the server program stores the status information into database so that it can use the latest status information for abnormality detection. In this regard, users can set their own update frequency to get status information from the server program via individual smartphone application. In addition, the warning service has also been developed. To be specific, whenever the status information is updated, the server program checks whether the status is abnormal or not according to predefined upper and lower thresholds for the energy consumption or concentration of coolant. If the value goes beyond the threshold, the server program sends a warning message to all mobile applications so that subscribers can take corresponding actions (e.g. turn off machines or adjust the concentration of coolant).

7. Mobile Application Development

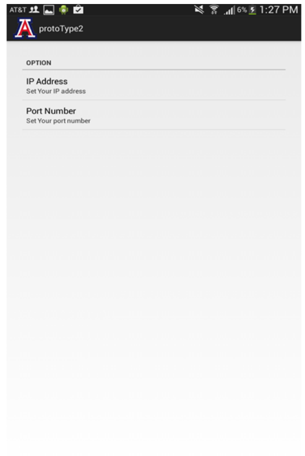
The major role of a mobile application is to display the status information such as energy consumption of each machine or the entire facility, as well as the coolant concentration for each machine. To be specific, the mobile application receives the status information from the server program so that users of the mobile application can take necessary actions accordingly. There are two major functions developed for the mobile application: (1) latest energy consumption and coolant concentration status display and (2) abnormality warning display via warning message.

7.1. Android platform development

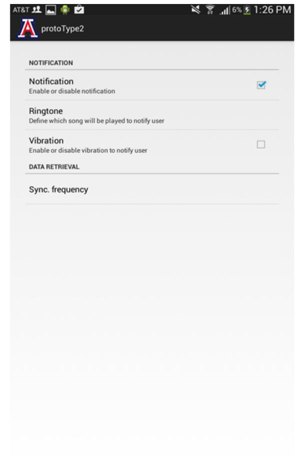
Figure 11 shows the snapshots of the mobile application developed under Android operating system, which is named Energy & Coolant Manager.



(a) Login window

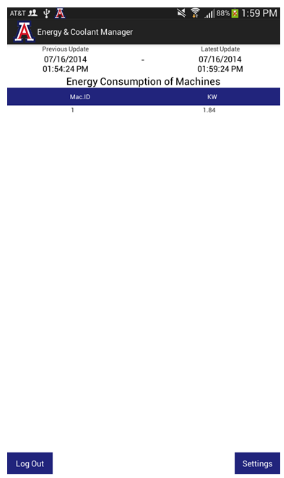


(b) Options window

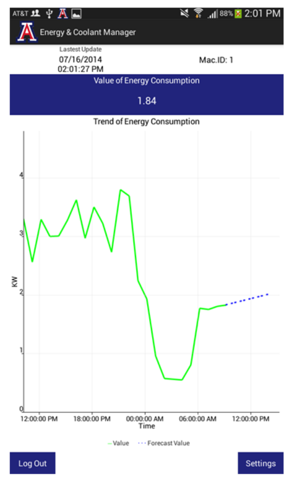


(c) Settings window

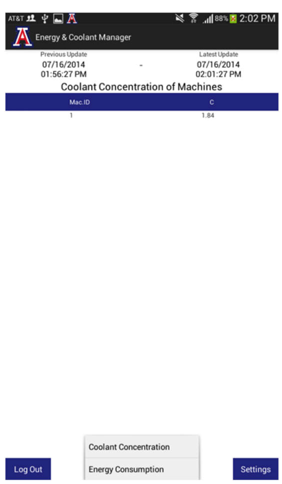
(d) Main window



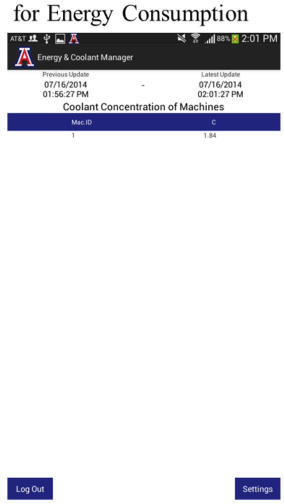
(e) Detail info. Window for Energy Consumption



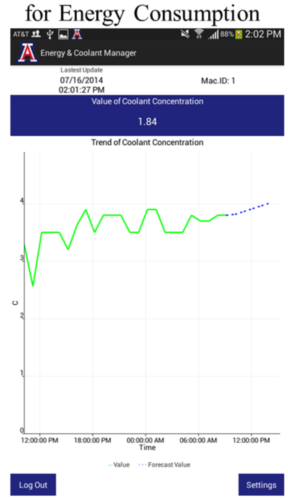
(f) Individual status window for Energy Consumption



(g) Switch option



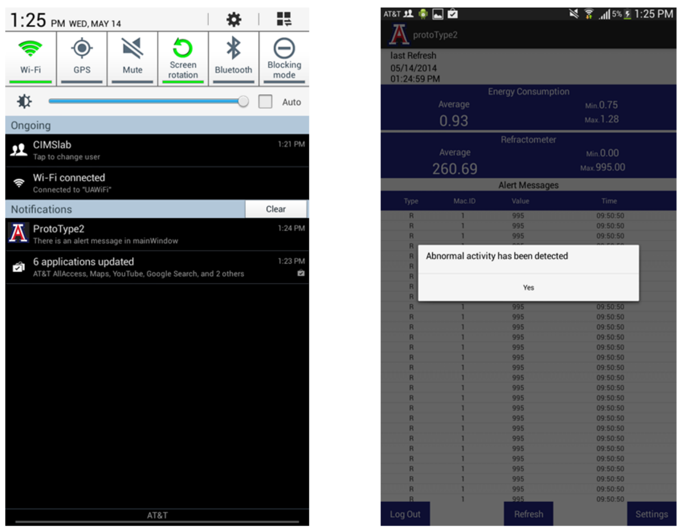
(h) Detail info. Window for Coolant Concentration



(i) Individual status window for Coolant Concentration

Figure 12. Snapshots of the energy application for Android

Figure 12(a) is the Login window of the Android application. Since the server program stores all login information, users can login by using their own login ID and password. If the server IP address or port number are incorrect, the information can be modified in the Options window shown in Figure 12(b) by clicking option button as shown in Figure 12 (a). Once users login the application, the Main window is shown (see Figure 12(d)). The Main window reveals summary of statuses of all sensors (i.e., power meter and refractometer) and warning messages. If users want to know the status of each machine (e.g. energy consumption), they can move to the Detail information window for energy consumption (see Figure 12(e)) by clicking the value of energy consumption in Figure 12(d). If users want to know the status of each machine for coolant concentration, they can move to the Detail information window for coolant concentration (see Figure 12(h)) by clicking the value of coolant concentration in Figure 12(d). The Detail information window includes status values of all sensors so that users can understand which sensor has abnormality. If users click the rows in the table shown in Figure 12(e), they can access the energy consumption status of individual machines via the Individual status window (see Figure 12(f)). Similarly, the coolant concentration status of individual machines shown in Figure 12(i) can be accessed by clicking each row in the table shown in Figure 12(h). Users can also switch views from Detail information window for energy consumption to Detail information window for coolant concentration, and vice versa by clicking options that shows up by pressing menu button on device in Figure 12(g).



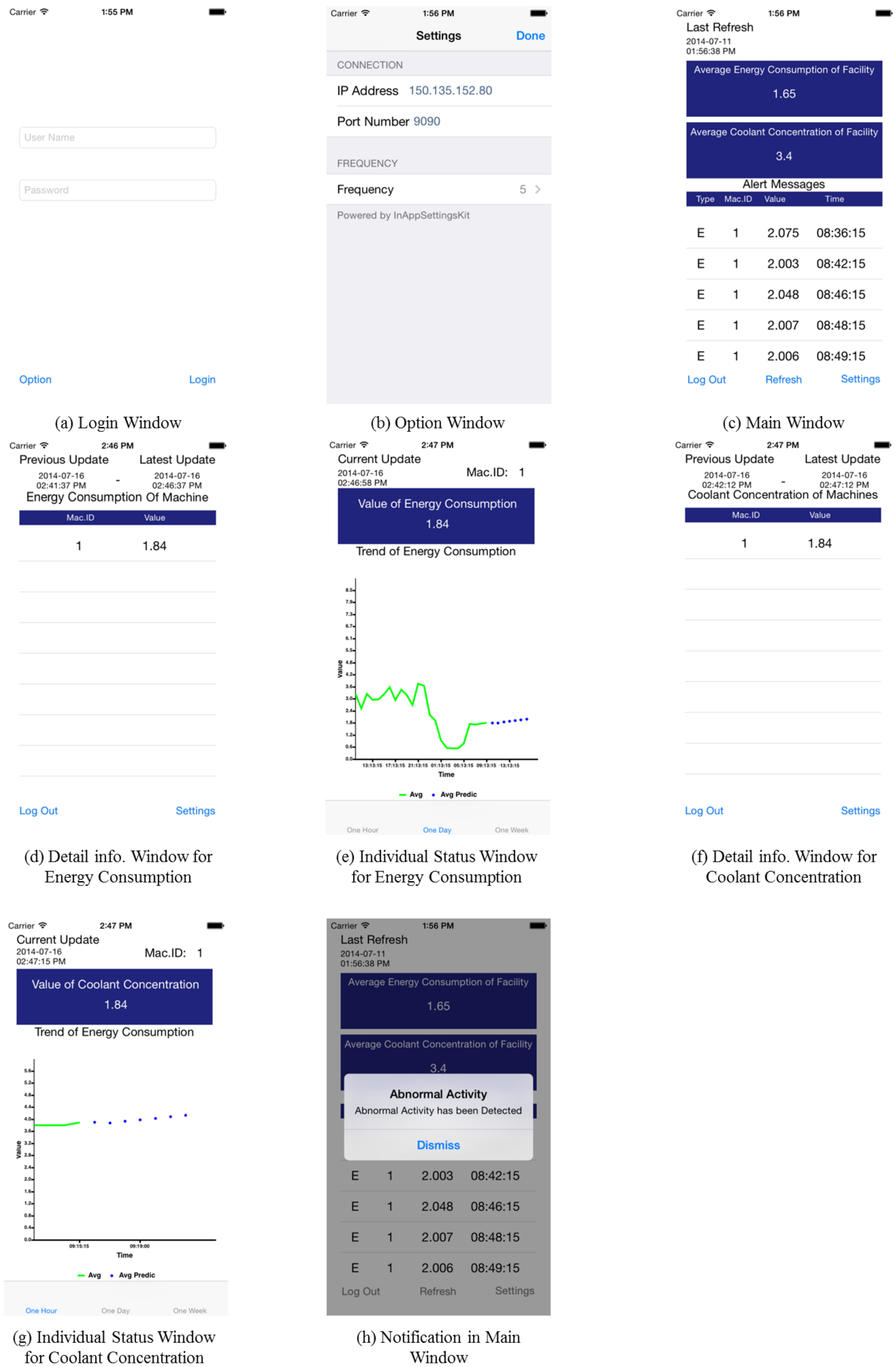
(a) Notification in status (b) Dialog in Main window

Figures 13. Snapshots of warning notification

Figures 13 reveal the snapshots of warning notification in the application. If the status of sensor is abnormal (e.g., more or less than assigned threshold), the server program sends a warning message to the mobile application. Once the mobile application receives the warning message, smart phone inform the user by warning services (see Figure 13(a)). In this case, there exists a message box in the application until users confirm the warning message (see Figure 13(b)). Therefore, users can notice the abnormal status about specific equipment and take appropriate actions to prevent any potential problems.

7.2. iOS platform development

Figure 14 shows the snapshots of the mobile application for iOS mobile phone.



(a) Login Window

(b) Option Window

(c) Main Window

(d) Detail info. Window for Energy Consumption

(e) Individual Status Window for Energy Consumption

(f) Detail info. Window for Coolant Concentration

(g) Individual Status Window for Coolant Concentration

(h) Notification in Main Window

Figure 14. Snapshots of the energy application for iOS

Figure 14(a) is the Login window of the application. Since the server program has all login information, users can login by using their login ID and password. If the server IP address or port number are incorrect, the information can be modified in the Options window shown in Figure 14(b) by clicking option button as shown in Figure 14(a). Once users login the energy app, the Main window is shown (see Figure 14(c)). The Main window reveals values of all sensors and warning messages (see Figure 14(h)). If users want to know the status of each machine (e.g. energy consumption), they can move to the Detail information window for energy consumption (see Figure 14(d)) by clicking the value of energy consumption in Figure 14(c). If users want to know the status of each machine for coolant concentration, they can move to the Detail information window for coolant concentration (see Figure 14(f)) by clicking the value of coolant concentration in Figure 14(c). The Detail information window includes status values of all sensors so that users can understand which sensor has abnormality. If users click the rows in the table shown in Figure 14(d), they can access the energy consumption status of individual machines via the Individual status window (see Figure 14(e)). The dotted line represents the estimated energy consumption based on the current data. Similarly, the coolant concentration status of individual machines shown in Figure 14(g) can be accessed by clicking each row in the table shown in Figure 14(f).

8. Shop Operation Simulation Development and Experiment

8.1. Simulation model

In order to predict the energy consumption of individual equipment and the entire facility under different shop operation schedules, we develop a System Dynamics model in the simulation software AnyLogic®. The developed simulation model includes all the major energy intensive equipment for shop operations at the south facility of Sargent. As shown in Figure 15 below, the operations of individual equipment are simulated via a machine level module (e.g. the amplified view in Figure 15). Besides, the load of each equipment is displayed in real-time via animation plots (as shown in Figure 16) and outputted to the simulation output database. The energy consumption is driven by the real process energy consumption profiles that are developed via off-line experiments.

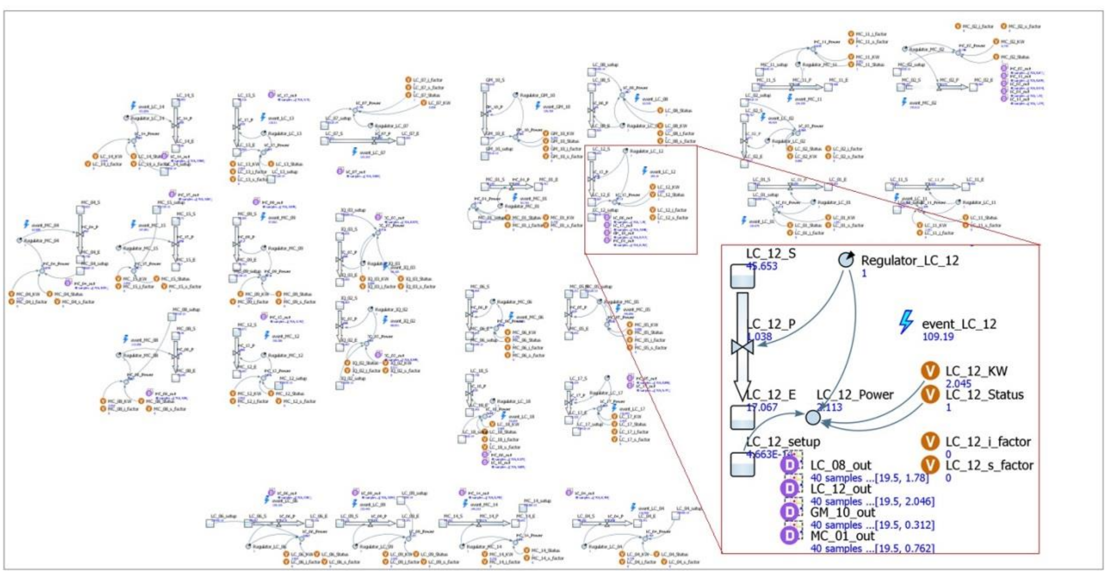


Figure 15. Simulation logic for shop operations

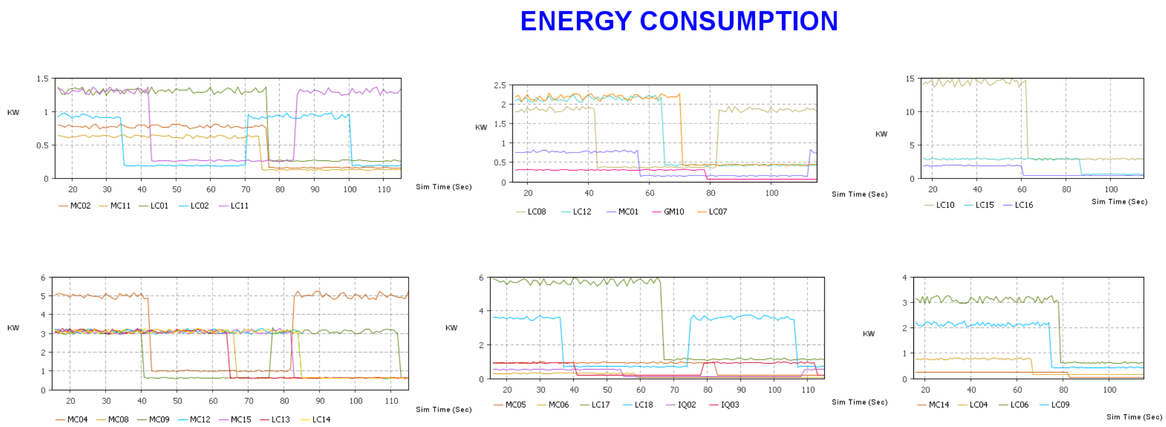


Figure 16. Animation for instant load of individual equipment

8.2. What-If Analysis

The developed simulation is data-driven and capable of various what-if analyses. Based on the information provided by Sargent, we have performed two sets of analyses. Tables 4-6 provide partial information on CNC machine power specifications, one instant of workforce schedule and the product machining times, respectively. The data in Tables 4 and 5 are real data, and the product machining time data is obtained considering realistic assumptions.

Table 4. Equipment power data

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Volts	208	208	208	208	208	480	480	208	208
Amps	25	20	30	42	42	200	40	60	60

Table 5. Workforce schedule for shop operations

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Day (# of operators)	3	3	3	3	3	1	1	1	2
Night (# of operators)	2	2	2	2	2	1	1	1	0

Table 6. Product machining times

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Rate (min/part)	74.88	75.54	32.84	76.11	39.86	62.30	86.88	59.37	39.39
Setup (min/part)	7.49	7.55	3.28	7.61	3.99	6.23	8.69	5.94	3.94
Total rate (min/part)	149.76	151.09	65.67	152.23	79.71	124.60	173.75	118.75	78.79

In the first experiment, we defined two scenarios where machines were standing by and completely turned off when they were idle. Figure 16 depicts the load of the south facility during 9:00AM-11:00AM (production started at 8:00AM). It is shown that turning off machines when they are idle can save energy use. However, turning on the machines produce load peaks (e.g. spikes for "Turn-off" scenario in Figure 17).

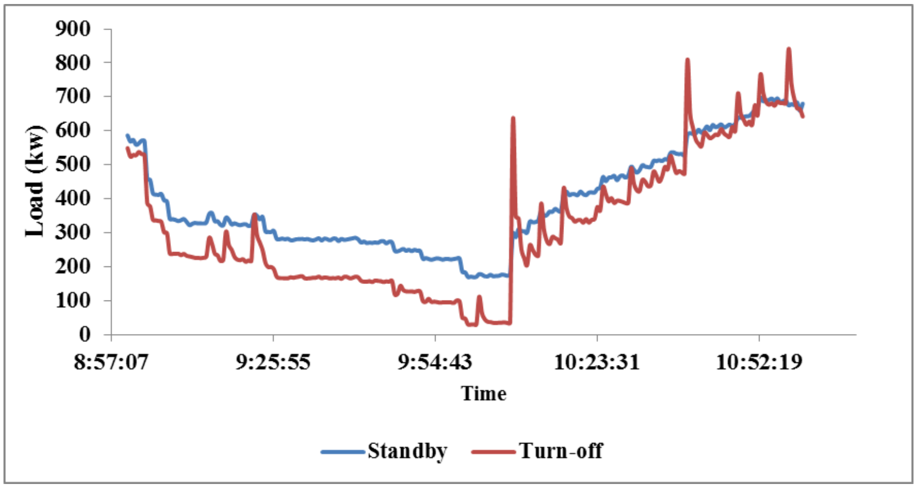


Figure 17. Instant load of the south facility

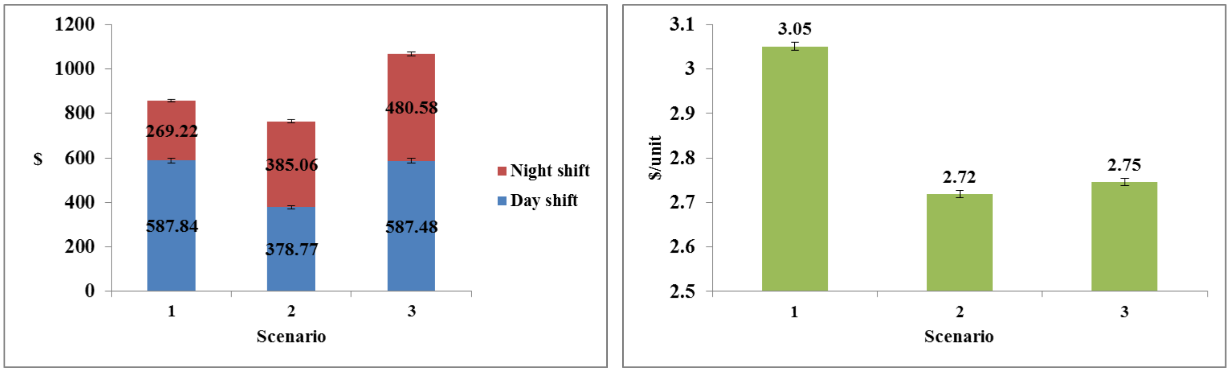
In the second experiment, we defined three scenarios to identify how the change of workforce schedule affects the electricity cost. Scenario 1 is one instance of schedule that Sargent is using. In this case, the day shift has more operators and more machines operate than the night shift. Scenario 2 is to switch the number of operators in the two shifts as defined in Scenario 1. Scenario 3 is that both shifts have the same number of operators for each machine. For the electricity price, we adopted the summer rate under Time of Use (TOU) given by Tucson Electric Power (see Table 7). The day shift is from 8AM to 5PM, and the night shift is from 8PM to 5AM of next day.

Table 7. Summer electricity rate for TOU

Time	On-peak (2pm-8pm weekdays)	Off-peak (other times)
Price ($/kwh)	0.1494	0.1112

Figure 18(a) depicts the electricity bills for day shift and night shift under the three designed scenarios, respectively. Figure 18(b) illustrates the average electricity cost for processing one product. The results suggest that due to the TOU, shifting the production to the night shift can save electricity cost.

In Figure 18(a), Scenario 2 can achieve $ 93.23 daily saving from the current schedule in the facility (i.e., Scenario 1). Besides, unit product electricity cost is $ 0.33 less than Scenario 1. It is worth to mention that there exists a trade-off between the electricity saving and labor cost increase since the hourly salary for night shift requires 35cents higher cost. Comparing scenario 2 with scenario 1, doing more jobs at night shift will increase the labor cost by $109.2 for operators (versus $93.23 electricity saving). Thus, the results suggest that due to the TOU, shifting the production to the night shift can save electricity cost.



(a) Daily electricity bill (south facility) (b) Average electricity cost for unit production

Figure 18. Simulation experiment results for electricity cost

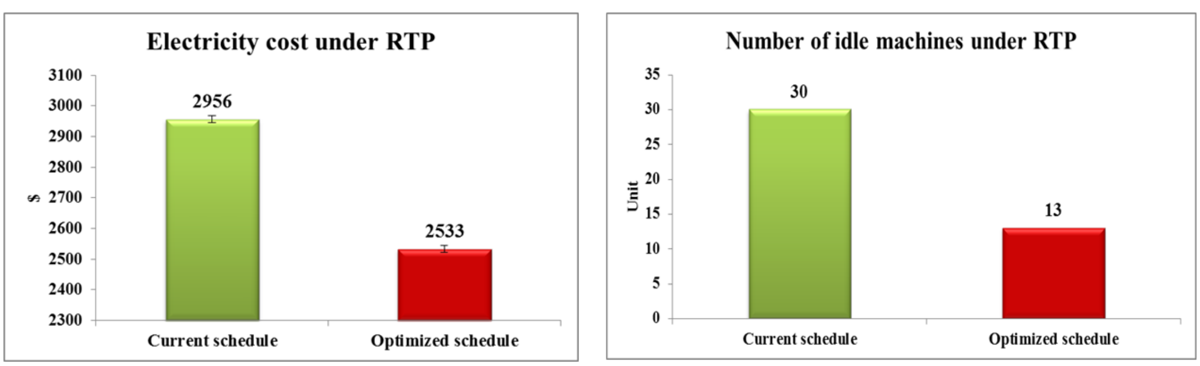
8.3. Optimization

In addition to the machine energy consumption profiles, two models of Demand Response (DR) program: Real Time Pricing (RTP) and Time of Use (TOU), are included in the simulation model. In this study, Real Time Pricing (RTP) model proposed by Zhao et al (2013) has been adopted.

$$p\left(l(t)\right) = p_{base} + \alpha\left(l(t) - l_{base}\right)^{k} \quad (1)$$

where $p(l(t))$ is the real time price (\$/kWh), and p_{base} is base price (\$/kWh), $l(t)$ is the load at time t (kW), and l_{base} is the base load for price calculation (kW). Besides, α and k are control parameters for shaping the price curve.

Figure 19 shows the minimization results of electricity cost under RTP. In this case, we ran the optimization module with 500 iterations and 10 replications per iteration. The simulation duration is 48 hours. Figure 19Figure 19. Optimization for machine status(a) reveals that the optimum schedule can save $ 423 for two days (14.3% saving) from current schedule. This is because the number of idle machines, which consume electricity constantly, is significantly reduced. Table 7 shows details of the optimal schedule.



(a) Electricity cost under RTP (b) Number of idel machines under RTP

Figure 19. Optimization for machine status

Table 1. Optimized machine status for periods between jobs

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10

Idle/off	off	off	idle	off	idle	idle
Equip ID	LC15	LC16	LC08	GM10	MC01	LC12
Idle/off	off	off	idle	off	idle	off
Equip ID	MC05	MC06	LC17	LC18	LC07	IQ02
Idle/off	off	off	idle	off	idle	idle
Equip ID	IQ03	LC13	MC09	MC12	LC14	MC15
Idle/off	off	off	idle	idle	off	off
Equip ID	MC08	MC04	LC06	LC09	MC14	LC04
Idle/off	off	off	idle	off	idle	idle

We further conducted experiments to generate optimum machine turn-on sequence after electricity outage. Since the machine consumes higher electricity than other status of machine (e.g., idle and machining), the turn-on sequence becomes a significant issue. Especially, if all machines are turned on at the same time or very closely, it would produce huge load peak and increases energy cost because we are considering RTP. Thus, two cases are considered: (1) turning on the machines at the same time and (2) turning on the machines with the optimized sequence to save energy consumption. For optimization, all the machines have to be turned on between 22:23 to 22:44. The optimization setting is the same as previous experiment.

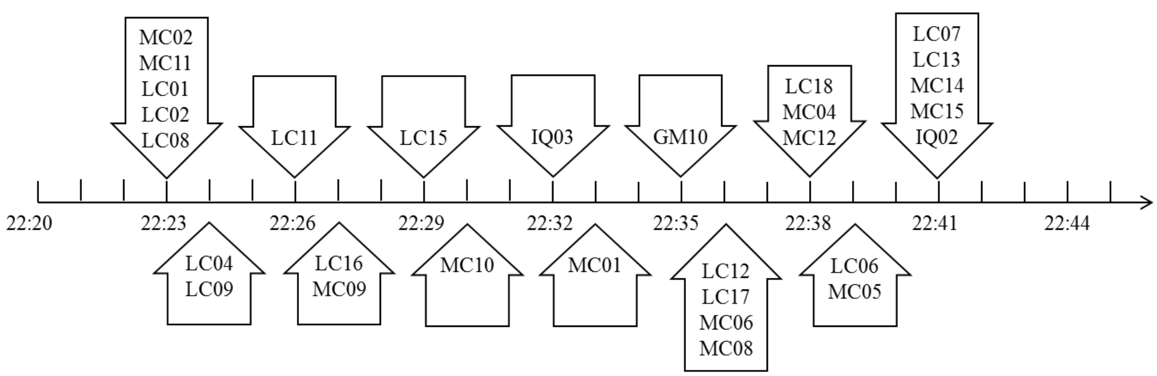


Figure 20. Optimal machine turn-on sequence

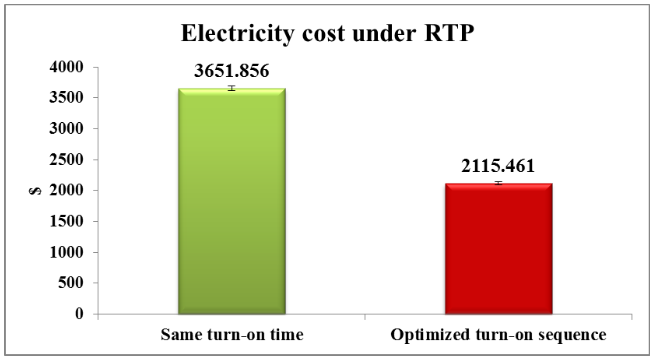


Figure 21. Electricity cost of optimized machine turn-on sequence

Figure 20 shows the optimized machine turn-on sequence given by OptQuest considering the energy consumption pattern of individual machine. The optimized turn-on sequence saves $ 1536.395 (42.1%) from the case that machines are turned on together after electricity outage as shown in Figure 21. Although the work flow in the facility includes 29 machines, the amount of saving will be increased if the work flow involves many machines. Therefore, by using the optimum machine turn-on sequence, we can reduce the load peaks and save energy cost.

9. Future Works

The future works include (1) developing add-on program for CAD/CAM software to estimate the energy consumption based on off-line experiments; (2) integrating Value Stream Mapping with the developed shop operation simulation model to perform what-if analysis and optimization for energy-saving operation schedule.

Reference

J. Zhao, S. Kucuksari, E. Mazhari, Y. Son, Integrated Analysis of High-Penetration PV and PHEV with Energy Storage and Demand Response, *Applied Energy*, 112, 2013, 35-51.

Project Final Report: Integrated Energy Reduction and Productivity Enhancement of CNC Machine Tool via Smart Monitoring and Control and CAD/CAM Integration; Integrated Energy Reduction and Productivity Enhancement of Machine Shop Operations via Simulation-based Optimization and Value Stream Mapping

Project Period: January 7, 2015~July 18, 2015

July 20, 2015

Submitted to: Arizona Commerce Authority

Southern & Central Arizona Aerospace & Defense Region 2014 Energy Reduction Challenge

Grant Competition Program

Submitted by: Dr. Young-Jun Son

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Director, Center for Advanced Integration of Manufacturing Systems and Technologies

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SME Partner:

Sargent Controls & Aerospace

THE UNIVERSITY OF ARIZONA. | Arizona's First University.

1. Goals

The first goal of this project is to estimate the energy consumption under given machining parameters and maximize the energy efficiency as well as the productivity of a CNC machine. To this end, the real-time monitoring system (i.e., coolant concentration via refractometers and energy consumption via power meters) developed by Dr. Son's research group is extended to estimate the energy consumption and the productivity of a CNC machine from a product's design involving machining parameters (i.e., G-code). Energy consumption prediction models are developed based on the collected data via an empirical experiment with a CNC machine in the CIMS lab at the University of Arizona. In the experiment, various machining conditions (e.g., different materials and machining parameters) are considered to understand the relationship between the machining parameters and the energy consumption. Therefore, the proposed system embedding the developed prediction model enables users to identify the proper machining parameters such that the productivity and the energy efficiency can be assured simultaneously. Moreover, the energy consumption and coolant concentration monitoring apps for smart phones (e.g., iPhone/Android) developed by Dr. Son's research group is used for the real-time monitoring the aforementioned sensing data. In this project, the proposed system is implemented in Sargent Aerospace and Defense. As the proposed system is generic, it is expected to be applicable to any equipment configuration involving sensors, microprocessor, host computer, and smart phones/devices.

The second goal of this project is to evaluate lean manufacturing tools and generate optimal production schedules to reduce the electricity cost and improve the productivity via simulation-based optimization and value stream mapping (VSM). Under a demand response program (e.g. Sargent is participating in a program provided by Tucson Electric Power) where the price of electricity depends on different time of the day and peak consumption levels, it is imperative to avoid peak/spike consumption by making proper production schedules. In this project, Dr. Son's research group worked with Sargent Aerospace and Defense to develop a working prototype of the aforementioned simulation-based optimization system involving VSM, which provides the current shop operating state. Therefore, the material flows of the machine shop are improved for minimizing the electricity consumption based on the current state maps.

2. Achievement Summary

Dr. Son's research group and Sargent have made the following achievements for the goals of the project:

- In addition to a power meter, a refractometer that developed by Dr. Son's group is also installed in OKUMA "Twin Star" CNC machine at Sargent.
- Real-time monitoring system via smart phone (e.g., iPhone/Android) is delivered to Sargent Aerospace and Defense.
- A generic energy consumption prediction model is developed to estimate energy consumption of an individual CNC machine under given machining parameters and material type.
- A simulation-based optimization tool in conjunction with VSM is developed.

The following sections explain the aforementioned achievements in detail.

3. Data Collection

Dr. Son's research group has been working closely with Sargent in order to implement the remote monitoring system. Sargent has provided onsite working place for Dr. Son's research group and major data such as value stream maps of Sargent facility and historical energy consumption and coolant concentration of CNC machines. To be specific, the following data has been collected for the system development and testing:

- Energy consumption information and samples for testing the implemented power meter system.
- Coolant information and samples for testing the implemented refractometer system.
- Current and future state maps for one type of product at Sargent.

4. Implementation of Remote Monitoring System at Sargent

The goal of the remote monitoring system is to collect real-time energy consumption data and detect abnormal activities to maximize the energy efficiency as well as the productivity of CNC machines. To this end, the real-time monitoring system developed by Dr. Son's research group is used to monitor the machining parameters as well as quality variables on equipment/tool condition (e.g., coolant concentration via a refractometer, and energy consumption via a power meter). Figure 1 depicts the overview of the proposed system for remote monitoring.

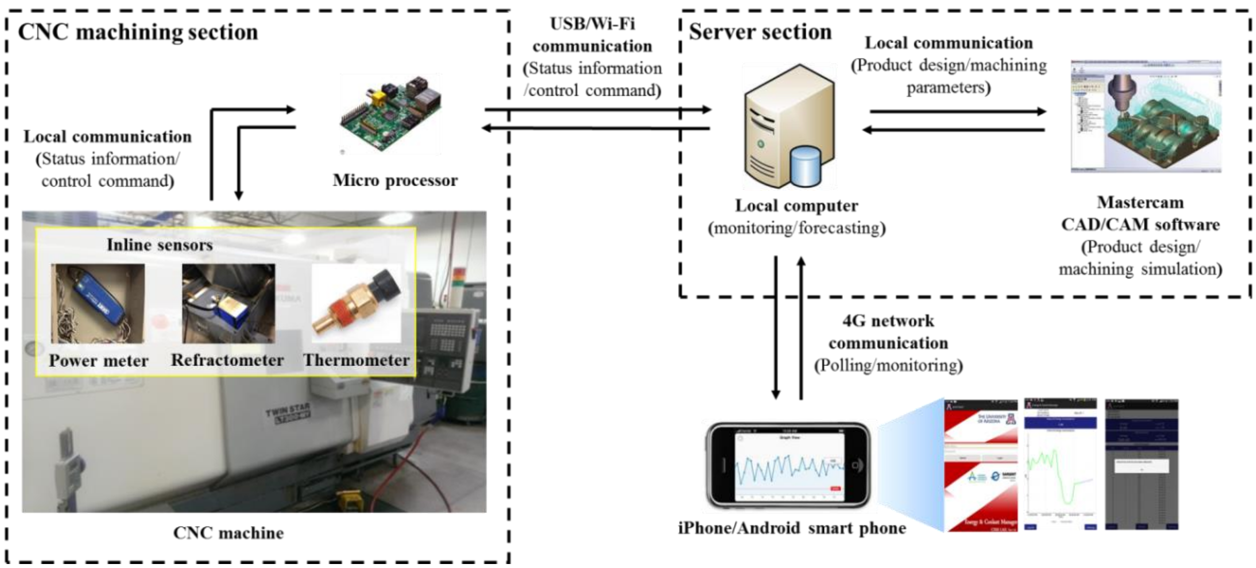


Figure 1: Overview of the proposed system for remote monitoring

The Real-time monitoring system for the shop floor includes five objects: (1) CNC machine with inline sensor, (2) Microprocessor, (3) Local computer, (4) iPhone/Android smart phone, and (5) Shop floor manager. The inline sensor can be either a refractometer or a power meter, and is used for measuring the coolant concentration and the energy consumption, respectively. The output of the inline sensors embedded in the machine and parameters of CNC machine are sent to a local/host computer via a microprocessor (via either USB communication or Wi-Fi communication). Then, the local/host computer sends notifications (e.g. warnings) to the iPhone/Android smart phone so that a shop floor manager can obtain the status of CNC machines. This loop continues until the system is turned off. Figure 2 reveals the interactions in a great detail.

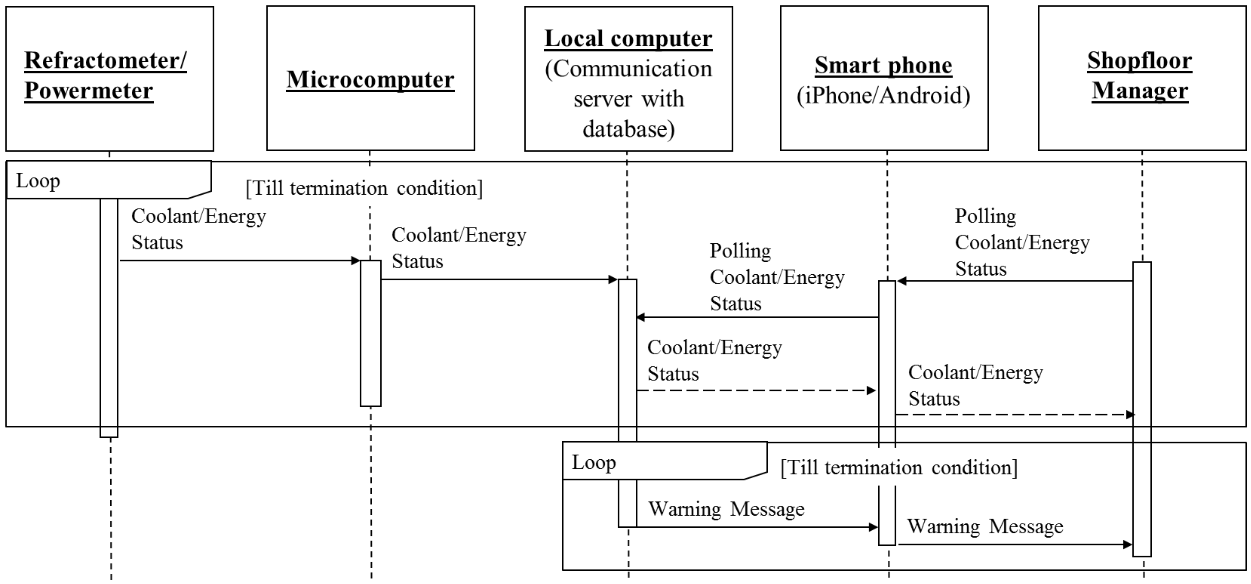


Figure 2: Time sequence diagram of monitoring and warning services

In addition to the local computer, a web server is included as a communication server to provide information to iPhone/Android smart phone (See Figure 3). In this case, a local computer pushes monitoring data collected by the refractometers and power meters to the web server, and the web server communicates with iOS/Android apps. The advantage of this process is that the shop floor manager is able to receive notifications and monitor the status of a CNC machine even outside of the manufacturing facility.

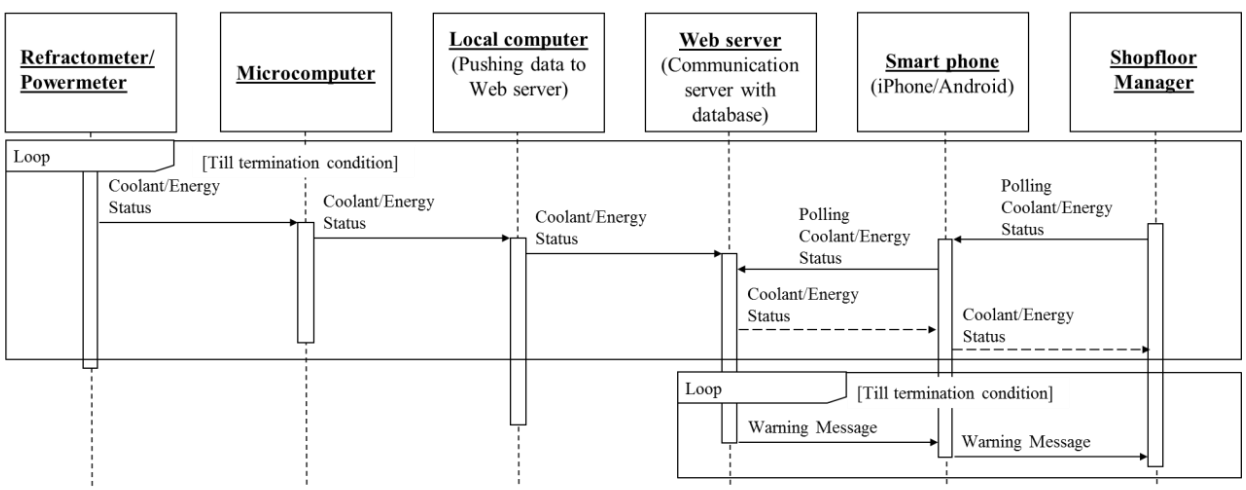
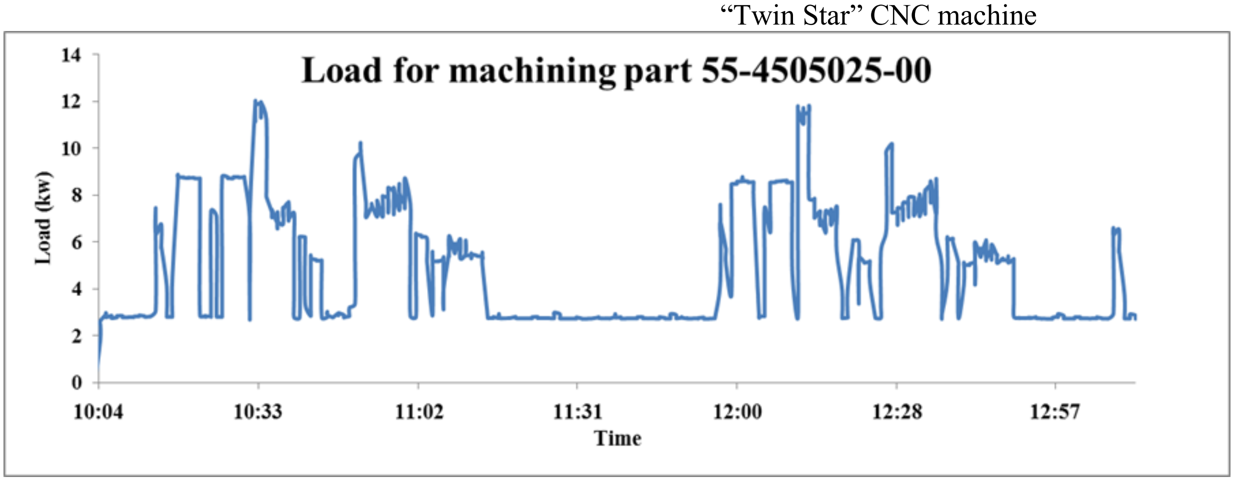


Figure 3: Time sequence diagram of monitoring and warning services

Figure 4 shows the implemented real-time monitoring system at the Sargent south facility. For the energy consumption monitoring, the same power meter (Dent ELITEpro SP^{tm}) used in the first year project has been installed in OKUMA “Twin Star” CNC machine. Thus, the energy consumption data is transmitted by data transmission program developed by Dr. Son’s research group to the database in the real-time monitoring system.

(a) Dent ELITEpro SP^{tm} power meter

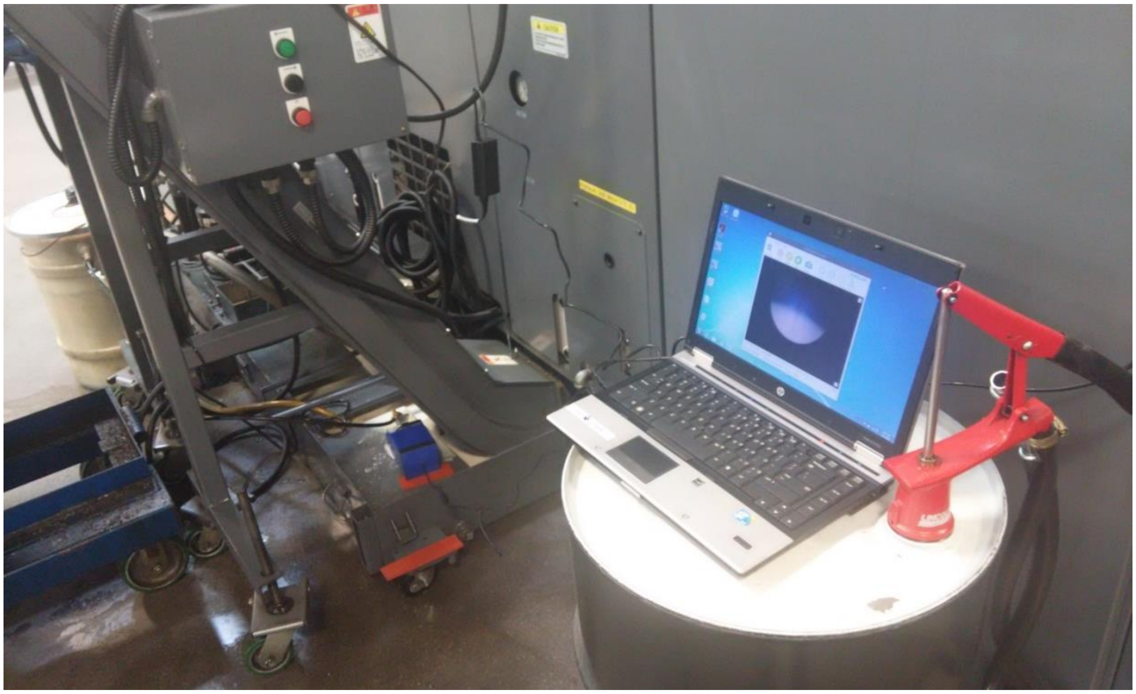
(b) Power meter installed in OKUMA "Twin Star" CNC machine



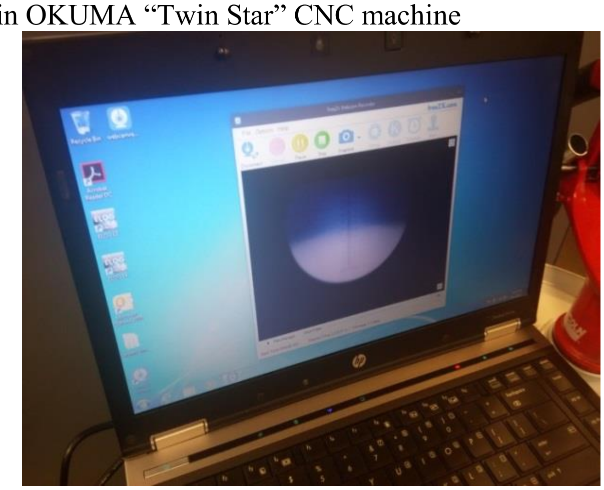
(c) Real-time energy consumption monitoring

Figure 4: Real-time monitoring system of energy consumption

Similarly, the real-time monitoring system of coolant concentration has been implemented in OKUMA "Twin Star" CNC machine (see Figure 5(a)). The reliability of the refractometer has been tested. As shown in Figure 5(a), once coolant from a nozzle of the CNC machine passes the lens of the refractometer, and the concentration level is automatically detected by the developed real-time monitoring program. Figures 5(b) and 5(c) show the inline refractometer and the interface of the coolant monitoring program. In Figure 5(c), the border between the blue area (background color of the refractometer) and the white area (color of the coolant) is the coolant concentration. The border detected between two areas is automatically sent to the database in the real-time monitoring system via the data transmission program developed by Dr. Son's research group.



(a) Inline refractometer installed in OKUMA “Twin Star” CNC machine



(b) Inline refractometer (c) Interface of the coolant monitoring program

Figure 5: Implemented real-time monitoring system at Sargent

A major advantage of the developed coolant concentration monitoring system is the low implementation cost. The system can accurately detect coolant concentration and also its implementation cost is much cheaper than that of existing inline refractometers on the market (e.g., cost of Cole-Parmer® PR-111 in-line refractometer is more than $5,000/unit). This is because the developed coolant concentration monitoring system utilized a handhold refractometer (about $120/unit) that is being used at Sargent with an auto focus web camera and a computer vision based coolant concentration detection algorithm (see Figure 6) to achieve similar performance as commercial inline refractometers. Therefore, small or medium size companies can afford to implement the proposed system with low cost.

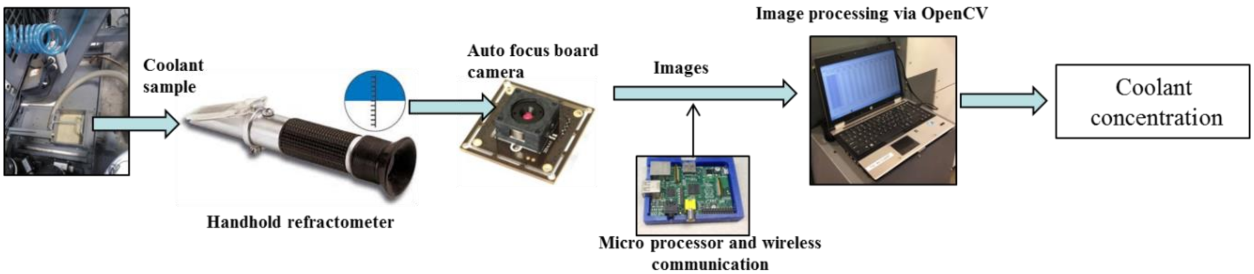
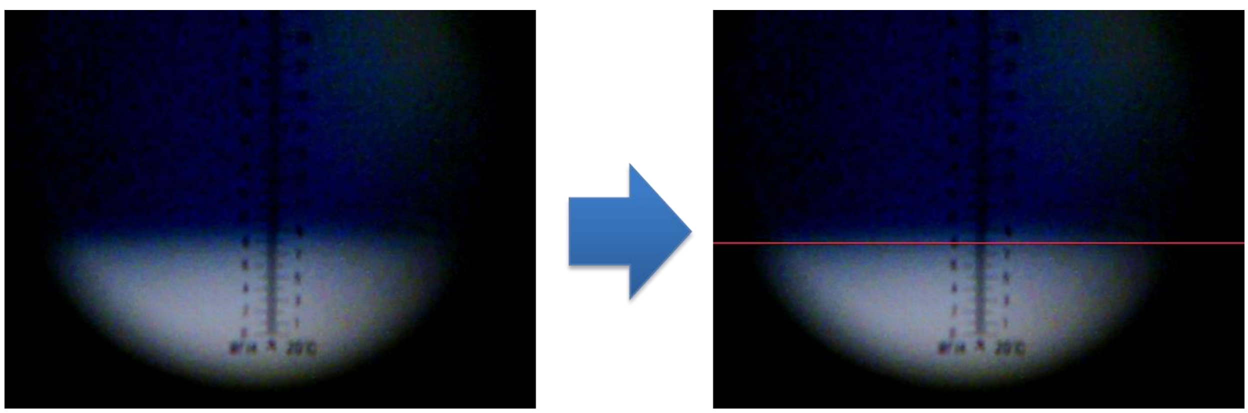


Figure 6: Refractometer system structure

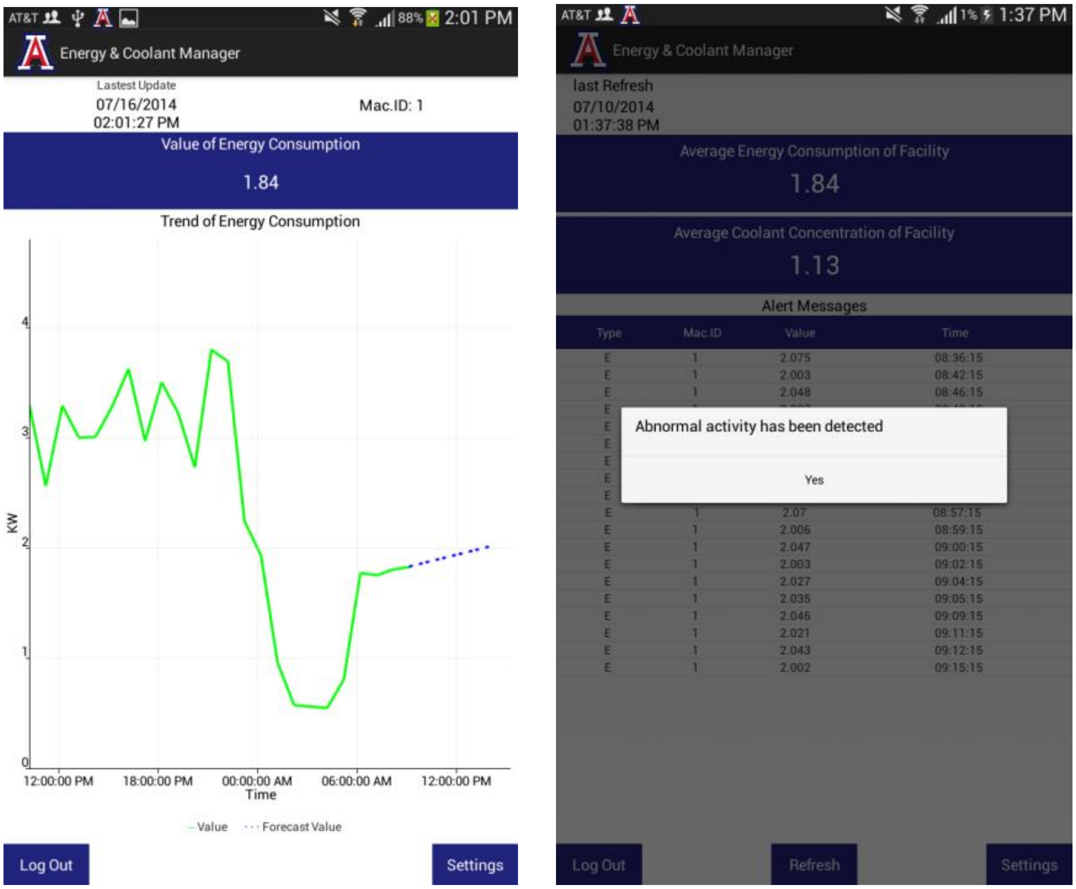
As shown in Figure 6, the coolant is continuously dripped on to the lens of the handhold refractometer. Then the web camera takes the reading view as digital image that is transmitted to the computer vision based detection algorithm. Dr. Son's research group has developed two versions of refractometer system: (1) wired version and (2) wireless version based on how the digital image is transmitted. In the wired system, digital images are transmitted to a local computer (where the database is located) via USB cable. This version is appropriate for monitoring the coolant in open space area. On the other hand, the wireless system uses microcomputer (e.g., Raspberry Pi) to connect with the web camera and processes the digital images via the embedded detection algorithm. Then it transmits the coolant concentration data to the local computer wirelessly (e.g., via WiFi). Due to the wireless transmission function, it can be installed inside of amachine. But, it requires additional power supply for long time operation. To detect the coolant concentration according to the digital images, the coolant concentration detection algorithm program is installed in the microcomputer (wireless version) or the local computer (wired version). Figure 7 shows a sample image obtained by the refractometer system.



(a) An original image (b) A processed image

Figure 7: A sample image from the developed coolant concentration monitoring system

In Figure 7(a), the original refractometer reading image is decomposed into two different areas (i.e., blue and white) in order to detect the corresponding concentration value. RGB information of the image has been used for the clustering and Manhattan distance has been used to compute the gap between the blue and the white areas. Since the metric value (i.e. concentration value) and its location in the handhold refractometer are already known, the program gives the concentration value once a border between two areas is detected. Based on this approach, the red line on Figure 7 (b) is generated (the concentration value is 8.1875 °Bx). By taking an image with specified sampling interval (e.g., 1 minute for this experiment), the refractometer system automatically provides the coolant concentration data.



(a) Electrical load plot (b) Abnormality warning

Figure 8: Snapshots of mobile application

Based on the data collected by the installed power meters and refractometers, the database server provides real-time monitoring service for mobile applications such that users can monitor the real-time energy consumption and coolant concentration. The mobile application has two major functions: (1) real-time and historical facility/equipment load display function under a given data update interval and (2) facility/equipment load abnormality warning function given certain load thresholds. Figure 8 shows the snapshots of a sample of the equipment electrical load data and an example of a load abnormality warning in the mobile application. In Figure 8(a), we can see the historical electrical load data for machine 1 (Mac ID: 1). If the status of any machine is abnormal (e.g., the electrical load goes beyond a predefined threshold), the database server sends a warning message to all the subscribed mobile applications. Once a mobile application receives the warning message, the smart phone informs the user by the abnormality warning function (see Figure 8(b)). In this case, there exists a message box in the application user interface until the user confirms the warning message. The same functions are also applied to coolant monitoring. Therefore, users can take appropriate actions to prevent any potential problems (e.g., power outage or coolant shortage).

5. Development of Energy Consumption Estimation Model

To improve the energy efficiency of CNC machines, machining parameters (e.g. cutting speed, depth of cut, feed) need to be optimized considering all the major metrics (e.g., tool life and energy consumption). Since CAD/CAM software (e.g., Mastercam®) that is being used at Sargent is unable to estimate the energy consumption, Dr. Son's research group develops an energy consumption estimation program based on the proposed machining parameters from CAD/CAM software (see Figure 9). By running the estimation program, the shop floor manager is able to find the best machining parameters for a product with minimal energy consumption. Besides, the program developed helps to design a product with low energy consumption during its manufacturing.

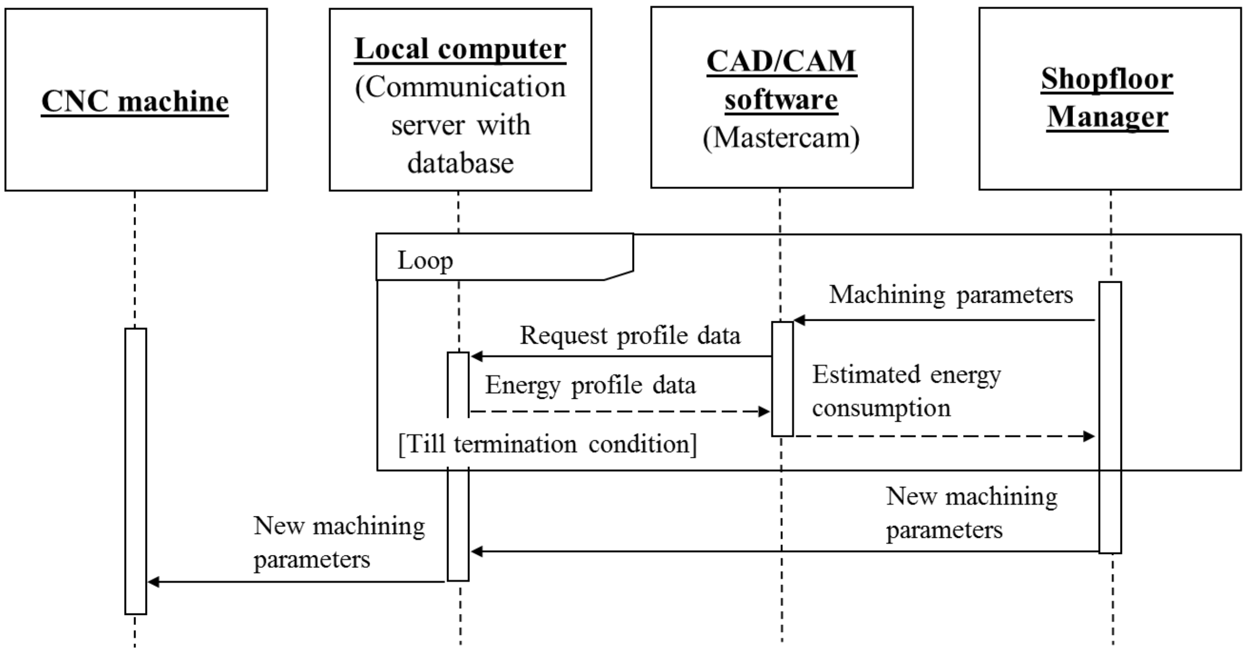


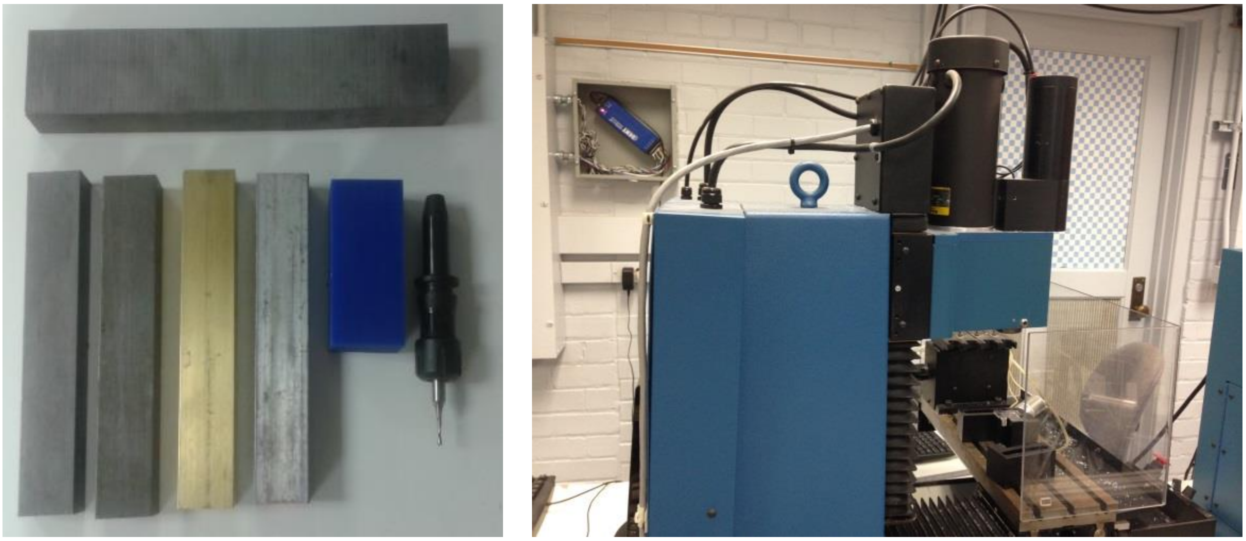
Figure 9: Time sequence diagram of energy consumption estimation and machine control services

In order to develop an energy consumption model for an individual CNC machine, two-level factorial experiment design has been devised for various materials (copper and aluminum). Three major machining parameters such as spindle speed (rpm), feed rate (ipm), and depth of cut (in) have been considered. Table 1 and Figure 10 show the parameter configurations of the experiment and a testbed of the experiment in CIMS lab at the University of Arizona, respectively.

Table 1: Experiment configurations

Exp. No.	Material	Spindle speed (rpm)	Feed rate (ipm)	Depth of cut (in)
1	Aluminum	1500	5	0.01
2	Aluminum	1500	5	0.03
3	Aluminum	1500	7.5	0.01
4	Aluminum	1500	7.5	0.03
5	Aluminum	2500	5	0.01
6	Aluminum	2500	5	0.03
7	Aluminum	2500	7.5	0.01
8	Aluminum	2500	7.5	0.03
9	Copper	1500	5	0.01
10	Copper	1500	5	0.03
11	Copper	1500	7.5	0.01
12	Copper	1500	7.5	0.03
13	Copper	2500	5	0.01

14	Copper	2500	5	0.03
15	Copper	2500	7.5	0.01
16	Copper	2500	7.5	0.03



(a) Sample materials and a tool (b) CNC machine quipped with power meter

Figure 10. Testbed in CIMS lab at the University of Arizona

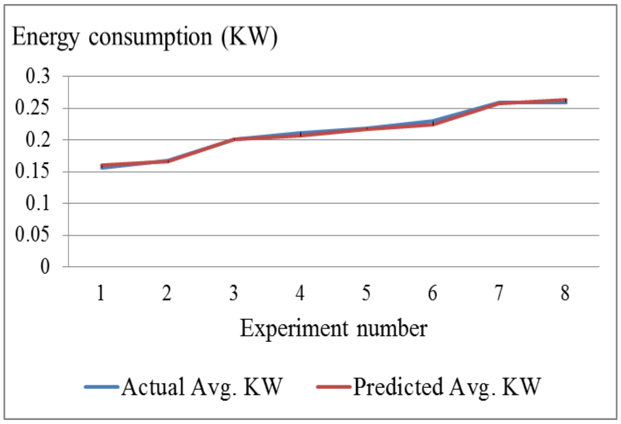
The energy consumption model of an individual CNC machine for each material type has been constructed via additive regression with nonlinear partial-regression function (Meng et al., 2013; Montgomery et al., 2012). From the collected data, an energy consumption model for copper material has been developed (see Eq. (1)).

$$E = -9.74 \times 10^{-3} + (5.73 \times 10^{-5})X_S + (1.62 \times 10^{-2})X_F + (2.95 \times 10^{-1})X_D \qquad (1)$$

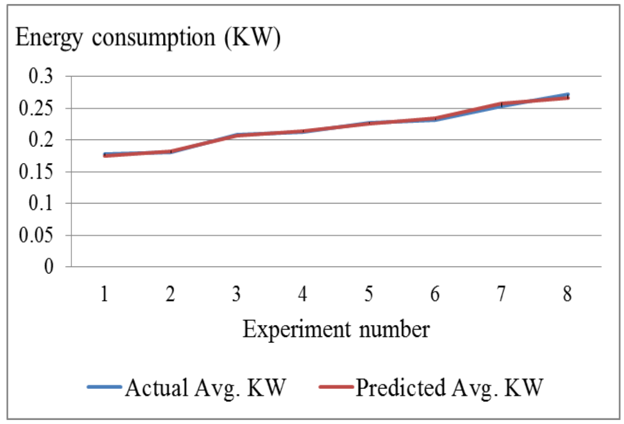
where X_s is the spindle speed (rpm), X_F is the feed rate (ipm), and X_D is the depth of cut (in). This model provides the estimated energy consumption when the machining parameters are given. Similarly, the following equation represents an energy consumption model of aluminum material:

$$E = 3.11 \times 10^{-2} + (5.09 \times 10^{-5})X_S + (1.27 \times 10^{-2})X_F + (3.86 \times 10^{-1})X_D \qquad (2)$$

Figure 11 shows the validation results of the Eq. (1) and Eq. (2) with actual energy consumption under 8 different parameter configurations (each configuration has 40 samples).



(a) Energy consumption (Copper)



(b) Energy consumption (Aluminum)

Figure 11: Comparison between actual consumption and prediction

Figure 11 reveals that the proposed additive regression models are able to provide accurate estimates of energy consumption. Tables 2 and 3 respectively show ANOVA test results of the proposed additive regression models for copper and aluminum (i.e., Eq. (1) and Eq. (2)).

Table 2: ANOVA test of the additive regression model (Copper)

Model	Sum of Squares	df	Mean Square	F	Significance
Regression	3.4638×10^{-1}	3	1.1546×10^{-1}	1206.9713	8.7606×10^{-6}
Residual	9.5661×10^{-5}	1	9.5661×10^{-5}		
Total	3.4648×10^{-1}	4			

Table 3: ANOVA test of the additive regression model (Aluminum)

Model	Sum of Squares	df	Mean Square	F	Significance
Regression	3.6623×10^{-1}	3	1.2208×10^{-1}	1497.5817	6.3393×10^{-6}
Residual	8.1515×10^{-5}	1	8.1515×10^{-5}		
Total	3.6631×10^{-1}	4			

Regarding the significance levels of both models, the estimates given by Eq. (1) and Eq. (2) are statistically accurate at 0.05 level of significance (i.e., $\alpha = 0.05$). Thus, both models are utilized to estimate the energy consumption from a G-code which is an output from CAD/CAM software.

Once energy consumption models are developed, they will be embedded in an energy consumption estimation program shown in Figure 12. The energy consumption estimation program requires three types of input data: (1) tool information including tool number and diameter, and (2) a G-code. If a feed rate of a CNC machine is not provided in the G-code, then a user needs to provide the feed rate and that feed rate will be utilized throughout the G-code to calculate the energy consumption. Based on the inputs, the energy consumption estimation program will return total energy consumption at the bottom of the program.

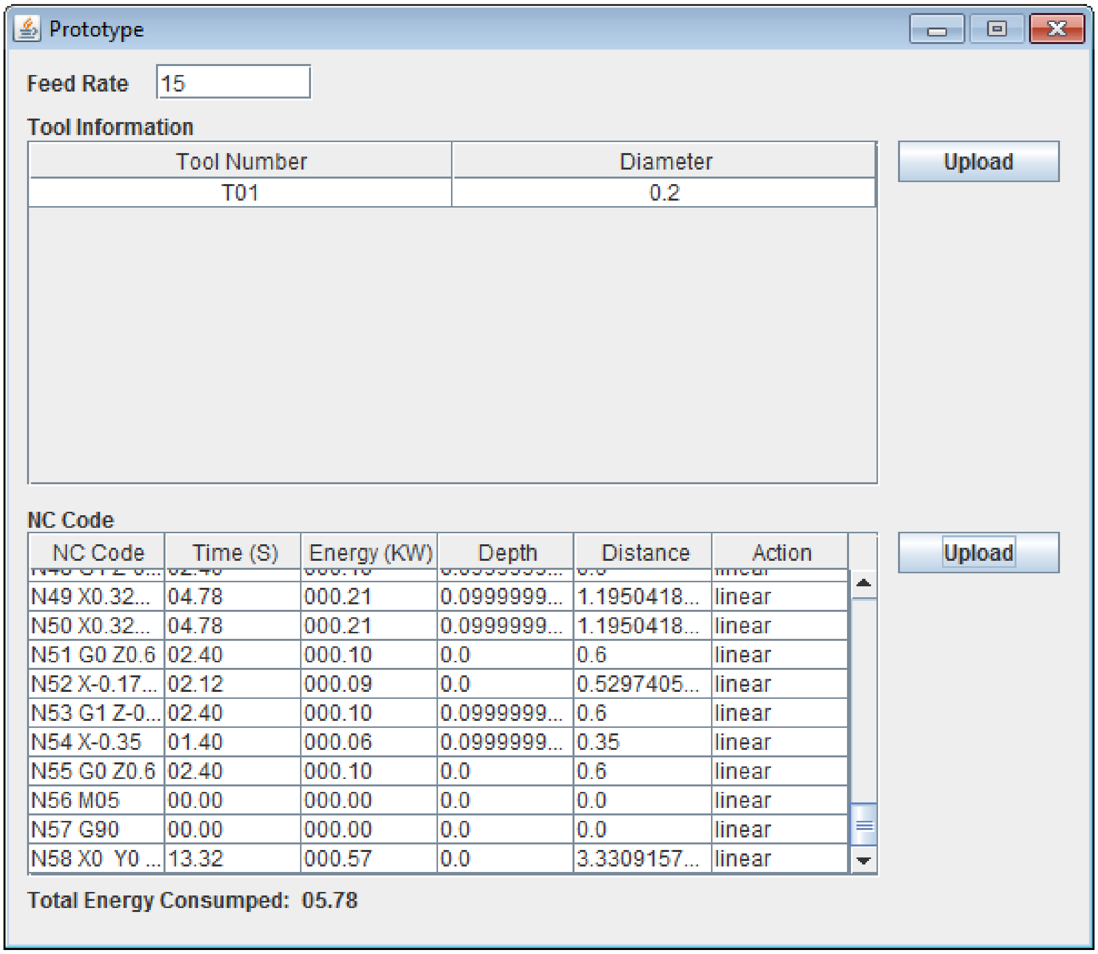


Figure 12: Energy consumption estimation program

6. Lean Manufacturing Implementation and Optimum Production Schedule via Simulation-based Optimization and Value Stream Mapping

6.1. VSM Interface Development

The purpose of the value stream mapping (VSM) interface is to automatically generate simulation models based on the value stream maps without additional coding, debugging and validation processes. Figure 13 below shows the function of VSM interface.

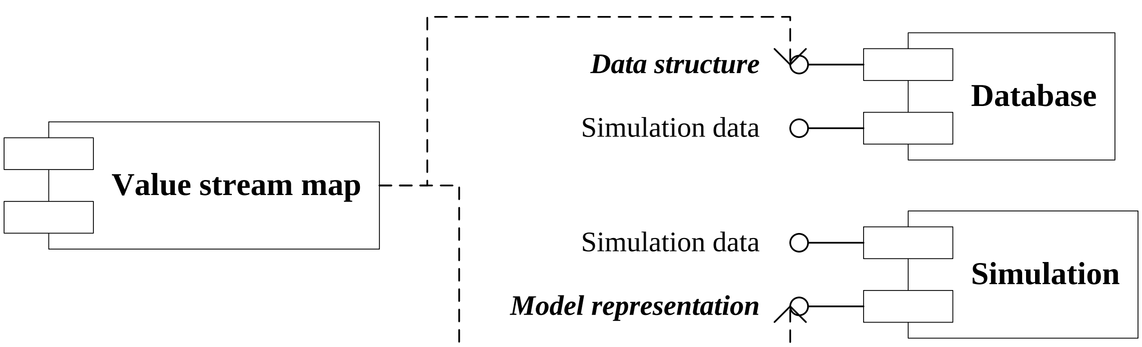


Figure 13: VSM interface function via UML component diagram

The proposed interface consists of three types of models: object model, activity model, and object state model. The object model is used to formally define the attributes of each type of objects (e.g. process, material/product, information, and performance measurement) in the physical system, and further define static model building blocks, dynamic objects (with attributes), global variables, statistics, and animation in simulation; the activity model is used to formalize information/material flow in the physical system and simulation; and the object state model is used to define the possible states of objects in the physical system and simulation. Figure 14 shows the object model developed in the Unified Modeling Language (UML) class diagram.

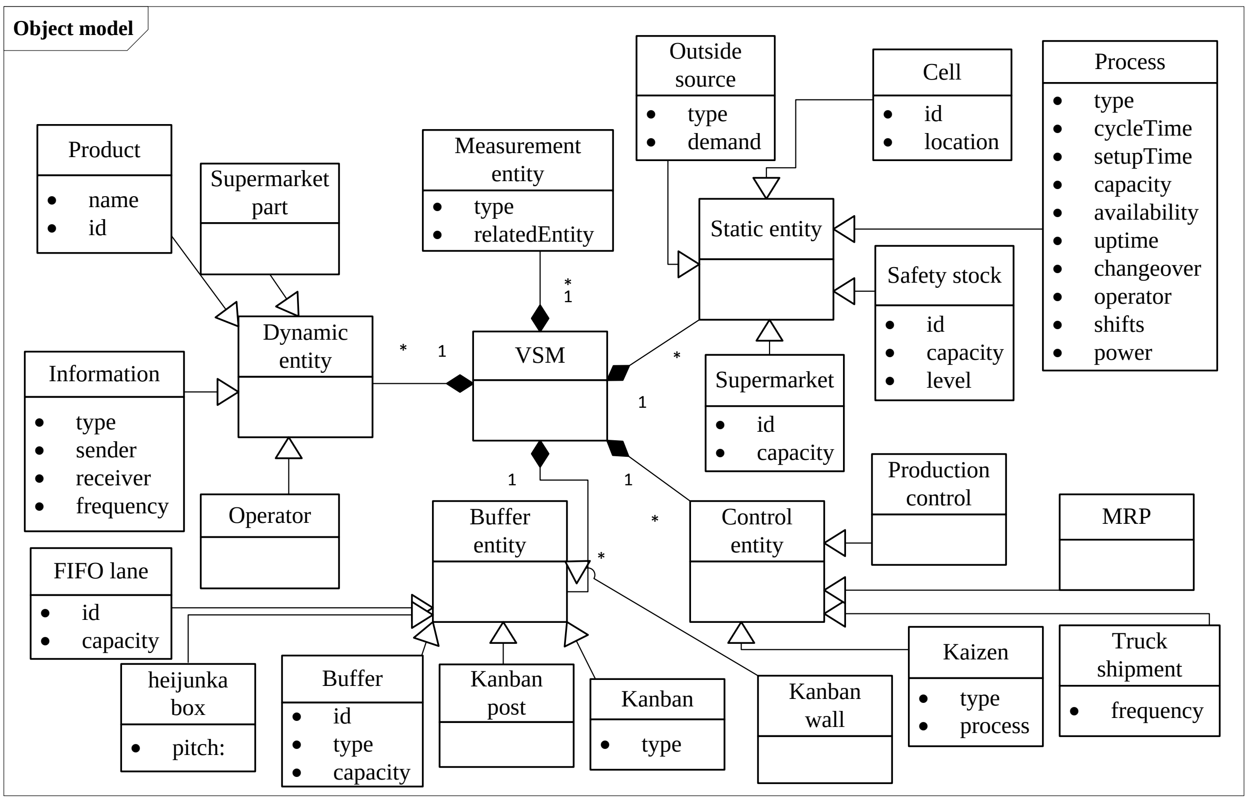


Figure 14: Object model for VSM interface

Currently, Microsoft Visio is a popular tool to electronically create value stream maps after hand drawing via the embedded Value Stream Mapping template. Figure 16 below shows an exemplary value stream created in Visio (current and future state maps). Especially, the future state map shown in Figure 16(b) is developed based on the future state map of Sargent south facility designed by the improvement team of Sargent (see Figure 15). Our proposed interface attempts to convert the value stream maps in Visio file to Extensible Markup Language (XML) and automatically generate discrete event simulation model based on the XML file.

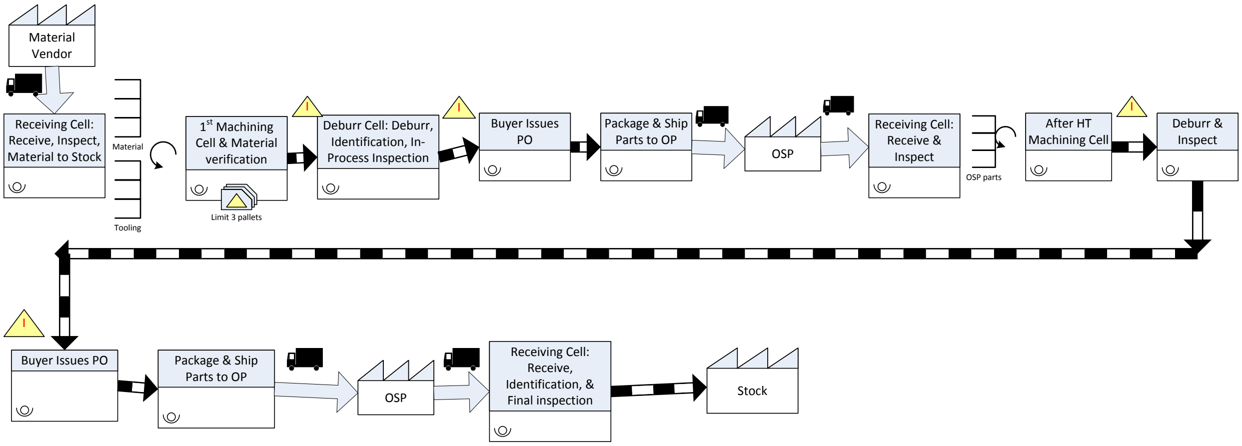
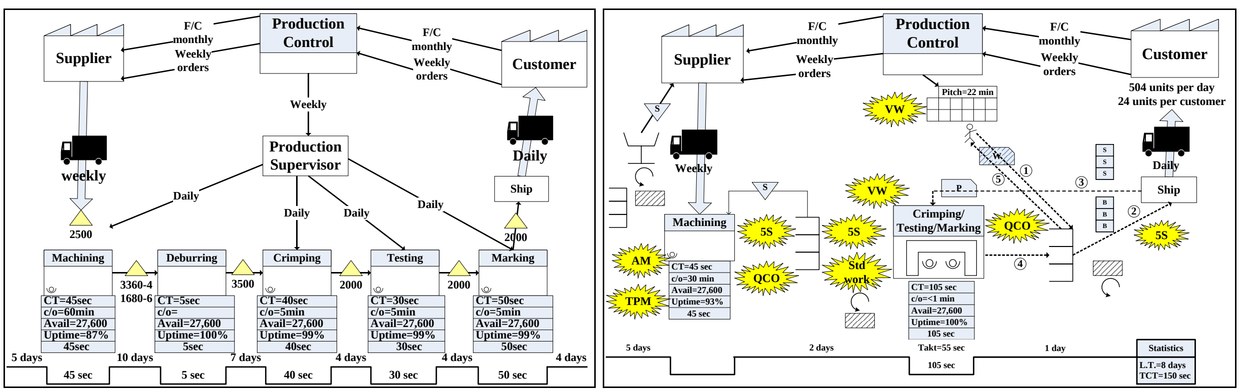


Figure 15: Future state map of Sargent south facility



(a) Current state map (b) Future state map

Figure 16: Value stream map used as test case

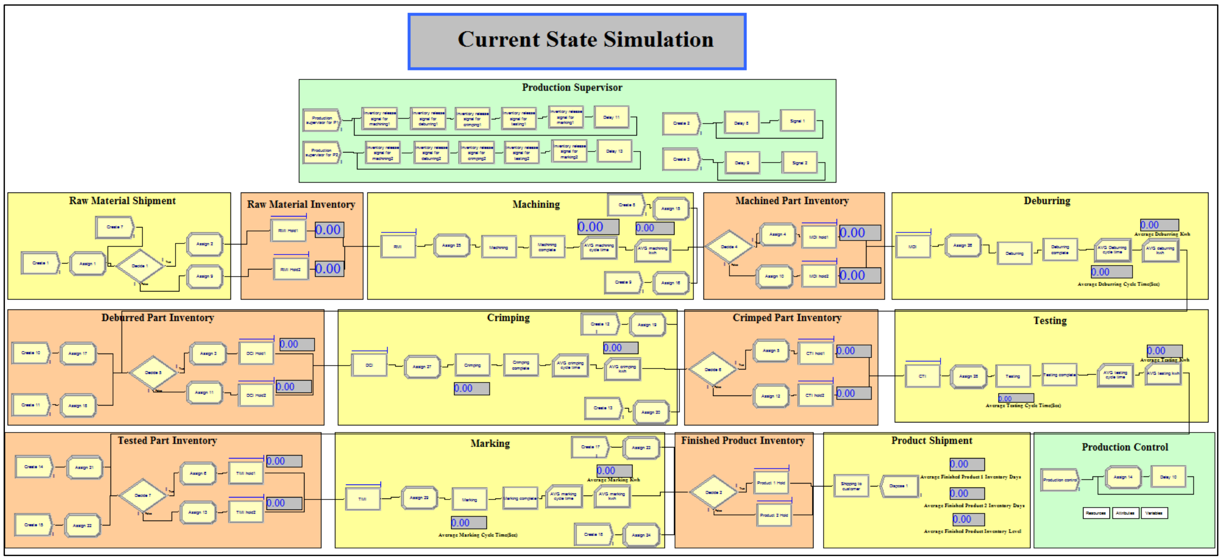
As shown in Figure 16(a), the system is using the push production mode since product demand is relatively stable. The raw material is transported to the company from a supplier, and put into raw material inventory. The entire production can be split into five processes, including machining, deburring, crimping, testing, and marking. Between processes, inventory is stored at different levels. Finished products are shipped to customers on a daily basis. In the future state map (see Figure 16(b)), the company implements JIT (just-in-time) production to its system by introducing Kanban, U-shape cell, and Kaizen activities. For production processes, deburring process is eliminated by improving programming and tooling maintenance. In addition, crimping, testing and marking processes are combined within one cell (see Tapping and Shuker (2003) for more information on the aforementioned production processes in the future state map).

In order to construct a generic data structure in XML, we adopted Core Manufacturing Simulation Data (CMSD) for the translation from Visio file to XML file. Table 4 below shows one machining process data in CMSD.

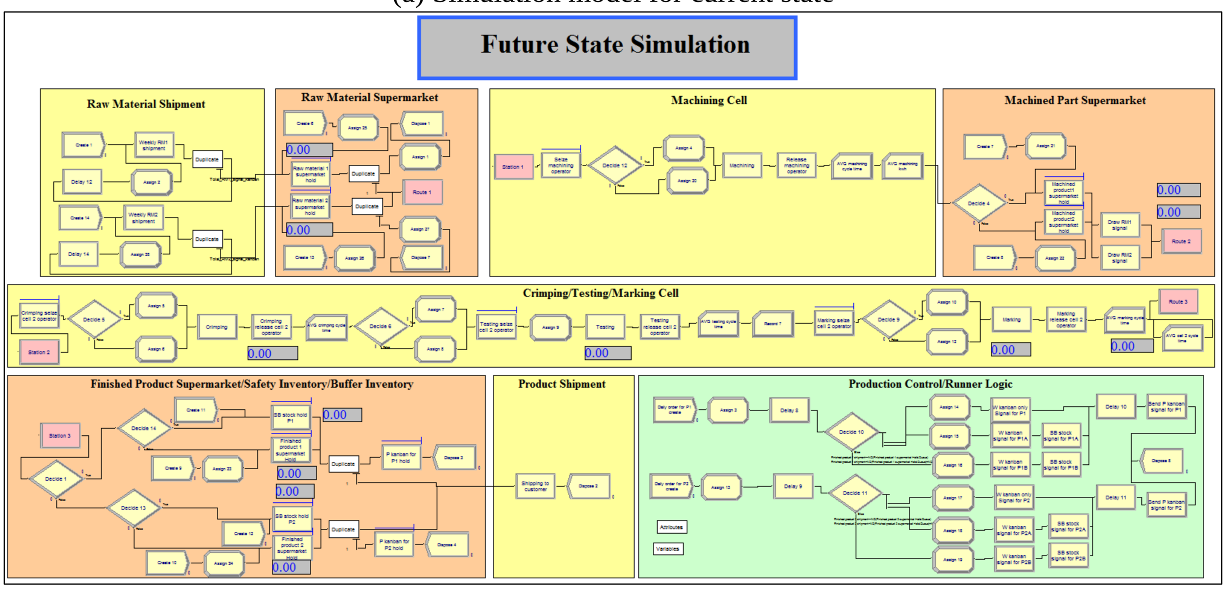
Table 4: Process information in XML

<Process>						
	<Identifier>	Machining	</Identifier>			
	<PredecessorProcess>	Inventory 1	</PredecessorProcess>			
	<SuccessorProcess>	Inventory 2	</SuccessorProcess>			
	<OperationTime>					
		<Unit>	second	</Unit>		
		<Value>	6	</Value>		
	</OperationTime>					
	<ResourceRequired>					
		<Description>	Operator	</Description>		
		<MinimumNumber>	1	</MinimumNumber>		
		<MaximumNumber>	1	</MaximumNumber>		
	</ResourceRequired>					
	<ResourceRequired>					
		<Description>	Machine 1	</Description>		
		<MinimumNumber>	1	</MinimumNumber>		
		<MaximumNumber>	1	</MaximumNumber>		
	</ResourceRequired>					
	<Property>					
		<Name>	Water usage	</Name>		
		<Unit>	gallon	</Unit>		
		<Distribution>				
			<Name>	Normal	</Name>	
			<DistributionParameter>			
				<Name>	mean	</Name>
				<Value>	6	</Value>
			</DistributionParameter>			
			<DistributionParameter>			
				<Name>	std	</Name>
				<Value>	2	</Value>
			</DistributionParameter>			
		</Distribution>				
	</Property>					
</Process>						

Based on the interface, we have developed a simulation model for the test case. The simulation model is developed in discrete event simulation software Arena®, and Figure 17 shows the snapshot of the simulation model involving the current state and future state.



(a) Simulation model for current state



(b) Simulation model for future state

Figure 17: Simulation model for the test case

7. Future Works

The future works include (1) developing a knowledge based optimization module of machining parameters to maximize the energy efficiency as well as the productivity of a CNC machine; (2) introducing a simulation-based decision support tool with a web-based dashboard displaying the real-time production status and algorithms for predicting potential production disruption events (e.g. tool failure); (3) integrating a real-time monitoring system developed by Dr. Son's research group with the MTConnect standard (MTConnect, 2009) for a reliable machine status data acquisition (e.g. job status, tool temperature, energy consumption, and coolant concentration) and communication with other programs (e.g. ERP system and decision support system) in manufacturing companies.

Reference

Meng, C., Kim, S., Son, Y. J., & Kubota, C. (2013, December). A SysML-based simulation model aggregation framework for seedling propagation system. In *Proceedings of the 2013 Winter Simulation Conference* (pp. 2180-2191). IEEE Press.

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PAYMENT IS REQUESTED ON THE PROJECT ENTITLED:
ATLAS: Develop a Knowledge Based Optimization Module of Machining Parameters

UNDER THE DIRECTION OF:	Son, Young-Jun	
AWARD NUMBER:	IAMG-15-03	
FOR PAYMENT:	4th 25% Segment 3/1/2016- 5/31/2016	**$ 37,500.00**
	Total Grantee Cost Share as of 5/31/2016	$ 77,330.36
	Total Partner Match as of 5/31/16	$58,000.00

AMOUNT DUE UPON RECEIPT: $37,500.00

Ashley Taylor

Doug Dawson / Ashley Taylor / Bruce Perlman / Tabatha Holan / Rachel Doty
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Integrated Energy Reduction and Productivity Enhancement of Machine Shop Operations - Focus Area: Develop a Knowledge Based Optimization Module of Machining Parameters; Focus Area: Automated/proactive Bottleneck Prediction and Notification System via Integrated Simulation and Value Stream Mapping

Project Period: December 21, 2015~June 10, 2016

June 10, 2016

Submitted to: Arizona Commerce Authority

Southern & Central Arizona Aerospace & Defense Region 2015 Energy Reduction Challenge Grant Competition Program

Submitted by: Dr. Young-Jun Son

Professor and Department Head, Systems and Industrial Engineering

Director, Center for Advanced Integration of Manufacturing Systems and Technologies

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1. Project Goals

The first goal of this project was to develop smart sensing, and software-enabled technologies, which will make older generation, energy-intensive machine tools smarter. This smart feature will allow us to achieve significant energy reduction as well as productivity enhancement of machine shop operations. The particular list of features and technologies that are developed in this project include (1) data acquisition software from individual CNC machine and its inline sensors (i.e., refractometer for coolant concentration, thermal imaging sensor for cutting tool temperature, and power meter for consumed energy), (2) server program with database to gather and store machining status, and (3) iPad/smartphone apps and web-based dashboard for monitoring the status and notifying warning messages. In the process for acquiring and collecting machining status data, MTConnect (Website reference 1) standard is adopted in order to guarantee the interoperability and to reduce the future integration cost. Also, in order to maximize energy efficiency in individual CNC machine, a knowledge-based optimization module for machining parameters is developed. The empirical data is firstly collected under various conditions (e.g., depth of cut, spindle speed, feed rate) to understand the relationship among the input (e.g., machining parameters) and output variables (e.g., energy consumption and productivity). From the database, calibrated models, and knowledge available in the literature, energy consumption and productivity estimation model is developed. The developed knowledge-based energy consumption program comes out very effective for finding the best machining parameters for a product with minimal energy consumption.

The second goal of this project was to develop simulation models in order to estimate the energy consumption at Sargent under the various condition and scenarios. In particular, three major simulation works are conducted in this project. First, establishing optimum starting, stopping, and idle times of older generation energy-intensive machine tools to reduce electricity cost without sacrificing productivity via a flexible, data driven simulation-based optimization system. Under a demand response program (e.g. Sargent is participating in a program provided by Tucson Electric Power) where the price of electricity depends on different time of the day and peak consumption levels, it is imperative to avoid peak/spike consumption and schedule machining vs. setup works such a way to reduce electricity cost. In particular, three major problems have been addressed. (1) Instead of starting up all pieces of equipment within a short time window at the beginning of each shift or periodic maintenance work or immediately after power outage, the desire is to sequence powering ups to reduce the peak energy consumption. (2) We compare the energy consumption (and corresponding electricity cost) between keeping the equipment on (during the gaps of jobs), vs. turning off and on again. (3) We study the impact when service equipment (or set-up activities) is scheduled during non-peak production hours to store energy for use in peak hours. Second, the simulation-based optimization tool is integrated with value stream mapping (VSM) to evaluate lean manufacturing tools and generate optimal production schedules. Therefore, the material flows of the machine shop are improved for minimizing the electricity consumption based on the current state maps. Third, the weather-dependent energy consumption model is developed since air-conditioning generally comprises a large portion of energy consumption at manufacturing facility and energy use of air-conditioner depends on the weather condition (e.g., ambient temperature, wind speed, and humidity). The regression model on the basis of the historical electricity billing and weather data is developed and allow us to estimate more precise energy consumption of the entire facility by combining future weather conditions.

2. Summary of Achievements

Dr. Son's research group and Sargent have made the following achievements during the period of the project:

- Refractometer and thermal sensing system which is compatible with MTConnect standard developed to automatically monitor the coolant concentration and tool temperature respectively
- Power meter and refractometer installed in OKUMA "Twin Star" CNC machine at Sargent
- Mobile application (Android and iOS) and web-based dashboard developed to monitor the energy consumption, coolant concentration, and thermometer
- MTConnect standard compatible database and communication server program developed to store energy consumption and sensing data, as well as communicate with mobile applications and web-based dashboard
- Shop operation simulation model developed to optimize the operation schedule and machine turn-on sequence for controlling the shop operations.
- Simulation experiments conducted to demonstrate energy cost saving by adopting optimized operation schedule and machine turn-on sequence.
- A generic energy consumption prediction model developed to estimate energy consumption of an individual CNC machine under given machining parameters and material type.
- A simulation-based optimization tool in conjunction with VSM is developed.
- A weather-dependent energy consumption model developed

The following sections explain the aforementioned achievements in detail.

3. Data Collection

Dr. Son's team has worked closely with Sargent in order to achieve the goals of this project. Sargent has provided onsite working place for Dr. Son's team and major data such as Sargent facility and historical utility bill. To be specific, the following data has been collected for system development:

- Equipment information (e.g. equipment ID, equipment type, and power) for simulation model development
- Monthly utility bill from 2007 to 2013 for analyzing the energy consumption pattern
- Machining parameters
- Coolant information and samples for developing and testing the refractometer system
- Energy consumption information and samples for testing the implemented power meter system.
- Current and future state maps for one type of product at Sargent.

4. Automated Data Acquisition and Monitoring System with MTConnect Standard

4.1. Overview

The automated data acquisition and monitoring system which developed by Dr. Son's research group is to provide a live monitoring tool to the plant managers and CNC machine operators by collecting real-time machine status (i.e., tool temperature, process remaining time, etc.). To guarantee the interoperability, the system have been developed based on the open and extensible standard like MTConnect. For the implementation of the system by following the latest version of MTConnect standard (MTConnect Institute, 2014), Dr. Son's research group has built the system architecture containing (1) Data acquisition, (2) Data gathering and store, and (3) Monitoring functions. Figure 1 depicts the overview of the proposed system for data acquisition and remote monitoring.

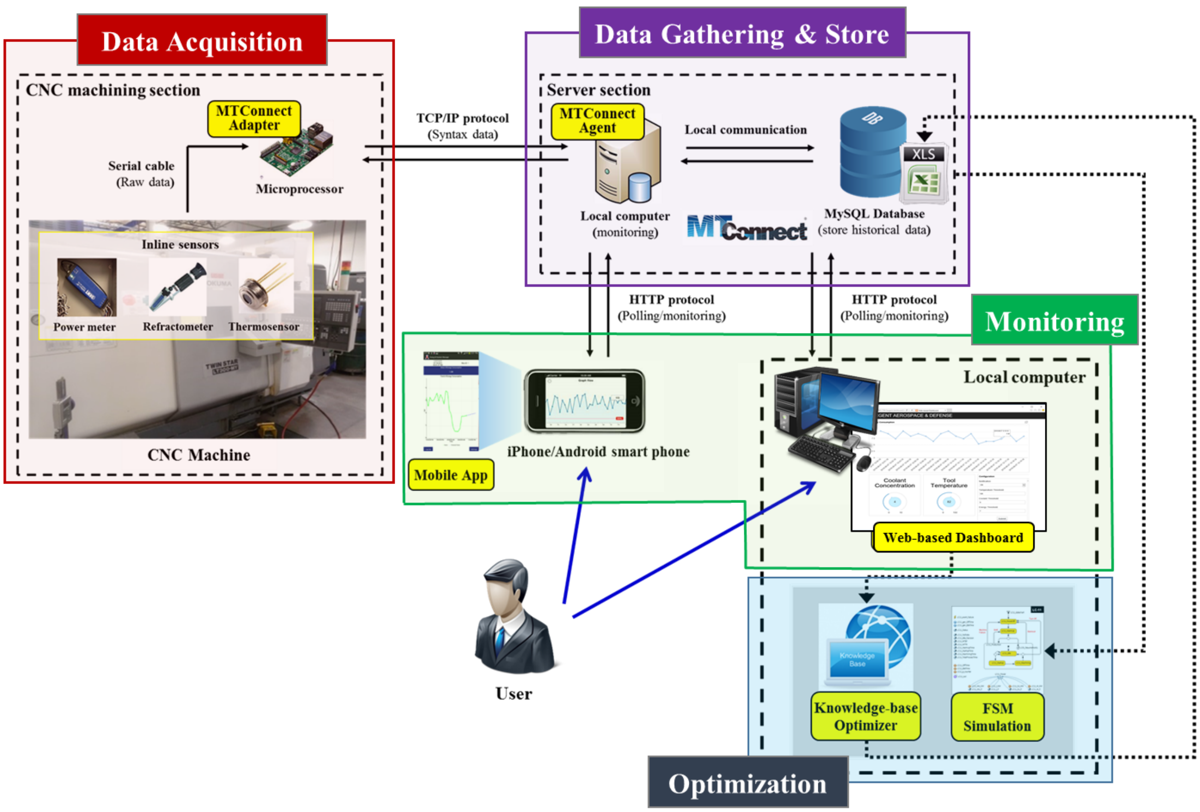


Figure 1: The Overview of the data acquisition and monitoring system with MTConnect standard

The Real-time data acquisition and monitoring system with MTConnect standard for the shop floor includes six objects: (1) CNC machine with inline sensors (e.g., power meter, refractometer, and thermal sensor), (2) Microprocessor with MTConnect adapter software, (3) Local computer with MTConnect agent and database, (4) Monitoring application (e.g., iPhone/Android smart phone app and Web-based dashboard), (5) optimization tools, and (6) Shop floor manager. The output of the inline sensors embedded in the machine and parameters of CNC machine are gathered by microprocessor via serial cable. These raw data are converted to string format by MTConnect adapter and sent to a localhost computer via either USB communication or Wi-Fi communication. MTConnect agent installed in localhost computer gathers and stores the data and sends them to iPhone/Android smart phone or computer so that a shop floor manager can monitor the status of CNC machines. The shop floor manager runs optimization tools by utilizing the gathered data in order to find the optimal machining parameters and shop operation schedule. This loop continues until the system is turned off. Figure 2 reveals the interactions among the objects in a great detail.

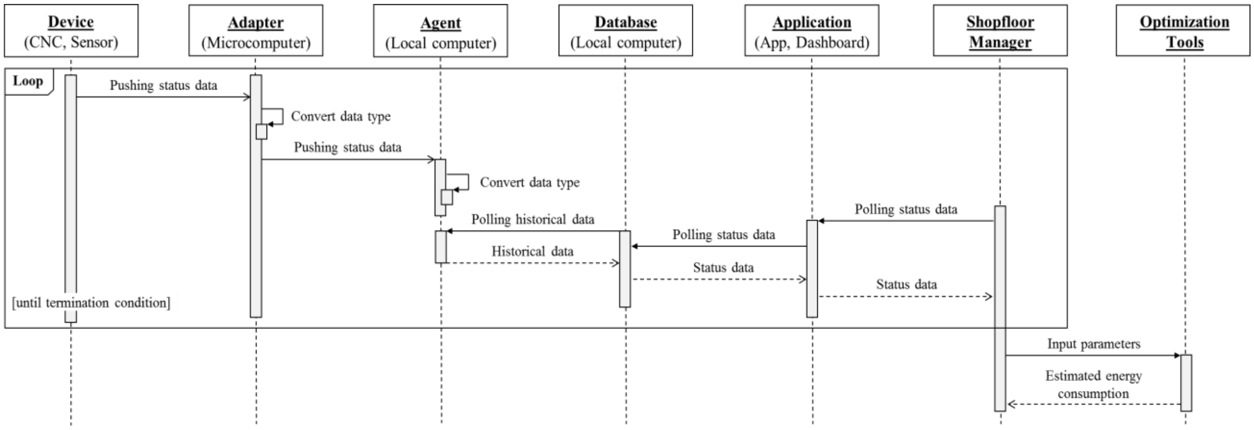


Figure 2: Time sequence diagram of the interactions in the data acquisition and monitoring system

4.2. Developments of Inline Sensors

4.2.1. Power Meter System Testing and Installation

For testing purpose, the power meter system has been first implemented in the CIMS lab at the University of Arizona. As shown in Figures 3, Dent ELITEpro SP^{tm} power meter (similar model that is installed at Sargent) has been purchased and installed in the CNC milling machine as a testbed.

(a) Power meter installed (b) testbed with power meter

Figures 3: Power meter system implemented in CIMS lab at the University of Arizona

The power meter has been set up to automatically log the energy consumption of the manufacturing facility (see Figure 4), and the data is available for the database/communication server program (see Section 6).

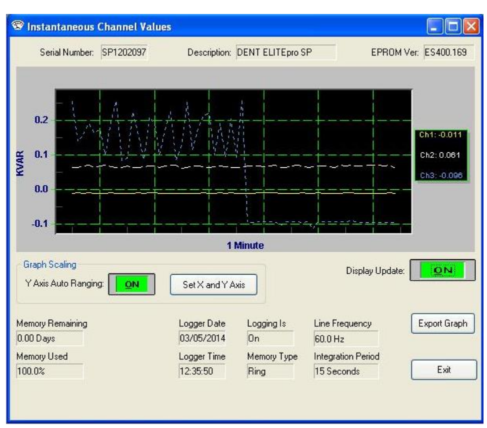


Figure 4: Real-time energy consumption monitoring

The energy consumption data is logged into both ".dat" and ".csv" format files. Sample data is provided in Table 1.

Table 1: Sample data from power meter

Number	Date	End Time	Min. Volt	Min. Time	Max. Volt	Max. Time	Avg. Volt	Min. Amp	Min. Time	Max. Amp
1	2/16/2014	15:33:15	119.1	15:33:02	119.4	15:33:08	119.3	2.7	15:33:12	3.93
2	2/16/2014	15:33:30	119.2	15:33:22	119.4	15:33:17	119.3	2.7	15:33:20	3.93
3	2/16/2014	15:33:45	119.2	15:33:37	119.4	15:33:30	119.3	2.71	15:33:30	3.96
4	2/16/2014	15:34:00	119.2	15:33:48	119.4	15:33:58	119.3	2.7	15:33:45	3.33
5	2/16/2014	15:34:15	119.3	15:34:08	119.4	15:34:04	119.3	2.69	15:34:04	3.67
6	2/16/2014	15:34:30	119.2	15:34:22	119.4	15:34:15	119.3	2.68	15:34:15	4.16
7	2/16/2014	15:34:45	119.2	15:34:41	119.4	15:34:30	119.3	2.68	15:34:41	3.24
8	2/16/2014	15:35:00	119.3	15:34:45	119.4	15:34:53	119.3	2.69	15:34:51	3.62
9	2/16/2014	15:35:15	119.2	15:35:04	119.4	15:35:11	119.3	2.73	15:35:13	3.88
10	2/16/2014	15:35:30	118.4	15:35:25	119.4	15:35:24	119.3	2.73	15:35:19	3.79

Since the power meter does not provide API for connecting the developed database (See Section 6), Dr. Son's team has developed executable file (.exe) to periodically transferring the energy consumption data from .csv files to the developed database. The same system has been installed at Sargent south facility as shown in Figure 5. Figure 6 shows one instant data collected by the installed power meter.

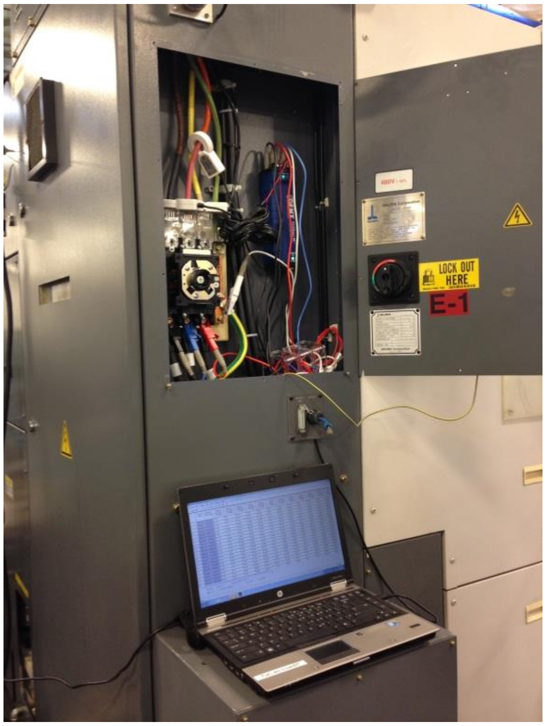


Figure 5: Power meter installed in OKUMA "Twin Star" CNC machine

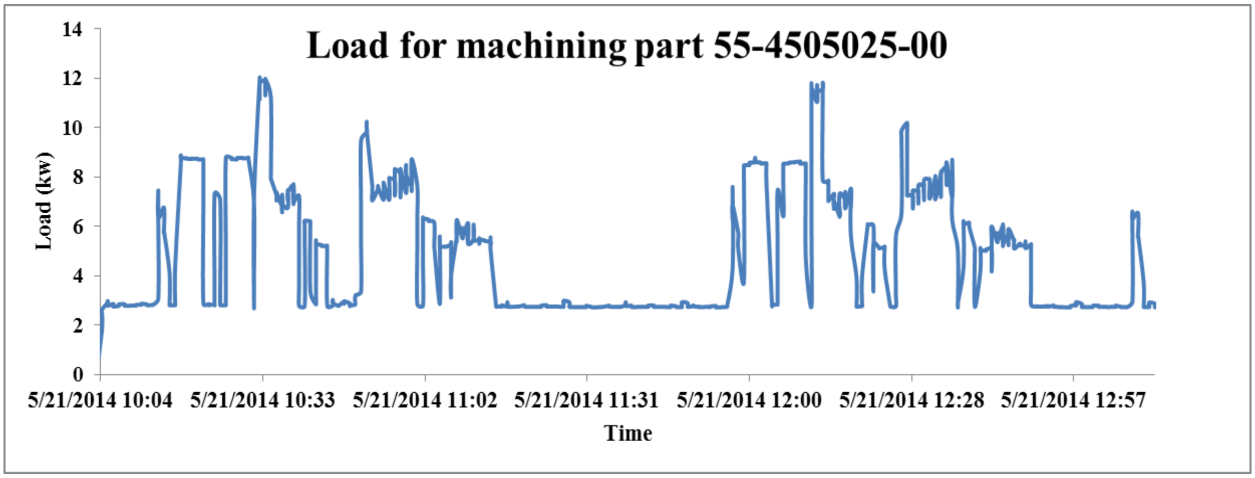


Figure 6: Instant load data collected for processing part 55-4505025-00

4.2.2. Refractometer System

For real-time monitoring of coolant concentration, Dr. Son's team has implemented computer vision and clustering techniques into a handhold refractometer based platform. Although there exist multiple models of inline refractometer on the market (e.g., Cole-Parmer® PR-111 in-line refractometer) to support real time monitoring of coolant concentration, its high cost (e.g., more than $5,000/unit) is not feasible for small or medium size companies. Thus, a handhold refractometer (about $120/unit) that is being used at Sargent has been utilized with an auto focus web camera and a computer vision based coolant concentration detection algorithm (see Figure 7) to achieve similar performance as commercial inline refractometers.

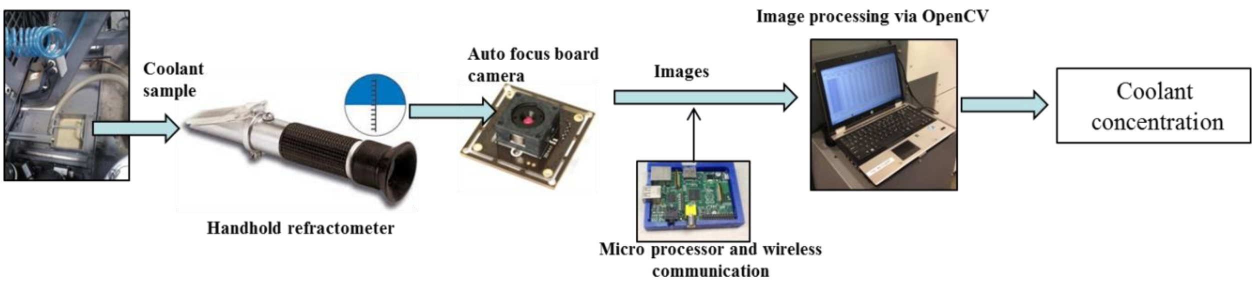


Figure 7: Refractometer system structure

As shown in Figure 7, the coolant is continuously dripped on to the lens of the handhold refractometer. Then the web camera takes the reading view as digital image that is transmitted to the computer vision based detection algorithm. Dr. Son's team has developed two versions of refractometer system: (1) wired version and (2) wireless version based on how the digital image is transmitted. In the wired system, digital images are transmitted to a local computer (where the database is located) via USB cable. This version is appropriate for monitoring the coolant in open space area. On the other hand, the wireless system uses microcomputer (e.g. Raspberry Pi) to connect with the web camera and processes the digital images via the embedded detection algorithm. Then it transmits the coolant concentration data to the local computer wirelessly (e.g. WiFi). Due to the wireless transmission function, it can be installed inside of machine. But, it requires additional power supply for long time operation. To detect the coolant concentration according to the digital images, the coolant concentration detection algorithm program is installed in the microcomputer (wireless version) or the local computer (wired version). Figure 8 illustrates the proposed detection algorithm in detail.

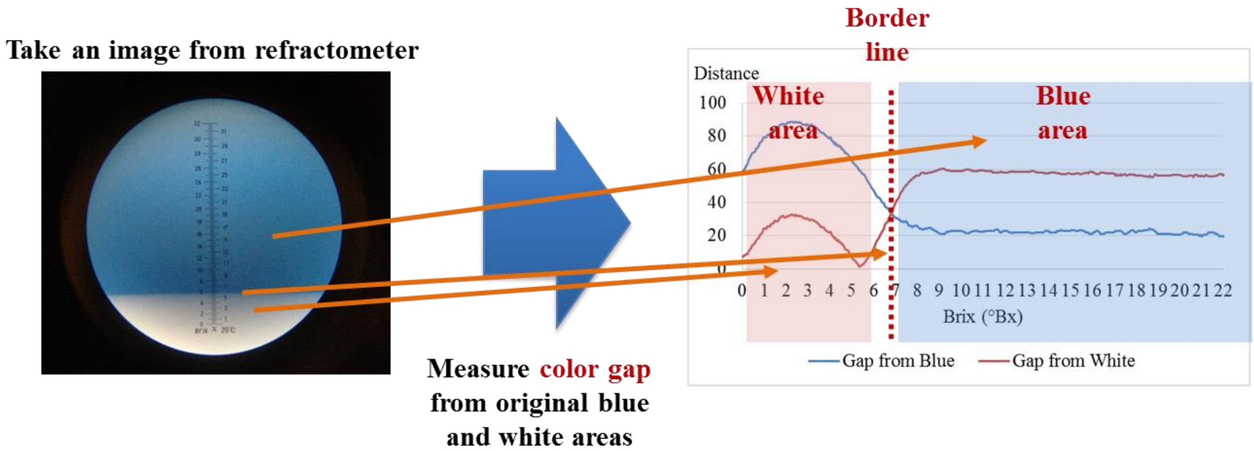
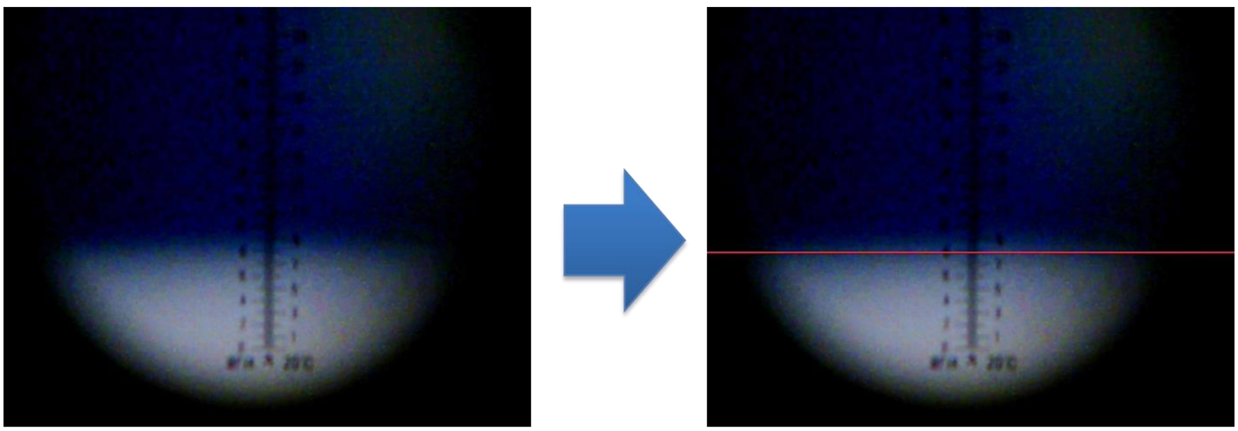


Figure 8: Procedure of a computer vision based detection algorithm

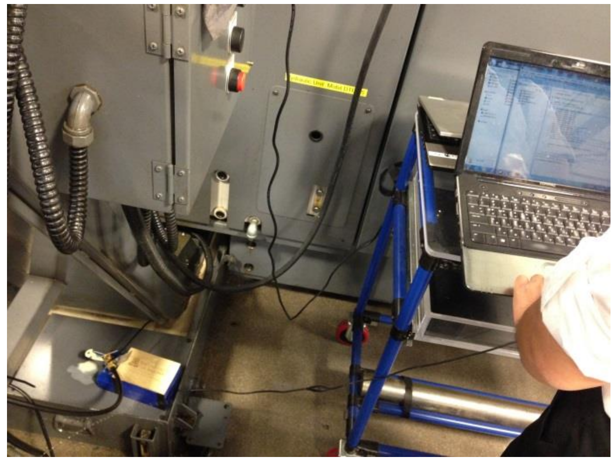
In Figure 8, the original refractometer reading image is decomposed into two different areas (i.e., blue and white) in order to detect the corresponding concentration value. RGB information of the image has been used for the clustering and Manhattan distance has been used to compute the gap between the blue and the white areas. Since the metric value (i.e. concentration value) and its location in the handhold refractometer are already known, the program gives the concentration value once a border between two areas is detected. Based on this approach, Figure 9 shows a sample image obtained by the refractometer system. The red line on Figure 9 (b) is the detected border and the concentration value is 8.1875 °Bx. By taking an image with specified sampling interval (e.g., 1 minute for this experiment), the refractometer system automatically provides the coolant concentration data. Figure 10 shows the implement of wired refractometer system at Sargent and the wireless refractometer system developed.



(a) An original image (b) A processed image

Figure 9: A sample image from the refractometer system

(a) Wired refractometer system implemented



(b) Coolant concentration data collection

(c) Wireless refractometer system

(d) Raspberry Pi for wireless refractometer system

Figure 10: Refractometer systems

4.2.3. Thermal Imaging Sensing System

Dr. Son's group developed prototype thermometer sensor to detect temperature of machining tool and materials because temperature above threshold value has a detrimental effect on tool life and surface finish. But measuring the temperature of tool during machining is not an easy task and making the measured temperature data available wirelessly make the problem even more complex. As the tool is continuously moving during machining, it is not feasible to measure the temperature using the pointed infrared measuring device. Therefore Dr. Son's team has proposed a low cost solution based on thermal imaging sensor and Raspberry Pi. For this purpose, Raspberry Pi 2B, IR array thermal sensor (mlx90620), and Raspberry pi camera module were utilized to develop the thermometer sensor. IR array thermal sensor continuously collects raw temperature data and Dr. Son's research group' program collects the data from sensor and program converts raw temperature data to Celsius and Kelvin. Temperature in Celsius is utilized in data acquisition process (see Figure 11) and temperature in Kelvin is used to provide temperature overlay image. Temperature sensor program continuously collects data and sends the data to agent with previously configured interval. When temperature provided by program exceeds user provided temperature threshold agent will display warning and sends warning message to dashboard and mobile applications.

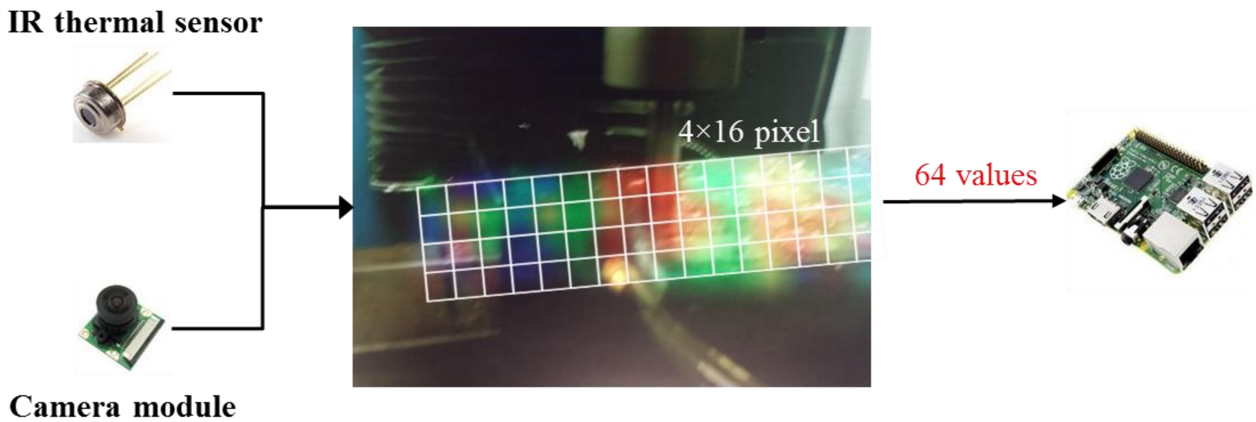


Figure 11: Collected temperature sensor converted to 4×16 color array over layered on captured image

4.3. Development of Communication Protocol with MTConnect Standard

The developed system with MTConnect standard is composed of three types of software utilities: Adapter, Agent, and Application (i.e., web-based dashboard, mobile app, and SQL database). The Adapter is a program to collect raw data from a device (e.g., machining tool or sensor). Since devices generate different types of data with various interfaces, the Adapters should be developed for each of devices. The Adapter is run in microprocessor (i.e., Raspberry Pi) to collect the raw data pushed by device. The collected device-specific raw data are converted into string data which is readable by the MTConnect Agent. Figure 12 illustrates the communication between the Adapter and the Agent.

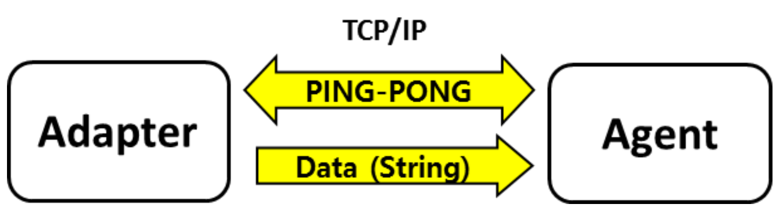


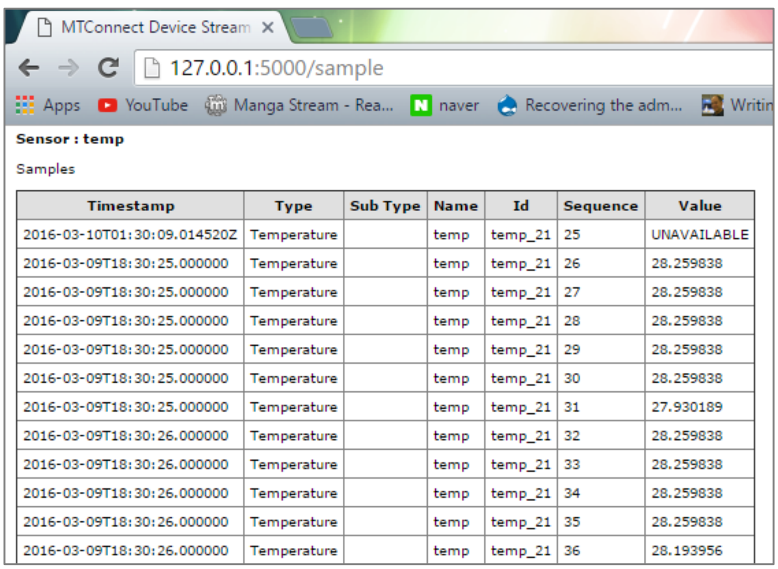
Figure 12: The communication between Adapter and Agent

The Adapter communicates with the Agent as a simple TCP (Transmission Control Protocol) Socket server. As the beginning of the communication, the Adapter open its TCP Socket and wait for the Agent. When the Agent sends a string data with "* *PING*" to open the communication, the Adapter also sends a string data with "* *PONG [Heartbeats]*" as its response. And then, the communication will begin. The *Heartbeats* means a frequency in millisecond to check and maintain the connection between the Adapter and Agent. After checking the first "PING-PONG" communication, the Adapter pushes its converted device data (i.e., string data) to Agent. The data transmitted by the Adapter should start with a timestamp in UTC (Coordinated Universal Time) with ISO 8601 format (i.e., *YYYY-MM-DDTHH:MM:SS.FFFZ*). Whenever collecting the string type device data, the Agent encodes them in XML (eXtensible Markup Language) which is the data format that enables other software programs to access this data across a network. The proposed system is being applied version 1.3 of MTConnect XML schema which is the latest standard released in 2014.

The MTConnect Agent is the computer program which play a key role in connecting devices and users. Thus, the standard strongly regulates the role and the protocol of the Agent. For this reason, the Agent in this system has been developed by strictly following the requirements in MTConnect standard (MTConnect Institute, 2014).

- The Agent must support HTTP version 1.0 or greater
- The agent must support HTTP GET verb as the request. If this verb is no used, the Agent must respond with a "*HTTP 400 Bad Request*"
- The Application should use below HTTP GET verbs only:
    - *probe*: to retrieve information of devices
    - *current*: to retrieve the latest values of all data items or device state
    - *sample*: to retrieve the time series values of all data items or device state
    - *asset*: to retrieve the most recent state of an asset
- The response to HTTP request must be with UTF-8 encoded XML document
- To keep the connection with the Applications, the Agent must respond to every requests. Even if there is no data available, the empty stream must be sent by the Agent

Figure 13 shows the collected temperature data from the thermometer by Agent in real-time. This result can be shown by using *sample* request.



Sensor : temp

Samples

Timestamp	Type	Sub Type	Name	Id	Sequence	Value
2016-03-10T01:30:09.014520Z	Temperature		temp	temp_21	25	UNAVAILABLE
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	26	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	27	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	28	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	29	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	30	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	31	27.930189
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	32	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	33	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	34	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	35	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	36	28.193956

Figure 13: The collected time-series temperature data by the MTConnect Agent

To follow the standardized communication protocol, the developed mobile app has been modified. Currently, the mobile app sends requests to the Agent in order to retrieve the latest (or time-series) temperature, level coolant concentration, level of power consumption as below:

- Current temperature:
  http://[domain:port]/Thermometer/current?path=//DataItem[@type="TEMPERATURE"]
- Level of coolant concentration in time-series:
  http://[domain:port]/Refractometer/sample?path=//DataItem[@type="CONCENTRATION"] &from=10&count=100
- Current level of power consumption:
  http://[domain:port]/Powermeter/current?path=//DataItem[@type="ELECTRICAL_ENERGY"] &from=10&count=100

The Agent support two types of data streaming: Push-based and Pull-based. The Pull-based communication is adopted in web-based dashboard and mobile app. In this communication, the Application (i.e., dashboard and mobile app) repeatedly request data by using *current* or *sample* HTTP verb. The procedure of Pull-based conversation between the Agent and the Application is in Figure 14.

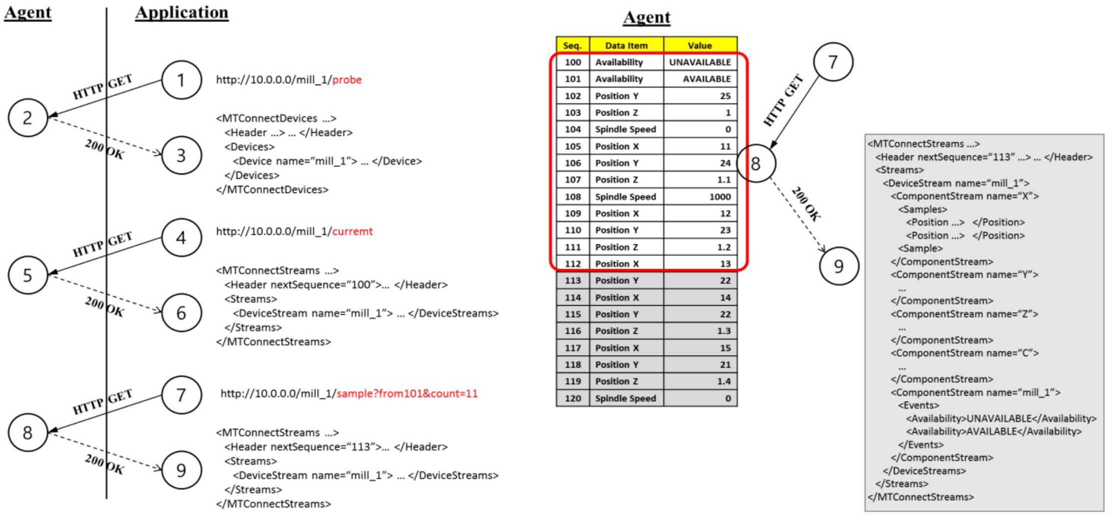


Figure 14: The procedure of Pull-based communication between Agent and Application

On the other hand, the communication between the Agent and SQL database uses Push-based data streaming. In Push-based communication, the Application (i.e., database) only send sample request once, but it contains *interval* parameter in millisecond. If the interval is defined to "0", the updates will be occurred in real time. Figure 15 shows the UML time sequence diagram which describe the interactions among MTConnect components.

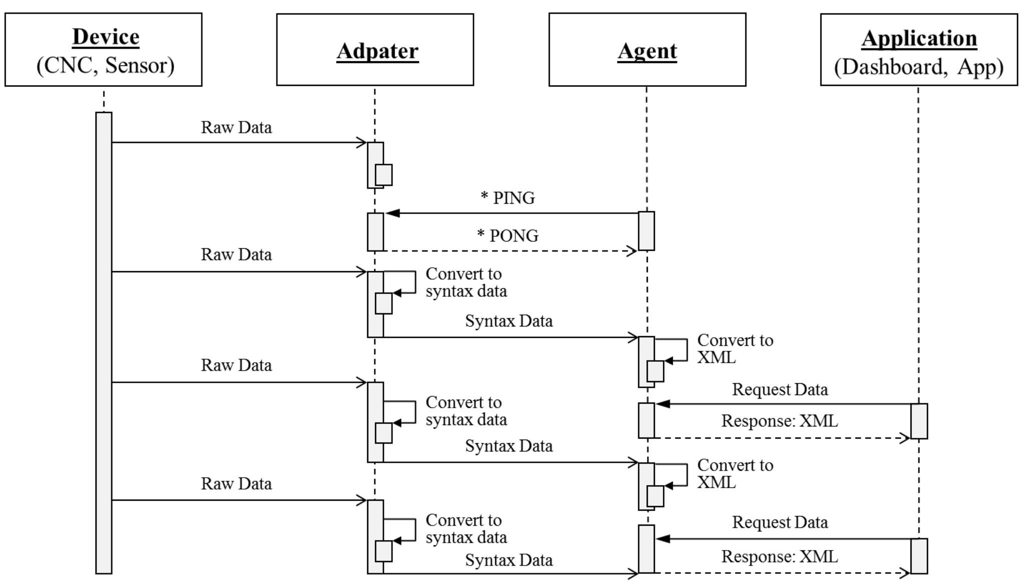


Figure 15: UML time sequence diagram of interactions among MTConnect components

For detail information regarding MTConnect standard, please see Appendix A "Implementation of MTConnect® Standard."

4.4. Development of Database

A database and a communication server program have been developed in the CIMS lab to help users to access the status information (e.g. energy consumption, coolant concentration, and temperature) of equipment in the testbed and warning messages (when abnormality occurs) via a smartphone application (see Section 5). Figure 16 shows the schema of the developed database. There are seven tables designed, including ‘*Users*’, ‘*ActionLogInfo*’, ‘*Sensors*’, ‘*Equipment*’, ‘*Energy*’, ‘*Coolant*’, and ‘*Temperature*’. ‘*Users*’ table includes users’ information on account ID, first name, last name, e-mail address, phone number, and cell phone number. ‘*ActionLogInfo*’ table records actions of users such as login/logout or sending a command to control equipment. ‘*Sensors*’ table includes sensor ID, location of sensor (i.e., equipment ID), status (i.e., on or off), and description of a sensor (e.g., vender or specification). Those two tables are updated by a database administrator. ‘*Equipment*’ table includes equipment ID, equipment type, status of equipment (i.e., on/off), and description of an equipment. ‘*Energy*’ table is about energy consumption status information given by power meter sensors. It includes record number, updated time, sensor ID, status of KW, time of KW status. Table 2 shows an example of ‘*Energy*’ table.

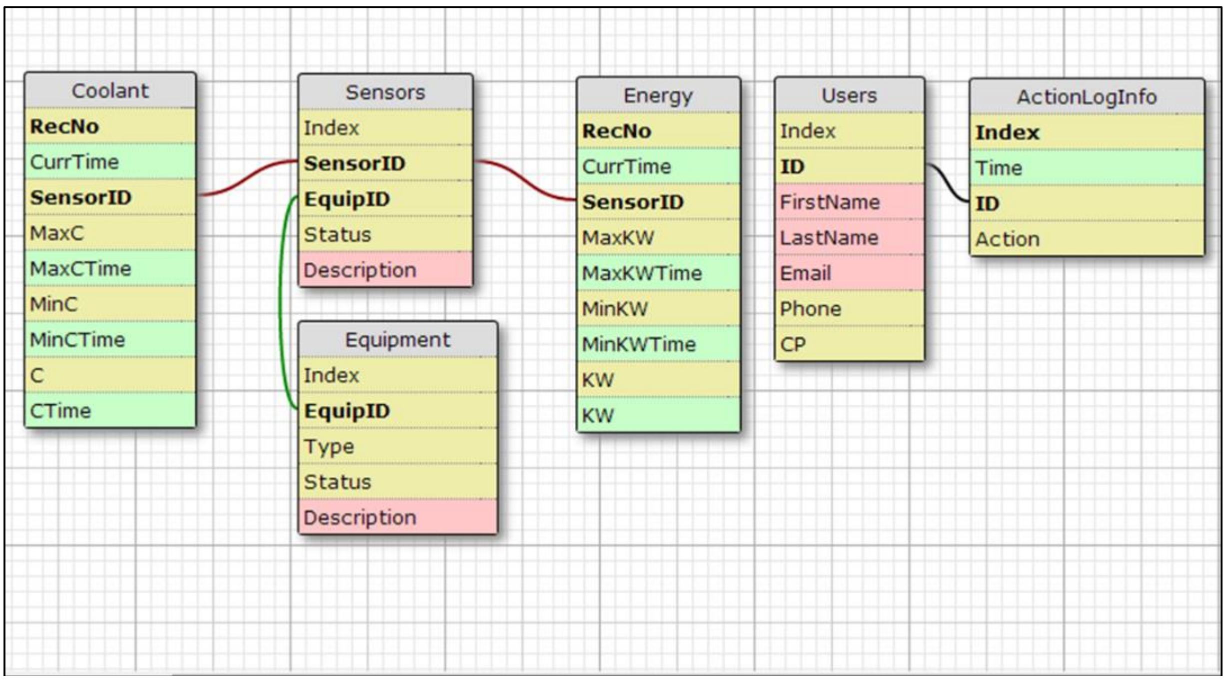


Figure 16: Database schema

Table 2: Example of ‘*Energy*’ table

RecNo	CurrTime	SensorID	MaxKW	MaxKW Time	MinKW	MinKW Time	KW	KW Time
1	2014-05-13 13:09:00	1	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.532	2014-05-13 13:09:00
2	2014-05-13 13:09:15	1	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.542	2014-05-13 13:09:15
3	2014-05-13 13:09:30	1	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.541	2014-05-13 13:09:30
4	2014-05-13 13:09:35	1	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.548	2014-05-13 13:09:35

Similar to ‘*Energy*’ table, the ‘*Coolant*’ table (Table 3) records coolant concentration status involving record number, updated time, sensor ID, status of coolant (*C* represents coolant), time of coolant status. Table 3 shows an example of ‘*Coolant*’ table.

Table 3: Example of '*Coolant*' table

RecNo	CurrTime	SensorID	MaxC	MaxC Time	MinC	MinC Time	C	C Time
1	2014-05-13 13:09:00	1	85	2014-05-13 13:07:15	70	2014-05-13 12:06:00	75	2014-05-13 13:09:00
2	2014-05-13 13:09:15	1	85	2014-05-13 13:07:15	70	2014-05-13 12:06:00	78	2014-05-13 13:09:15
3	2014-05-13 13:09:30	1	84	2014-05-13 13:08:30	68	2014-05-13 12:06:15	73	2014-05-13 13:09:30
4	2014-05-13 13:09:35	1	84	2014-05-13 13:08:30	68	2014-05-13 12:06:15	71	2014-05-13 13:09:35

Similar to '*Energy*' table, the '*Temperature*' table (Table 3) records temperature status involving record number, updated time, sensor ID, tool temperature (TempC represents tool temperature in Celsius), time of temperature status. Table 4 shows an example of '*Temperature*' table.

Table 4: Example of '*Temperature*' table

RecNo	CurrTime	SensorID	TempC
1	2014-05-13 13:09:00	1	26.5
2	2014-05-13 13:09:15	1	27.1
3	2014-05-13 13:09:30	1	26.7
4	2014-05-13 13:09:35	1	26.5

The status tables (i.e., '*Energy*', '*Coolant*', and '*Temperature*') are updated by the data from sensors (i.e. powermeter, refractometer, and thermometer). In this case, the proposed system uses real-time update client software (MTConnect adapter) in microcomputer or local computer connected to sensors. Thus, the real-time update client changes the original sensed data's format to the status tables' formats. For example, the energy consumption data given by power meters (see Table 1) is sent to the communication server program according to the format of '*Energy*' table shown in Table 2. As a result, the communication server program receives the status data of energy consumption and coolant concentration in real time.

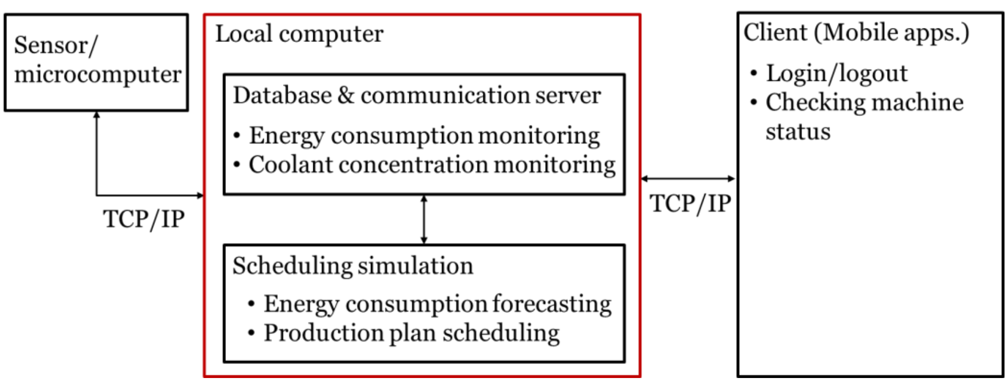


Figure 17: Architecture of automatic monitoring system

As illustrated in Figure 17, the proposed automatic monitoring system consists of five major components such as the sensors (i.e., refractometer, power meter, and thermometer), microcomputer with MTConnect adapter, local computer (communication server with database and MTConnect agent), and client (mobile applications, and web dashboard). In the system, the communication server program populates the database with the latest status information given by MTConnect agent and provides monitoring and warning services to clients (i.e., smartphone application). MTConnect adapter collects its data from inline sensors such as refractometer, power meter, and thermometer and coverts data to MTConnect compatible data format and send the data to MTConnect agent. In the developed server program, MySQL workbench 6.0 has been used for developing the database. The server program executes MySQL queries to provide its services. As a result, users can get status information of coolant, energy consumption, or temperature via smartphone application and web-based dashboard.

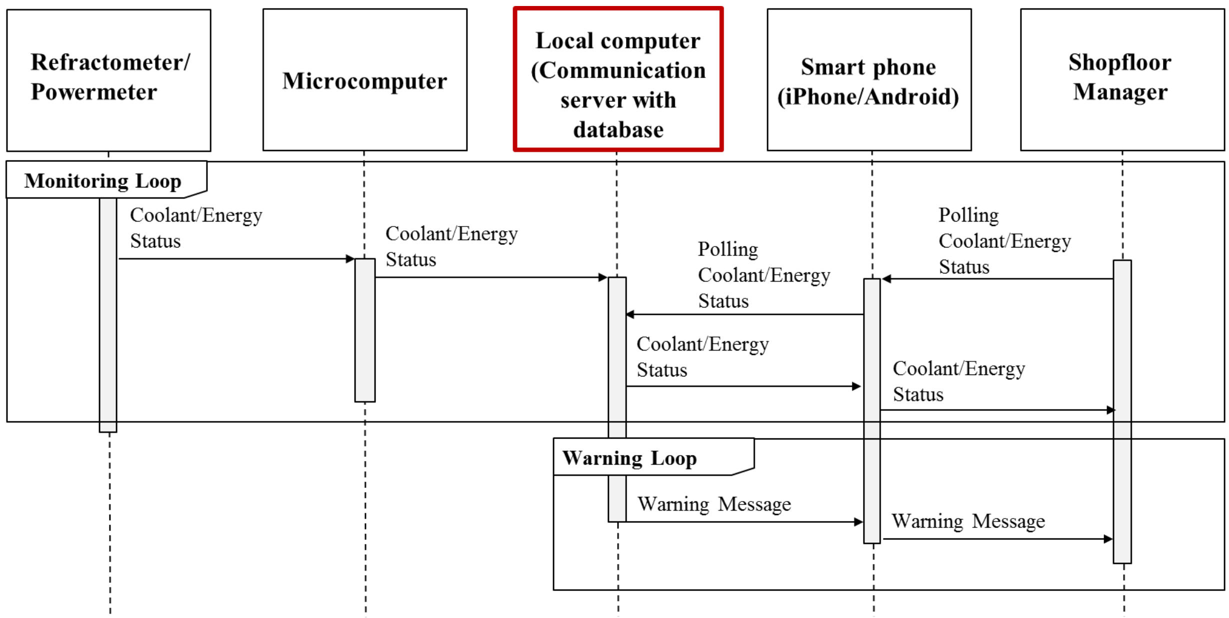


Figure 18: Sequence diagram of monitoring and warning services

Figure 18 uses sequence diagram to demonstrate the two major services provided by the server program: (1) monitoring the status of sensors (e.g., refractometer, power meter, and thermometer) and (2) warning the users when abnormality is detected. First, the monitoring service has been developed to include updating database with latest status information from sensors and providing the status information. To be specific, the server program initially receives real time status information from multiple sensors under given updating frequencies via microcomputer. Then, the server program stores the status information into database so that it can use the latest status information for abnormality detection. In this regard, users can set their own update frequency to get status information from the server program via individual smartphone application. In addition, the warning service has also been developed. To be specific, whenever the status information is updated, the server program checks whether the status is abnormal or not according to predefined upper and lower thresholds for the energy consumption or concentration of coolant. If the value goes beyond the threshold, the server program sends a warning message to all mobile applications so that subscribers can take corresponding actions (e.g. turn off machines or adjust the concentration of coolant).

4.5. Development of Monitoring System

4.5.1. Mobile Application

The major role of a mobile application is to display the status information such as energy consumption of each machine or the entire facility, as well as the coolant concentration and tool temperature for each machine. To be specific, the mobile application receives the status information from the server program so that users of the mobile application can take necessary actions accordingly. There are two major functions developed for the mobile application: (1) latest energy consumption, coolant concentration, and temperature status display and (2) abnormality warning display via warning message.

4.5.1.1. Android Platform

Figure 19 shows the snapshots of the mobile application developed under Android operating system, which is named Energy & Coolant Manager.

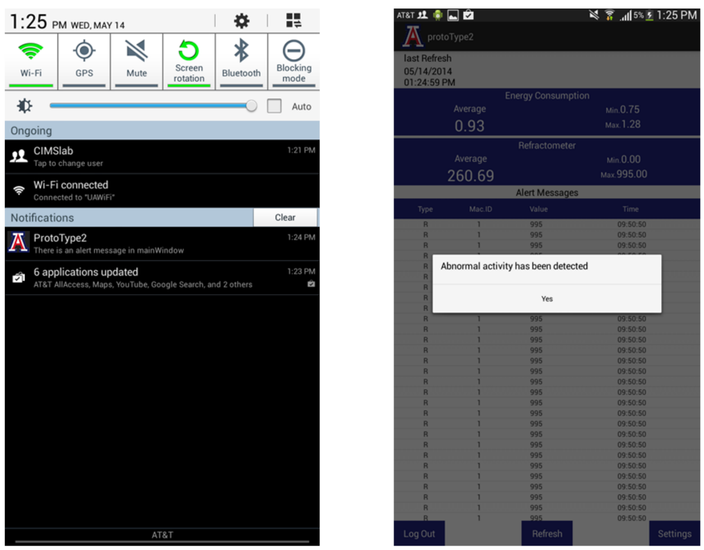
(a) Login window (b) Options window (c) Settings window (d) Main window

(e) Detail info. Window for Energy Consumption (f) Individual status window for Energy Consumption (g) Switch option (h) Detail info. Window for Coolant Concentration

(i) Individual status window for Coolant Concentration (h) Detail info. Window for Tool Temperature (i) Individual status window for Tool Temperature

Figure 19: Snapshots of the energy application for Android

Figure 19(a) is the Login window of the Android application. Since the server program stores all login information, users can login by using their own login ID and password. If the server IP address or port number are incorrect, the information can be modified in the Options window shown in Figure 19 (b) by clicking option button as shown in Figure 19(a). Once users login the application, the Main window is shown (see Figure 19(d)). The Main window reveals summary of statuses of all sensors (i.e., power meter and refractometer) and warning messages. If users want to know the status of each machine (e.g. energy consumption), they can move to the Detail information window for energy consumption (see Figure 19(e)) by clicking the value of energy consumption in Figure 19(d). If users want to know the status of each machine for coolant concentration, they can move to the Detail information window for coolant concentration (see Figure 19(h)) by clicking the value of coolant concentration in Figure 19(d). The Detail information window includes status values of all sensors so that users can understand which sensor has abnormality. If users click the rows in the table shown in Figure 19(e), they can access the energy consumption status of individual machines via the Individual status window (see Figure 19(f)). Similarly, the coolant concentration status of individual machines shown in Figure 19(i) can be accessed by clicking each row in the table shown in Figure 19(h). The tool temperature status of individual machines shown in Figure 19(k) can be accessed by selecting each row in the table shown in Figure 19(j). Users can also switch views from Detail information window for energy consumption to Detail information window for coolant concentration or Detail information window for temperature, and vice versa by clicking options that shows up by pressing menu button on device in Figure 19(g).

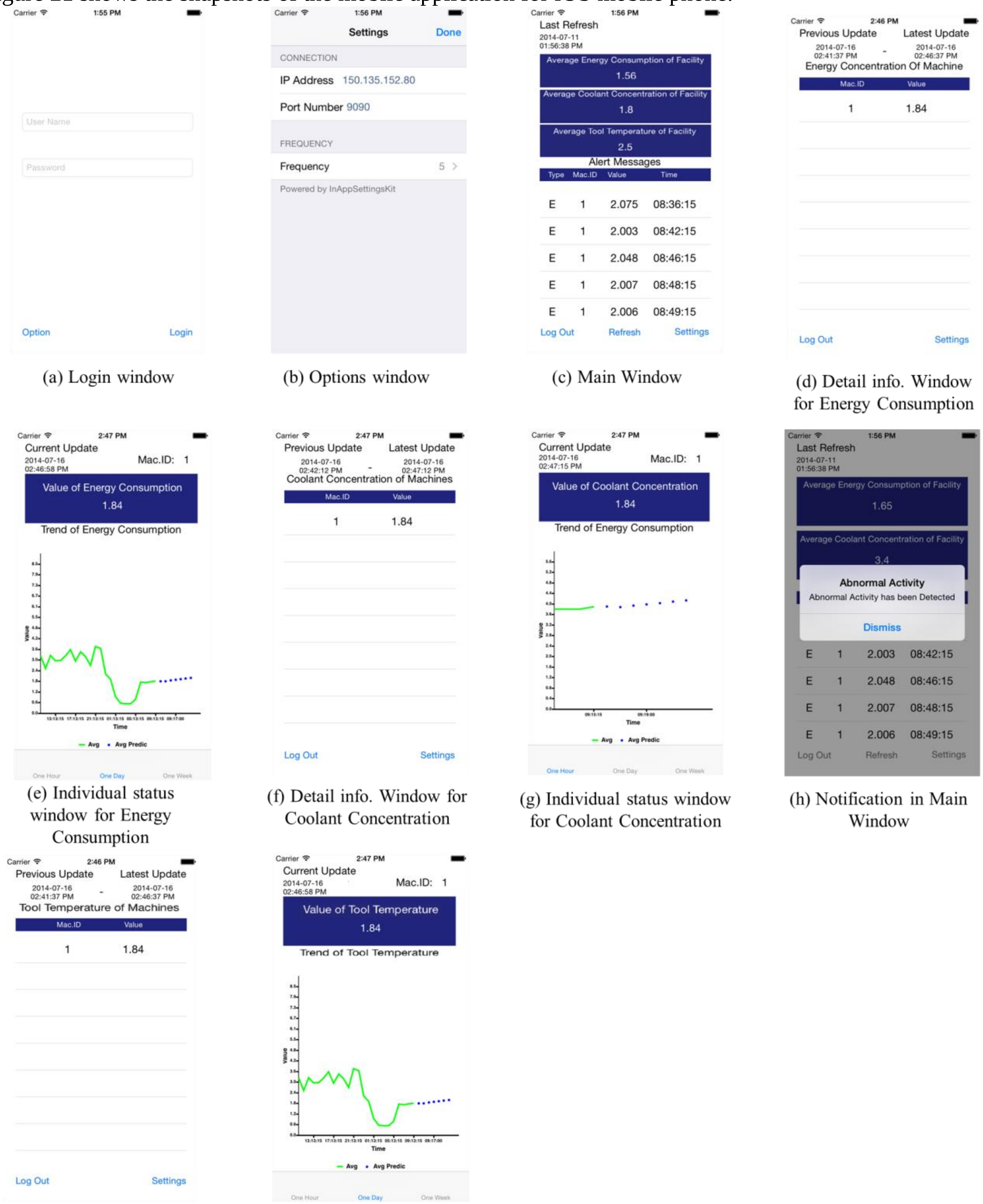


(a) Notification in status (b) Dialog in Main window

Figures 20: Snapshots of warning notification

4.5.1.2. iOS Platform

Figure 21 shows the snapshots of the mobile application for iOS mobile phone.



(a) Login window

(b) Options window

(c) Main Window

(d) Detail info. Window for Energy Consumption

(e) Individual status window for Energy Consumption

(f) Detail info. Window for Coolant Concentration

(g) Individual status window for Coolant Concentration

(h) Notification in Main Window

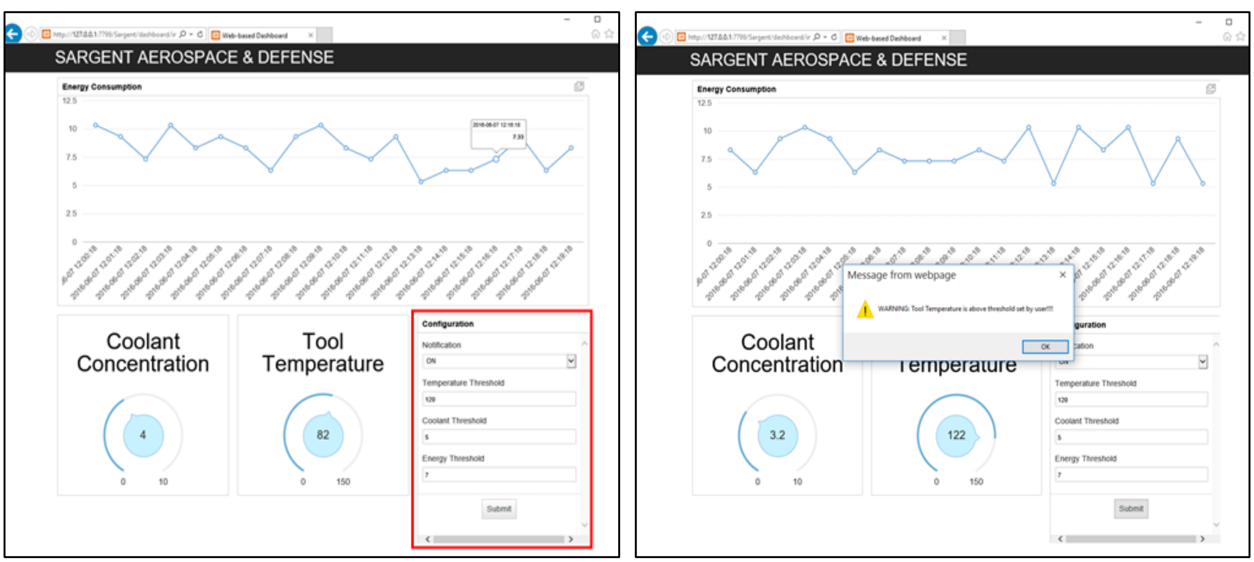
(h) Individual status window for Tool Temperature

Figure 21: Snapshots of the energy application for iOS

Figure 21(a) is the Login window of the application. Since the server program has all login information, users can login by using their login ID and password. If the server IP address or port number are incorrect, the information can be modified in the Options window shown in Figure 21(b) by clicking option button as shown in Figure 21(a). Once users login the energy app, the Main window is shown (see Figure 21(c)). The Main window reveals values of all sensors and warning messages (see Figure 21(h)). If users want to know the status of each machine (e.g. energy consumption), they can move to the Detail information window for energy consumption (see Figure 21(d)) by clicking the value of energy consumption in Figure 21(c). If users want to know the status of each machine for coolant concentration, they can move to the Detail information window for coolant concentration (see Figure 21(f)) by clicking the value of coolant concentration in Figure 21(c). The Detail information window includes status values of all sensors so that users can understand which sensor has abnormality. If users click the rows in the table shown in Figure 21(d), they can access the energy consumption status of individual machines via the Individual status window (see Figure 21(e)). The dotted line represents the estimated energy consumption based on the current data. Similarly, the coolant concentration status of individual machines shown in Figure 21(g) can be accessed by clicking each row in the table shown in Figure 21(f). The tool temperature status of individual machines shown in Figure 21(j) can be accessed by selecting each row in the table shown in Figure 21(i).

4.5.2. Web-based Dashboard

The major role of a web-based dashboard is to show the real-time status data such as energy consumption of each machine, coolant concentration, and tool temperature. Specifically, the dashboard retrieves data from the database which stores real-time sensing data collected via the data acquisition system. There are two major functions developed for the web-based dashboard: (1) displaying the latest energy consumption, coolant concentration, and tool temperature and (2) abnormality warning (i.e., high energy consumption, high coolant concentration, and high tool temperature) display via warning message. To get the warning messages from the dashboard, the user should set the configurations (see the red box in Figure 22(a)): (1) alarm on-off, (2) temperature threshold, (3) coolant concentration threshold, and (4) energy consumption level threshold. After setting the values in the configuration form and clicking the "Submit" button, the setting will be immediately reflected in the system. Figure 22(b) shows the example of the alarm message.



(a) Configuration setting form (b) High temperature alarm message

Figure 22: Snapshots of the web-based dashboard

5. Machining Parameters Optimization to reduce Energy Consumption via CAD/CAM Simulation

The major goal of this project is to reduce the energy consumption for machine shops by improving the energy efficiency of the CNC machine. To achieve high energy efficiency, appropriate machining parameters like cutting speed, depth of cut, feed etc. need to be optimized toward the minimization of energy consumption. In this project, we consider several factors like recommended speed and feed for tool and workpiece material combination, surface finish required, tool life, tool temperature to minimize the energy consumption as well as retain the productivity. Previously, Dr. Son's team developed an energy consumption estimation program to find the energy consumption for producing a part using the CNC machine of the CIMS lab. Since the existing CAM software MasterCAM (used by Sargeant) cannot provide any estimation of energy consumption priori, the proposed energy consumption estimation program comes out very effective for finding the best machining parameters for a product with minimal energy consumption (see figure 23). With the progress of the project Dr. Son's team continuously working to improve the way to solve the energy minimization problem more rigorously. The time sequence diagram has been modified and new two modules have added 1) Knowledge based energy optimization program 2) Shop level energy optimizer. Here the shop floor manager sends the part specification and the material information which is then used by the CAD/CAM Software (e.g. MasterCAM) to generate the NC code. The Knowledge based energy optimization program works based on the recommended parameter for machining (e.g. Surface feet per minute, Inch feet per tooth) for a tool and material combination alter the speed and feed of the NC code which yield minimum production cost. In the shop floor there are multiple machine capable to do the same job. But the energy requirement may not be the same for each machine. This program evaluate NC code against all of the machines to find the parameter that minimize the production cost. After evaluating all of the NC codes, shop floor manager uses the shop level energy optimizer to assign the jobs in such manner to minimize the overall production cost of all parts. This new process plan will be send to the local computer for execution.

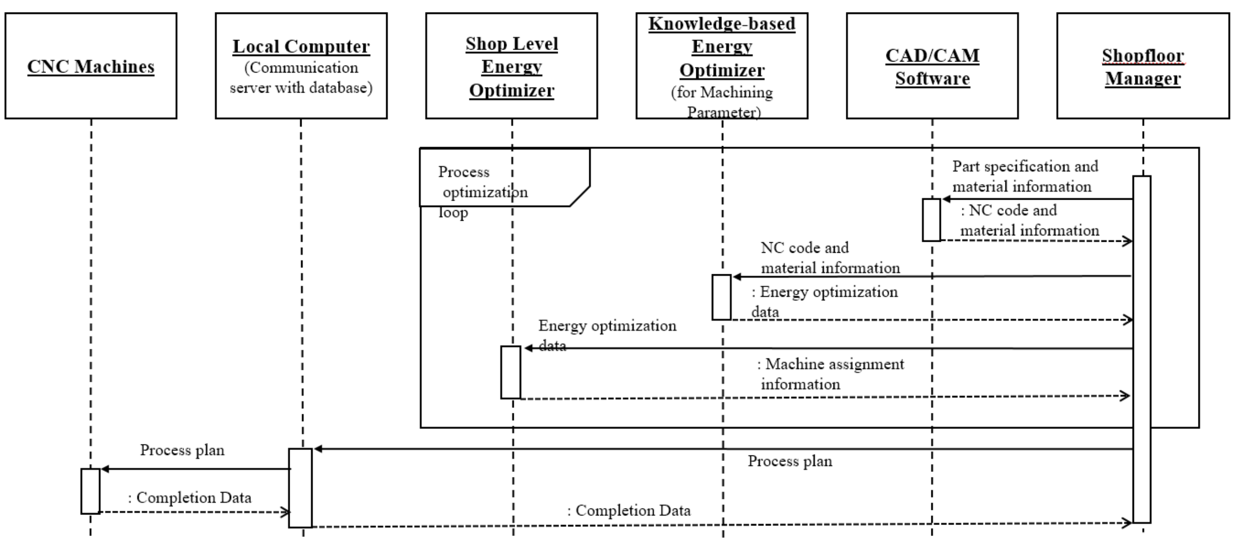
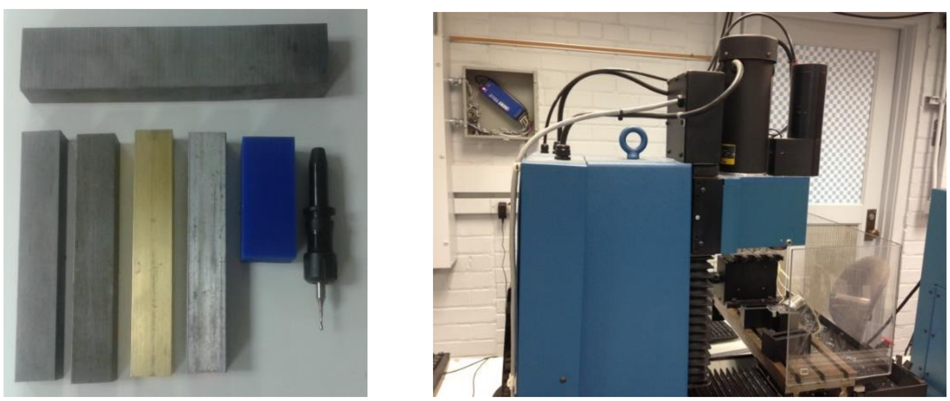


Figure 23: Time sequence diagram of energy consumption estimation and machine control services

In order to develop an energy consumption model for an individual CNC machine, two-level factorial experiment design has been devised for various materials (copper and aluminum). Three major machining parameters such as spindle speed (rpm), feed rate (ipm), and depth of cut (in) have been considered. Table 5 and Figure 24 show the parameter configurations of the experiment and a testbed of the experiment in CIMS lab at the University of Arizona, respectively.

Table 5: Experiment configurations

Exp. No.	Material	Spindle speed (rpm)	Feed rate (ipm)	Depth of cut (in)
1	Aluminum	1500	5.0	0.01
2	Aluminum	1500	5.0	0.03
3	Aluminum	1500	7.5	0.01
4	Aluminum	1500	7.5	0.03
5	Aluminum	2500	5.0	0.01
6	Aluminum	2500	5.0	0.03
7	Aluminum	2500	7.5	0.01
8	Aluminum	2500	7.5	0.03
9	Copper	1500	5.0	0.01
10	Copper	1500	5.0	0.03
11	Copper	1500	7.5	0.01
12	Copper	1500	7.5	0.03
13	Copper	2500	5.0	0.01
14	Copper	2500	5.0	0.03
15	Copper	2500	7.5	0.01
16	Copper	2500	7.5	0.03



(a) Sample materials and a tool (b) CNC machine quipped with power meter

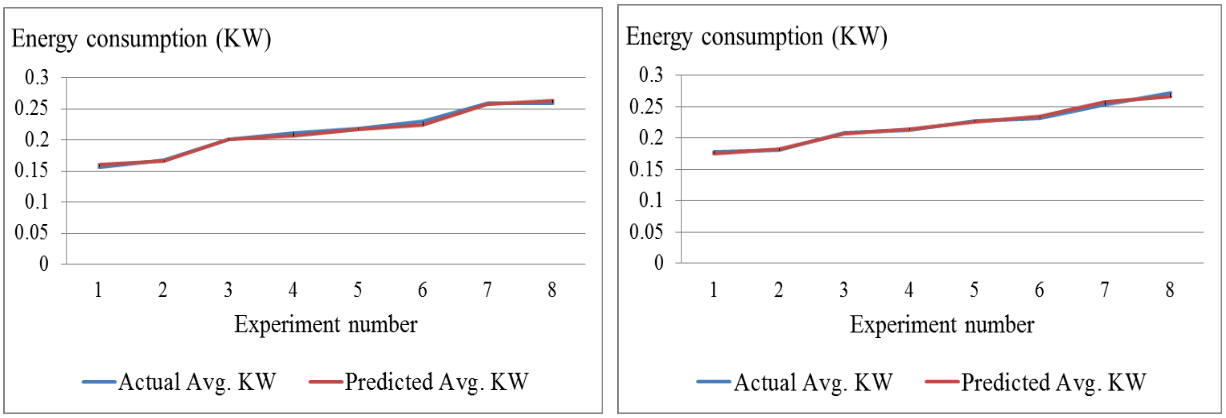
Figure 24: Testbed in CIMS lab at the University of Arizona

The energy consumption model of an individual CNC machine for each material type has been constructed via additive regression with nonlinear partial-regression function (Meng et al., 2013; Montgomery et al., 2012). From the collected data, an energy consumption model for copper material has been developed (see Eq. (1)).

$$E_{Cu} = -9.74 \times 10^{-3} + (5.73 \times 10^{-5})X_S + (1.62 \times 10^{-2})X_F + (2.95 \times 10^{-1})X_D \quad (1)$$

where X_s is the spindle speed (rpm), X_F is the feed rate (ipm), and X_D is the depth of cut (in). This model provides the estimated energy consumption when the machining parameters are given.
Similarly, the following equation represents an energy consumption model of aluminum material:

$$E_{Al} = 3.11 \times 10^{-2} + (5.09 \times 10^{-5})X_S + (1.27 \times 10^{-2})X_F + (3.86 \times 10^{-1})X_D \quad (2)$$



(a) Energy consumption (Copper) (b) Energy consumption (Aluminum)

Figure 25: Comparison between actual consumption and prediction

Table 6: ANOVA test of the additive regression model (Copper)

Model	Sum of Squares	*df*	Mean Square	*F*	Significance
Regression	3.4638×10^{-1}	3	1.1546×10^{-1}	1206.9713	8.7606×10^{-6}
Residual	9.5661×10^{-5}	1	9.5661×10^{-5}		
Total	3.4648×10^{-1}	4			

Table 7: ANOVA test of the additive regression model (Aluminum)

Model	Sum of Squares	df	Mean Square	F	Significance
Regression	3.6623×10^{-1}	3	1.2208×10^{-1}	1497.5817	6.3393×10^{-6}
Residual	8.1515×10^{-5}	1	8.1515×10^{-5}		
Total	3.6631×10^{-1}	4			

Regarding the significance levels of both models, the estimates given by Eq. (1) and Eq. (2) are statistically accurate at 0.05 level of significance (i.e., $\alpha = 0.05$). Thus, both models are utilized to estimate the energy consumption from a G-code which is an output from CAD/CAM software. Figure 26 shows validation results of the equation for E_{Cu} and E_{Al} with actual energy consumption under 8 different parameter configurations (each configuration has 40 samples) which reveals that the proposed additive regression models are able to provide accurate estimates of energy consumption. Later Dr. Son's team conducted more experiments to enrich the knowledge based energy optimization program. Experiments on four other different materials, Mild Steel(MS), Stainless Steel(SS), Cast Iron(CI), Brass(Br), has been conducted at CIMS lab of the University of Arizona. In these experiments three different values were considered for each machining parameter (e.g. speed, feed, depth of cut) which shown in Table 8. All of these experiments were done by using Carbide coated tool. Figure 16 shows the part design used to conduct the design of experiment and Figure 27 shows the sample materials after machining is done.

Table 8: Experiment configurations

Exp. No.	Material	Spindle Speed (rpm)	Feed Rate (ipm)	Depth of Cut (in)
1	Mild Steel, Stainless Steel, Cast Iron, and Brass	1500	5.0	0.01
2		1500	7.5	0.01
3		1500	10.0	0.01
4		1500	5.0	0.02
5		1500	7.5	0.02
6		1500	10.0	0.02
7		1500	5.0	0.03
8		1500	7.5	0.03
9		1500	10.0	0.03
10		2000	5.0	0.01
11		2000	7.5	0.01
12		2000	10.0	0.01
13		2000	5.0	0.02
14		2000	7.5	0.02
15		2000	10.0	0.02
16		2000	5.0	0.03
17		2000	7.5	0.03
18		2000	10.0	0.03
19		2500	5.0	0.01
20		2500	7.5	0.01
21		2500	10.0	0.01
22		2500	5.0	0.02
23		2500	7.5	0.02
24		2500	10.0	0.02
25		2500	5.0	0.03
26		2500	7.5	0.03
27		2500	10.0	0.03

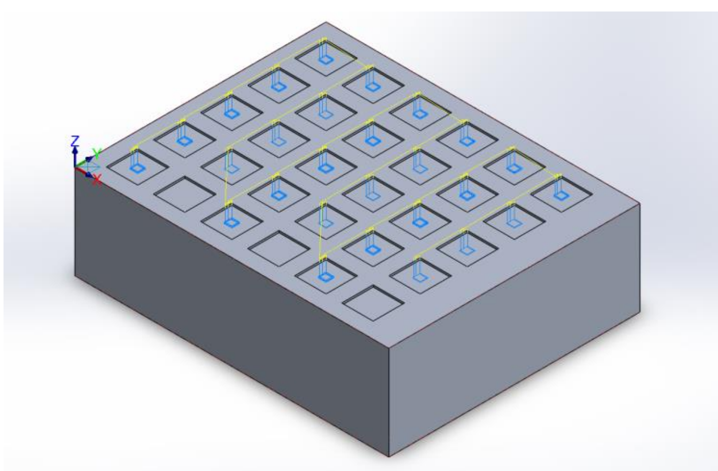
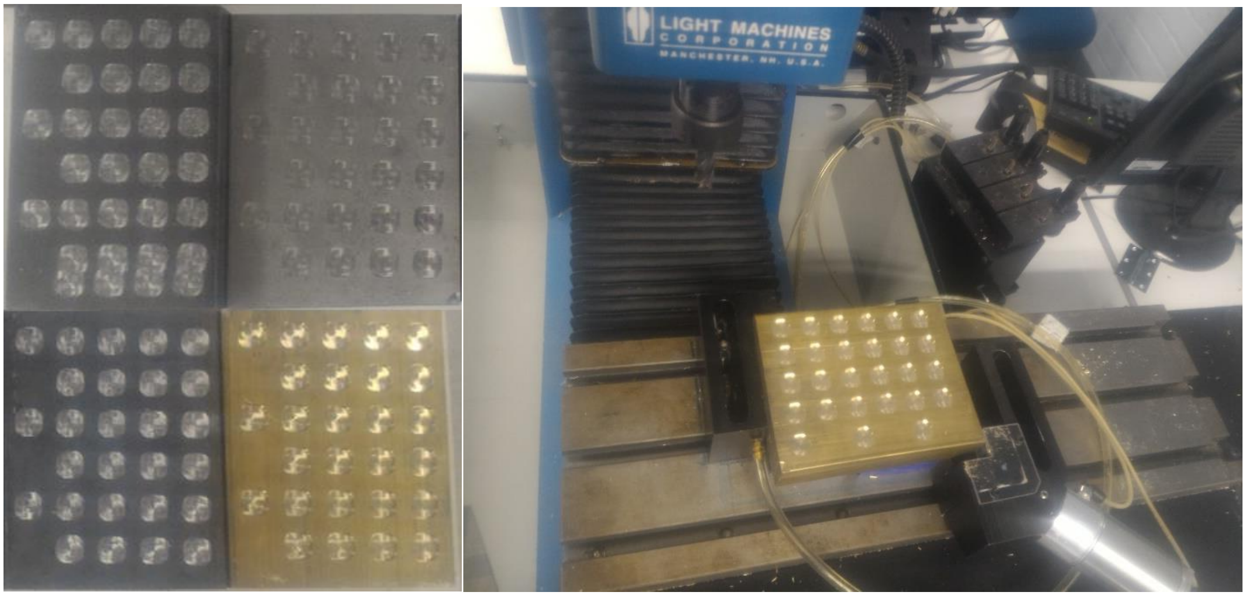


Figure 26: Design of Experiment Part design



(a) Sample materials (b) CNC machine used for conducting DOE

Figure 27: Testbed in CIMS lab at the University of Arizona

Energy consumption model obtained from the design of experiment for each of these materials are as follows:

Mild Steel:

$$E_{MS} = -5.92 \times 10^{-3} + (7.53 \times 10^{-5})X_S + (5.45 \times 10^{-3})X_F + (27 \times 10^{-1})X_D \quad (3)$$

Stainless Steel:

$$E_{SS} = 1.01 \times 10^{-1} + (5.19 \times 10^{-5})X_S - (7.61 \times 10^{-4})X_F - (6.62 \times 10^{-1})X_D \quad (4)$$

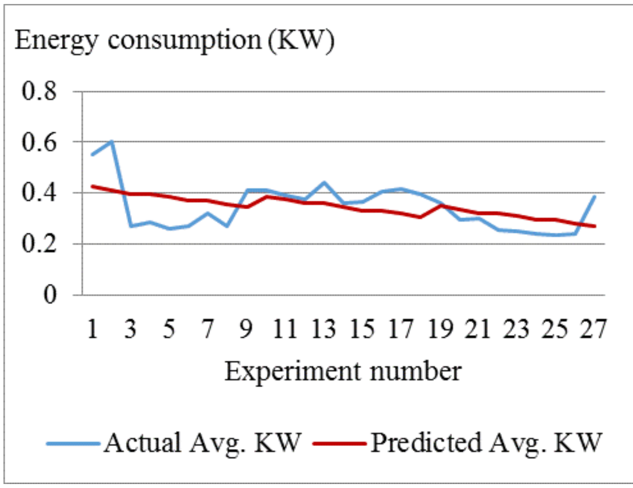
Cast Iron:

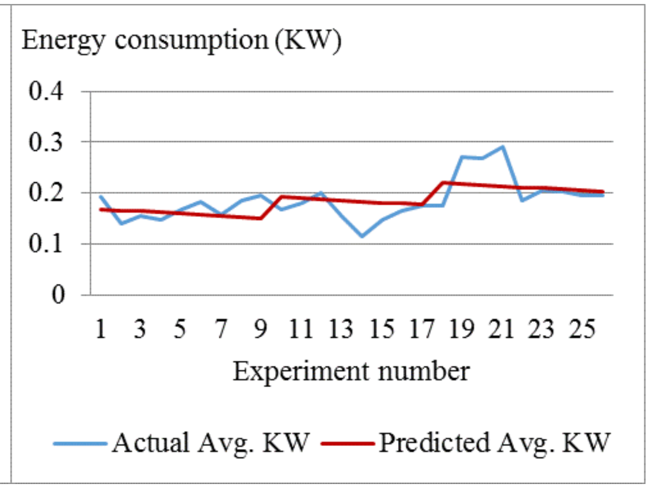
$$E_{CI} = -7.26 \times 10^{-1} + (1.84 \times 10^{-4})X_S + (1.15 \times 10^{-2})X_F + (22.1 \times 10^{-1})X_D \quad (5)$$

Brass:

$$E_{Br} = -4.96 \times 10^{-1} + (1.08 \times 10^{-4})X_S + (1.00 \times 10^{-2})X_F + (29.1 \times 10^{-1})X_D \quad (6)$$

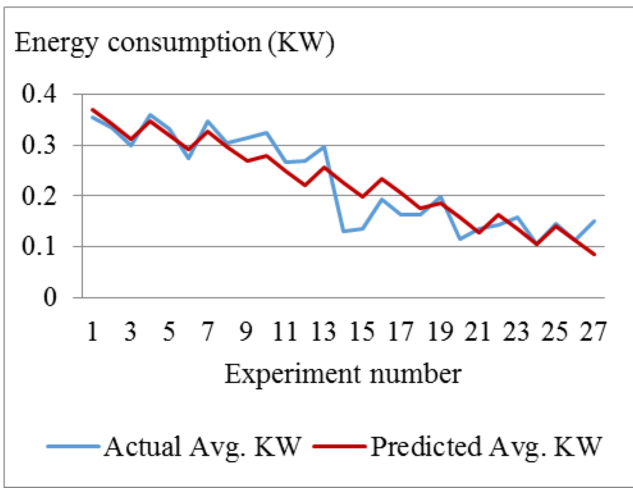
Here, E_{MS} , E_{SS}, E_{CI} and E_{Br} measures the energy consumption per unit time. Figure 28 shows validation results of the equation for E_{MS} , E_{SS}, E_{CI} and E_{Br} with actual energy consumption under 27 different parameter configurations

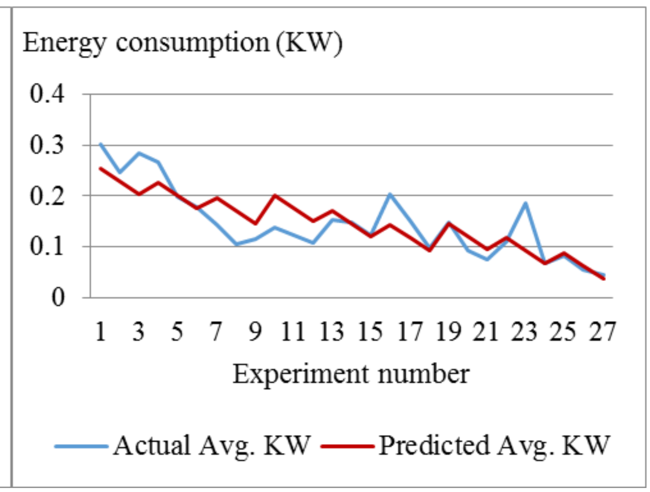




(a) Energy consumption (Mild Steel)

(b) Energy consumption (Stainless Steel)





(c) Energy consumption (Cast Iron)

(d) Energy consumption (Brass)

Figure 28: Comparison between actual consumption and prediction

These energy estimation equations provide the basis of building knowledge based energy optimization program. Let $C_1$is the cost per unit of energy $C_2$is the production cost per unit time. If T_p is the total production time to produce a part, total cost of production can be expressed by the following equation:

$$C_1 E_{Cu/Al/MS/SS/CI/Br} T_p + C_2 T_p \quad (7)$$

where E_{Al}, E_{Cu}, E_{MS} , E_{SS}, E_{CI} and E_{Br} measures the energy consumption per unit time for machining Aluminium, Copper, Mild Steel, Stainless Steel, Cast Iron, and Brass respectively. Since total production time is a function of machining speed and length of travel while executing a NC code, it can be expressed as follows:

$$T_p = L/X_F \quad (8)$$

where, L is the length of travel and X_F is the feed rate (Feed in inches per minute).

However X_F is a function of cutter rpm, number of teeth in cutter and feet per tooth. If X_S is the revolutions per minute, T is the number of teeth in cutter and f is the feet per tooth in inches, X_F can be expressed as follows:

$$X_F = f \times T \times X_S \tag{9}$$

where X_S can be calculated from surface feet per minute (SFM) and diameter of the tool (D) for a specific part material and tool material combination by using the equation below:

$$X_S = \frac{SFM \times 10}{3.1416 \times D} \tag{10}$$

Combining all of the above expression the mathematical model can be expressed as follows:

min $\quad C_1 E_{Cu/Al/MS/SS/CI/Br} T_p + C_2 T_p$

Subject to

$$E_{Cu} = -9.74 \times 10^{-3} + (5.73 \times 10^{-5})X_S + (1.62 \times 10^{-2})X_F + (2.95 \times 10^{-1})X_D$$

$$E_{Al} = -3.11 \times 10^{-2} + (5.09 \times 10^{-5})X_S + (1.27 \times 10^{-2})X_F + (3.86 \times 10^{-1})X_D$$

$$E_{Cu} = -9.74 \times 10^{-3} + (5.73 \times 10^{-5})X_S + (1.62 \times 10^{-2})X_F + (2.95 \times 10^{-1})X_D$$

$$E_{Al} = 3.11 \times 10^{-2} + (5.09 \times 10^{-5})X_S + (1.27 \times 10^{-2})X_F + (3.86 \times 10^{-1})X_D$$

$$E_{MS} = -5.92 \times 10^{-3} + (7.53 \times 10^{-5})X_S + (5.45 \times 10^{-3})X_F + (27 \times 10^{-1})X_D$$

$$E_{SS} = 1.01 \times 10^{-1} + (5.19 \times 10^{-5})X_S - (7.61 \times 10^{-4})X_F - (6.62 \times 10^{-1})X_D$$

$$E_{CI} = -7.26 \times 10^{-1} + (1.84 \times 10^{-4})X_S + (1.15 \times 10^{-2})X_F + (22.1 \times 10^{-1})X_D$$

$$E_{CI} = -7.26 \times 10^{-1} + (1.84 \times 10^{-4})X_S + (1.15 \times 10^{-2})X_F + (22.1 \times 10^{-1})X_D$$

$$X_S = \frac{SFM \times 10}{3.1416 \times D}$$

$$X_F = f \times T \times X_S$$

$$T_p = L/X_F$$

$$SFM_{min} \leq SFM \leq SFM_{max}$$

$$f_{min} \leq f \leq f_{max}$$

The last two expression shows the limit for SFM and f which can be obtained from the chart of recommended parameters. The recommended parameters for various tool and material configuration are shown in Table 9.

Table 9: Recommended Machining Parameter

Materials	Surface Speed- Surface Feet /Minute (SFM)		End Mill Diameter- Inches Per Tooth		
	HSS/Cobalt	Carbide	Up to 1/16”	1/16” – 1/8”	1/8” – 1/4”
Aluminum	200-600	600-1300	.0004-.0008	.0008-.0015	.0020-.0060
Copper	60-80	200-500	.0002-.0004	.0004-.0010	.0008-.0020
Mild Steel	75-100	150-250	.0004-.0008	.0006-.0015	.0010-.0040
Stainless Steel	60-80	250-500	.0003-.001	.0008-.002	.002-.003
Cast Iron	55-85	80-130	.0003-.0008	.0006-.0015	.0030-.0060
Brass	100-200	400-700	.0003-.0008	.0008-.0012	.0010-.0030

Moreover, the aim of developing the knowledge based energy optimization program is to find the optimum machining parameter (e.g. spindle speed, feed and depth of cut) and to estimate the production cost based on production hour and energy expenditure based on the NC code for a specific type of tool and material condition. Several new features have added in the energy consumption estimation program. Energy optimization program now requires six types of input data: (1) tool information including tool number and diameter, (2) tool material (3) Number of teeth (4) NC code (5) feed rate of a CNC machine and (6) material of the tool and workpiece. The layout of the new knowledge based energy optimization program is shown in Figure 29.

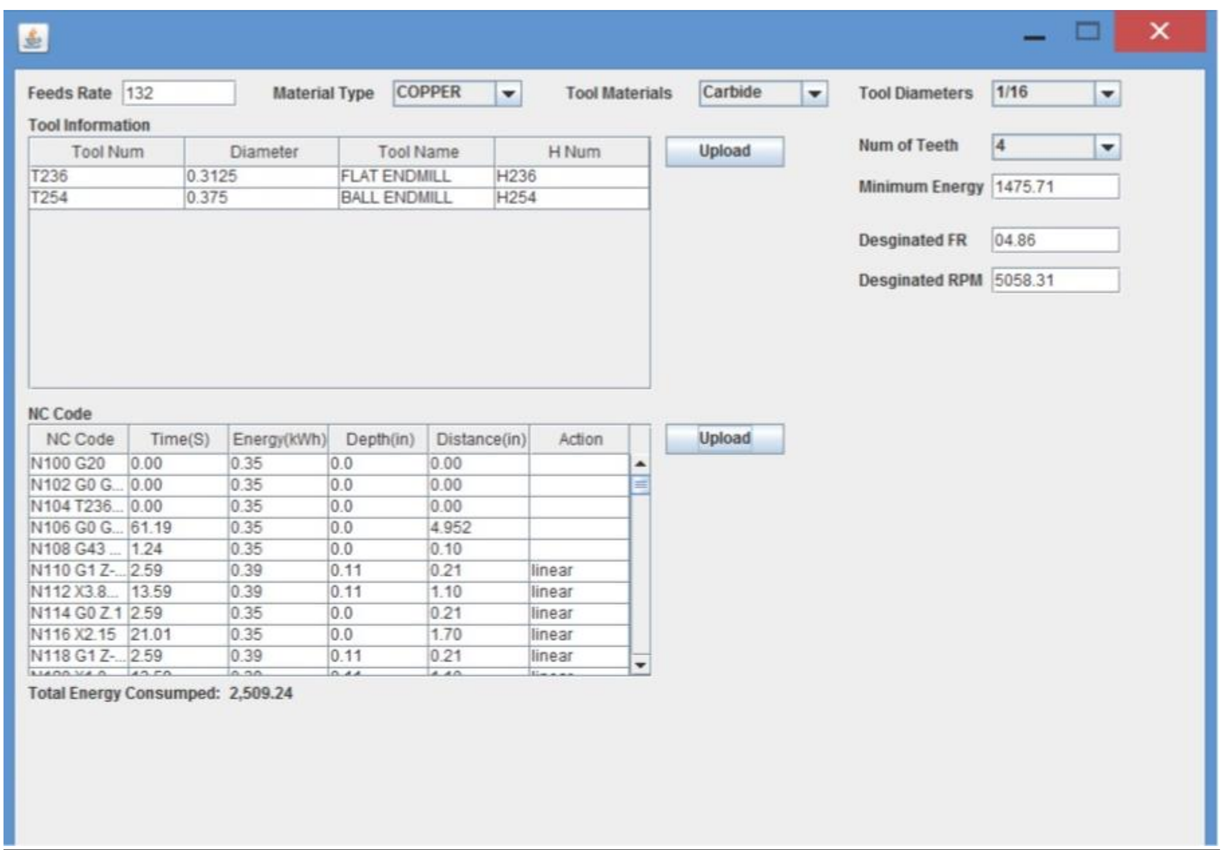


Figure 29: Energy consumption estimation program

If a feed rate of a CNC machine and the material information are not provided in the NC code then a user needs to provide the feed rate. User also need to provide the part material and tool material information. Tool material information consists of three different inputs which are (1) tool material (2) tool diameter (3) number of teeth. After having all these input, the knowledge based energy optimization program retrieves the recommended parameter from the database like surface feet per minute and inch per tooth. The program is designed to check the 100 different combination of speed and feed in the recommended range to find the optimum spindle speed and feed that yield minimum energy consumption to produce a part. This program will reduce the manufacturers' effort to find the optimum parameter for which it will cause minimum energy consumption. Currently the knowledge based energy optimization program supports six different part material (Aluminum, Copper, Brass, Mild Steel, Stainless Steel, Cast Iron), two different tool materials (High Speed Steel, Carbide) with size ranging from 1/16" to 1/4" and number of teeth from 2 to 8.

6. Shop Operation Simulation Development and Experiment

6.1. Simulation model

In order to predict the energy consumption of individual equipment and the entire facility under different shop operation schedules, we develop a System Dynamics model in the simulation software AnyLogic®. The developed simulation model includes all the major energy intensive equipment for shop operations at the south facility of Sargent. As shown in Figure Y1 below, the operations of individual equipment are simulated via a machine level module (e.g. the amplified view in Figure 30). Besides, the load of each equipment is displayed in real-time via animation plots (as shown in Figure 31) and outputted to the simulation output database. The energy consumption is driven by the real process energy consumption profiles that are developed via off-line experiments.

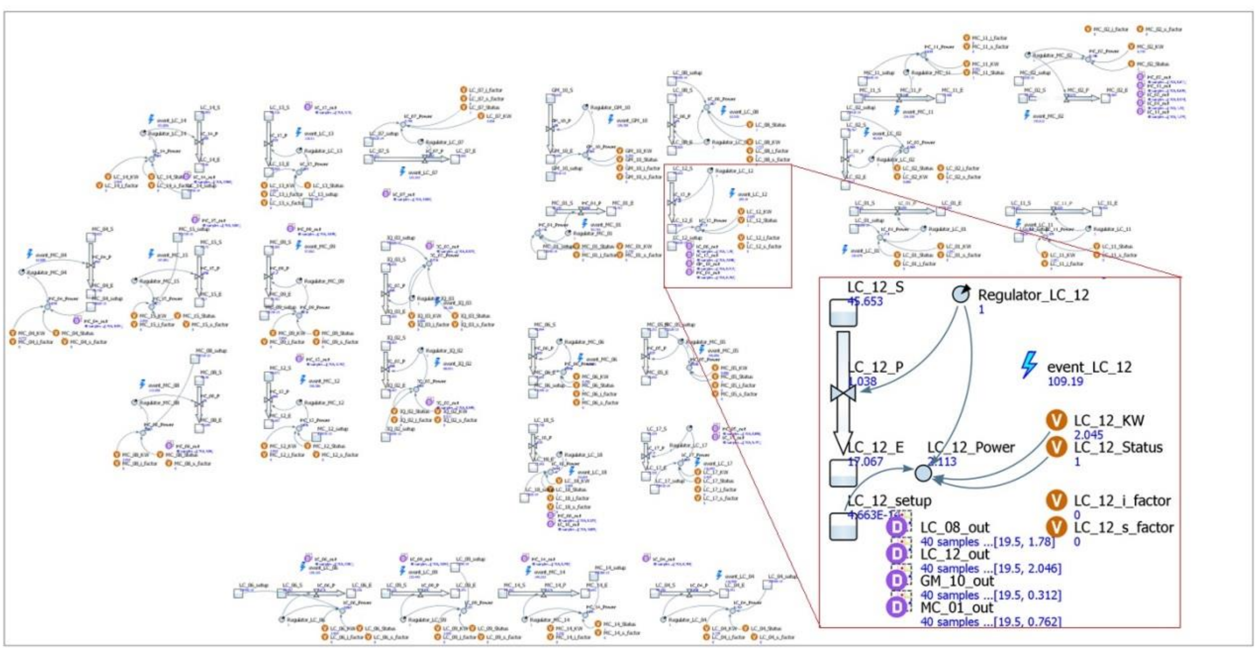


Figure 30: Simulation logic for shop operations

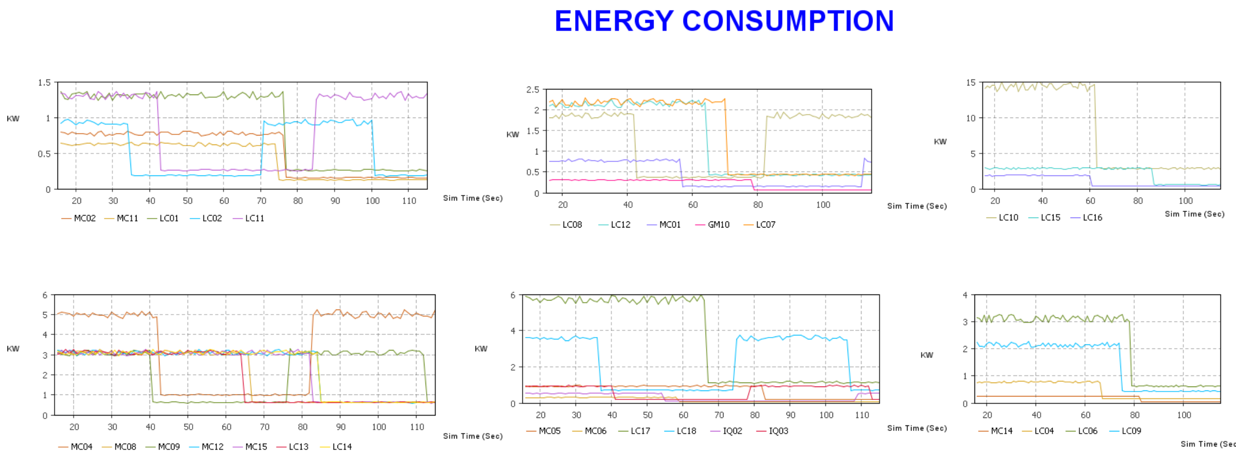


Figure 31: Animation for instant load of individual equipment

6.2. What-If Analysis

The developed simulation is data-driven and capable of various what-if analyses. Based on the information provided by Sargent, we have performed two sets of analyses. Tables 10-12 provide partial information on CNC machine power specifications, one instant of workforce schedule and the product machining times, respectively. The data in Tables 10 and 11 are real data, and the product machining time data is obtained considering realistic assumptions.

Table 10: Equipment power data

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Volts	208	208	208	208	208	480	480	208	208
Amps	25	20	30	42	42	200	40	60	60

Table 11: Workforce schedule for shop operations

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Day (# of operators)	3	3	3	3	3	1	1	1	2
Night (# of operators)	2	2	2	2	2	1	1	1	0

Table 12: Product machining times

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Rate (min/part)	74.88	75.54	32.84	76.11	39.86	62.30	86.88	59.37	39.39
Setup (min/part)	7.49	7.55	3.28	7.61	3.99	6.23	8.69	5.94	3.94
Total rate (min/part)	149.76	151.09	65.67	152.23	79.71	124.60	173.75	118.75	78.79

In the first experiment, we defined two scenarios where machines were standing by and completely turned off when they were idle. Figure 31 depicts the load of the south facility during 9:00AM-11:00AM (production started at 8:00AM). It is shown that turning off machines when they are idle can save energy use. However, turning on the machines produce load peaks (e.g. spikes for "Turn-off" scenario in Figure 32).

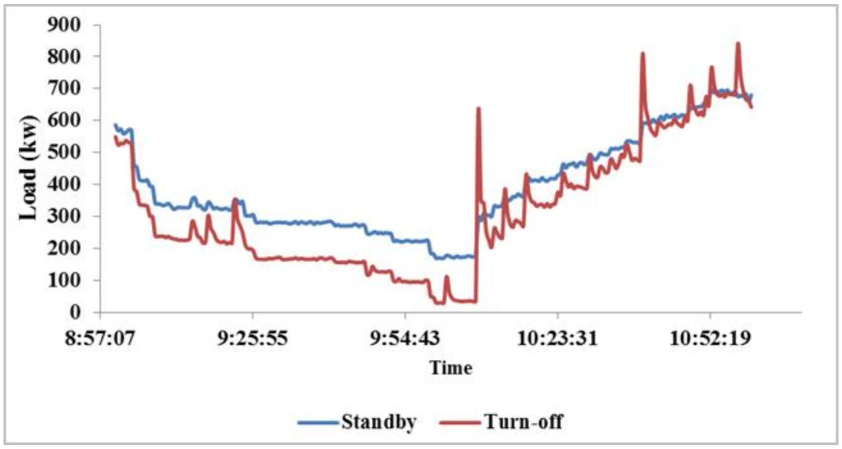


Figure 32: Instant load of the south facility

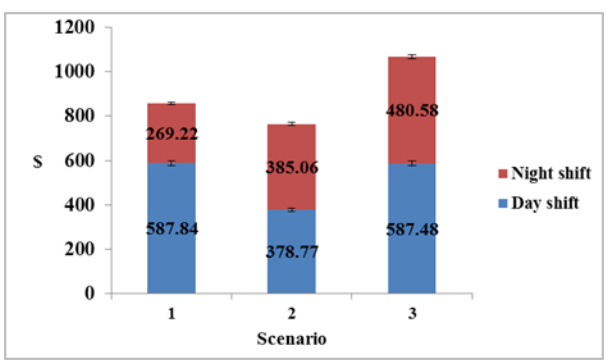
In the second experiment, we defined three scenarios to identify how the change of workforce schedule affects the electricity cost. Scenario 1 is one instance of schedule that Sargent is using. In this case, the day shift has more operators and more machines operate than the night shift. Scenario 2 is to switch the number of operators in the two shifts as defined in Scenario 1. Scenario 3 is that both shifts have the same number of operators for each machine. For the electricity price, we adopted the summer rate under Time of Use (TOU) given by Tucson Electric Power (see Table 13). The day shift is from 8AM to 5PM, and the night shift is from 8PM to 5AM of next day.

Table 13: Summer electricity rate for TOU

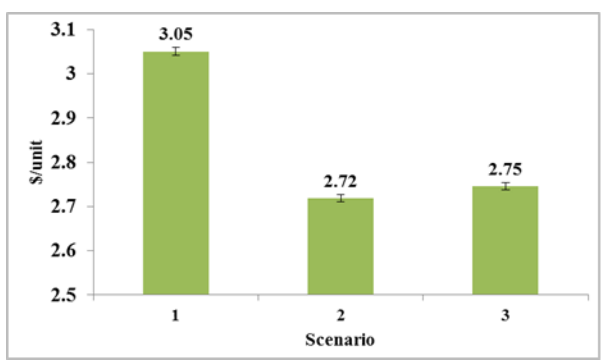
Time	On-peak (2pm-8pm weekdays)	Off-peak (other times)
Price ($/kwh)	0.1494	0.1112

Figure 33(a) depicts the electricity bills for day shift and night shift under the three designed scenarios, respectively. Figure 33(b) illustrates the average electricity cost for processing one product. The results suggest that due to the TOU, shifting the production to the night shift can save electricity cost.

In Figure 33(a), Scenario 2 can achieve $ 93.23 daily saving from the current schedule in the facility (i.e., Scenario 1). Besides, unit product electricity cost is $ 0.33 less than Scenario 1. It is worth to mention that there exists a trade-off between the electricity saving and labor cost increase since the hourly salary for night shift requires 35cents higher cost. Comparing scenario 2 with scenario 1, doing more jobs at night shift will increase the labor cost by $109.2 for operators (versus $93.23 electricity saving). Thus, the results suggest that due to the TOU, shifting the production to the night shift can save electricity cost.



(a) Daily electricity bill (south facility)



(b) Average electricity cost for unit production

Figure 33: Simulation experiment results for electricity cost

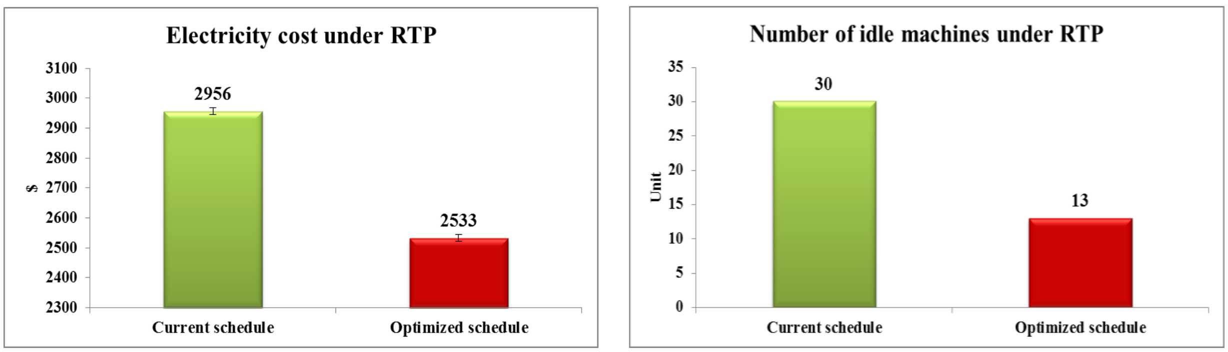
6.3. Optimization

In addition to the machine energy consumption profiles, two models of Demand Response (DR) program: Real Time Pricing (RTP) and Time of Use (TOU), are included in the simulation model. In this study, Real Time Pricing (RTP) model proposed by Zhao et al (2013) has been adopted.

$$p\left(l\left(t\right)\right) = p_{base} + \alpha\left(l\left(t\right) - l_{base}\right)^{k} \tag{7}$$

where $p(l(t))$ is the real time price ($/kWh), and p_{base} is base price ($/kWh), $l(t)$ is the load at time t (kW), and l_{base} is the base load for price calculation (kW). Besides, α and k are control parameters for shaping the price curve.

Figure 34 shows the minimization results of electricity cost under RTP. In this case, we ran the optimization module with 500 iterations and 10 replications per iteration. The simulation duration is 48 hours. Figure 34 (a) reveals that the optimum schedule can save $ 423 for two days (14.3% saving) from current schedule. This is because the number of idle machines, which consume electricity constantly, is significantly reduced. Table 14 shows details of the optimal schedule.



(a) Electricity cost under RTP (b) Number of idle machines under RTP

Figure 34: Optimization for machine status

Table 14: Optimized machine status for periods between jobs

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10
Idle/off	off	off	idle	off	idle	idle
Equip ID	LC15	LC16	LC08	GM10	MC01	LC12
Idle/off	off	off	idle	off	idle	off
Equip ID	MC05	MC06	LC17	LC18	LC07	IQ02
Idle/off	off	off	idle	off	idle	idle
Equip ID	IQ03	LC13	MC09	MC12	LC14	MC15
Idle/off	off	off	idle	idle	off	off
Equip ID	MC08	MC04	LC06	LC09	MC14	LC04
Idle/off	off	off	idle	off	idle	idle

We further conducted experiments to generate optimum machine turn-on sequence after electricity outage. Since the machine consumes higher electricity than other status of machine (e.g., idle and machining), the turn-on sequence becomes a significant issue. Especially, if all machines are turned on at the same time or very closely, it would produce huge load peak and increases energy cost because we are considering RTP. Thus, two cases are considered: (1) turning on the machines at the same time and (2) turning on the machines with the optimized sequence to save energy consumption. For optimization, all the machines have to be turned on between 22:23 to 22:44. The optimization setting is the same as previous experiment.

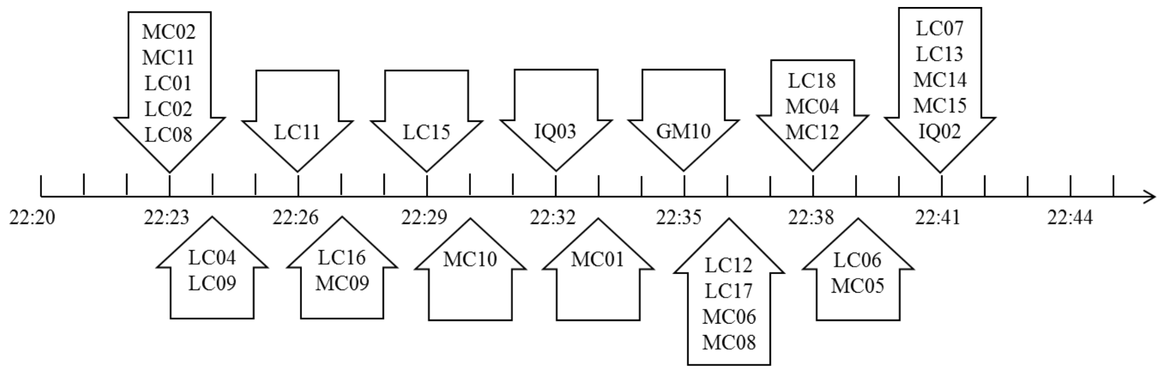


Figure 35: Optimal machine turn-on sequence

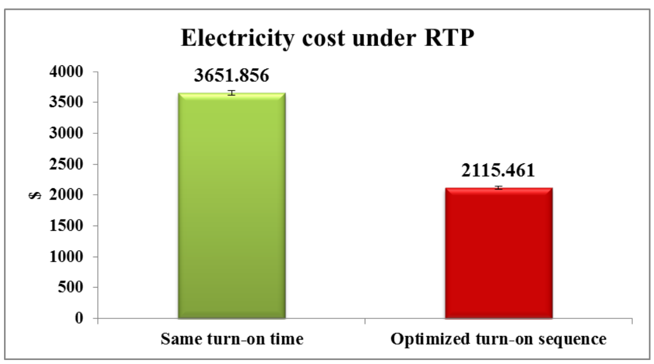


Figure 36: Electricity cost of optimized machine turn-on sequence

Figure 35 shows the optimized machine turn-on sequence given by OptQuest considering the energy consumption pattern of individual machine. The optimized turn-on sequence saves $ 1536.395 (42.1%) from the case that machines are turned on together after electricity outage as shown in Figure 36. Although the work flow in the facility includes 29 machines, the amount of saving will be increased if the work flow involves many machines. Therefore, by using the optimum machine turn-on sequence, we can reduce the load peaks and save energy cost.

6.4. Extension of the Simulation Model with Finite State Machine

Although the current System Dynamic model can capture the dynamic energy use at Sargent, it is hard to describe detailed energy consumption profiles and dynamic machine status. To extend this model into more realistic simulation model, Dr. Son's team has developed Finite State Machine (FSM) model for each energy intensive equipment at the south facility of Sargent. Figure 37 presents the extended model with FSM for individual CNC machine. In this model, the five typical energy consumption profiles are considered as the operation states: (1) Power-off (the machine being powered off), (2) Warm-up (before the machine is ready to be used), (3) Idle (the machine is on but not in machining), (4) Start-up (transition between Idle and Machining), and (5) Machining. This model also can depict the special cases such as blackout and machine failure based on the historical data (e.g., Mean Time Between Failure and Mean Time

To Repair). In addition, the major input such as the operation schedule and the estimated machining time by the knowledge-based optimizer can be driven from the MySQL database in the developed server.

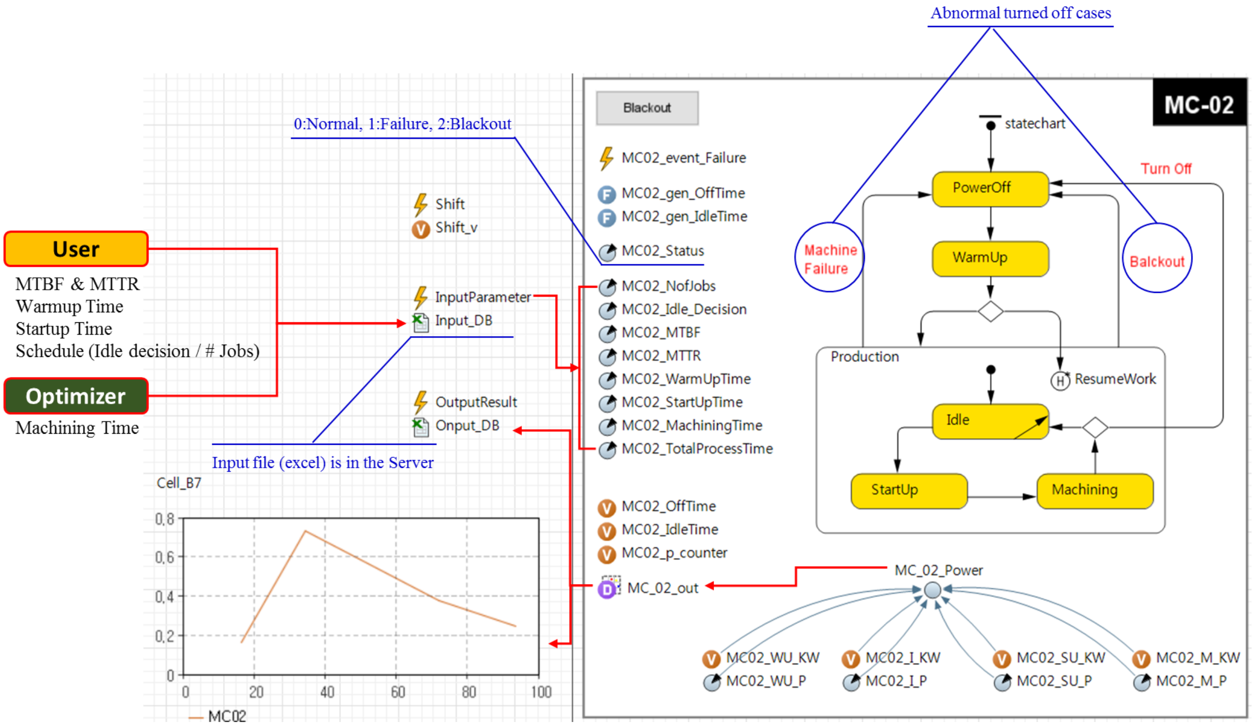


Figure 37: Finite State Machine model for individual CNC machine

7. Lean Manufacturing Implementation and Optimum Production Schedule via Simulation-based Optimization and Value Stream Mapping

7.1. VSM Interface Development

The purpose of the value stream mapping (VSM) interface is to automatically generate simulation models based on the value stream maps without additional coding, debugging and validation processes. Figure 38 below shows the function of VSM interface.

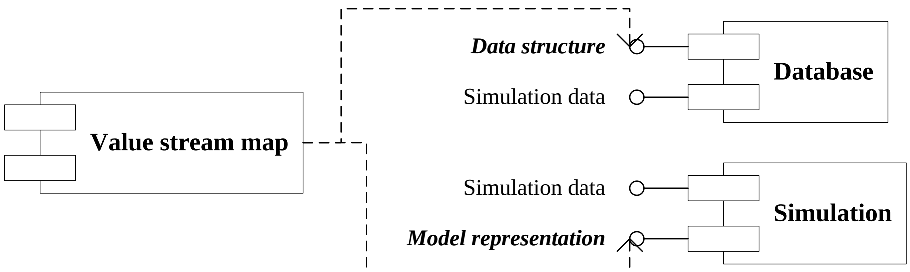


Figure 38: VSM interface function via UML component diagram

The proposed interface consists of three types of models: object model, activity model, and object state model. The object model is used to formally define the attributes of each type of objects (e.g. process, material/product, information, and performance measurement) in the physical system, and further define static model building blocks, dynamic objects (with attributes), global variables, statistics, and animation in simulation; the activity model is used to formalize information/material flow in the physical system and simulation; and the object state model is used to define the possible states of objects in the physical system and simulation. Figure 39 shows the object model developed in the Unified Modeling Language (UML) class diagram.

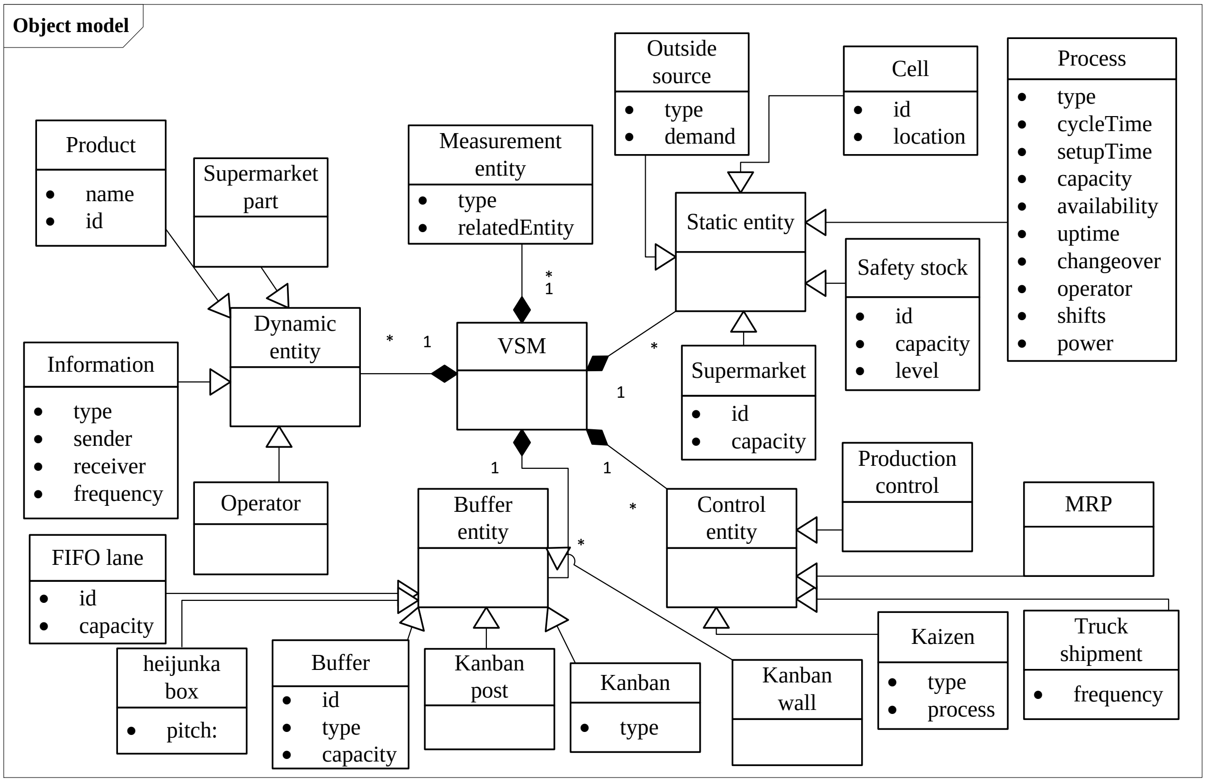


Figure 39: Object model for VSM interface

Currently, Microsoft Visio is a popular tool to electronically create value stream maps after hand drawing via the embedded Value Stream Mapping template. Figure 41 below shows an exemplary value stream created in Visio (current and future state maps). Especially, the future state map shown in Figure 41(b) is developed based on the future state map of Sargent south facility designed by the improvement team of Sargent (see Figure 40). Our proposed interface attempts to convert the value stream maps in Visio file to Extensible Markup Language (XML) and automatically generate discrete event simulation model based on the XML file.

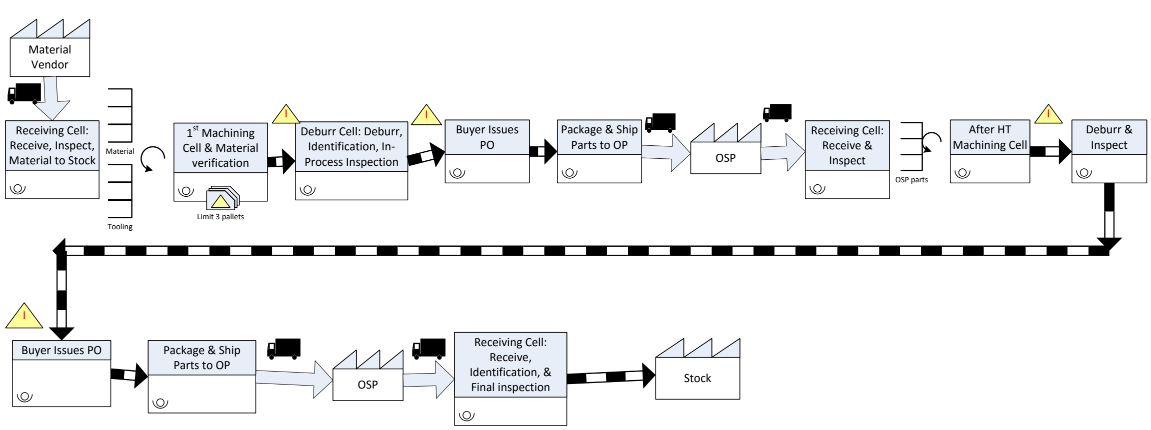
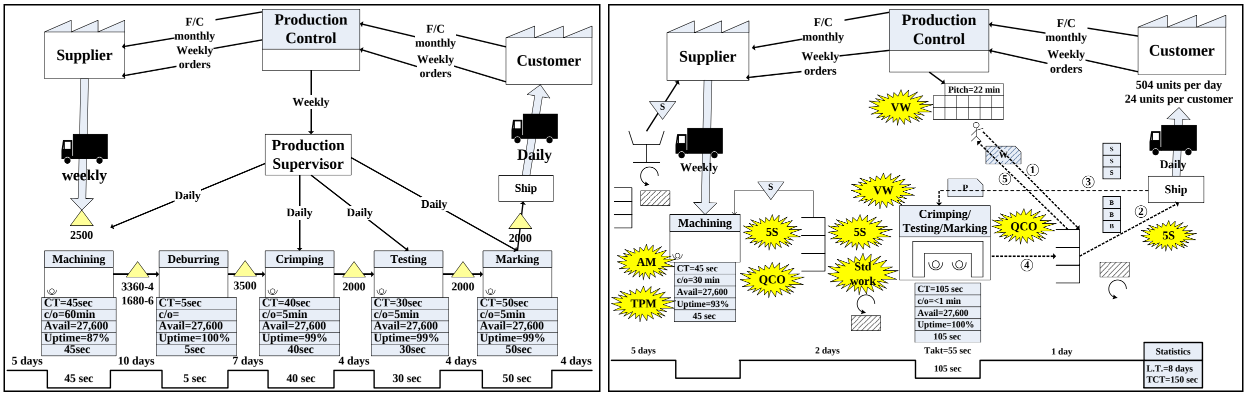


Figure 40: Future state map of Sargent south facility



(a) Current state map (b) Future state map

Figure 41: Value stream map used as test case

As shown in Figure 41(a), the system is using the push production mode since product demand is relatively stable. The raw material is transported to the company from a supplier, and put into raw material inventory. The entire production can be split into five processes, including machining, deburring, crimping, testing, and marking. Between processes, inventory is stored at different levels. Finished products are shipped to customers on a daily basis. In the future state map (see Figure 41(b)), the company implements JIT (just-in-time) production to its system by introducing Kanban, U-shape cell, and Kaizen activities. For production processes, deburring process is eliminated by improving programming and tooling maintenance. In addition, crimping, testing and marking processes are combined within one cell (see Tapping and Shuker (2003) for more information on the aforementioned production processes in the future state map).

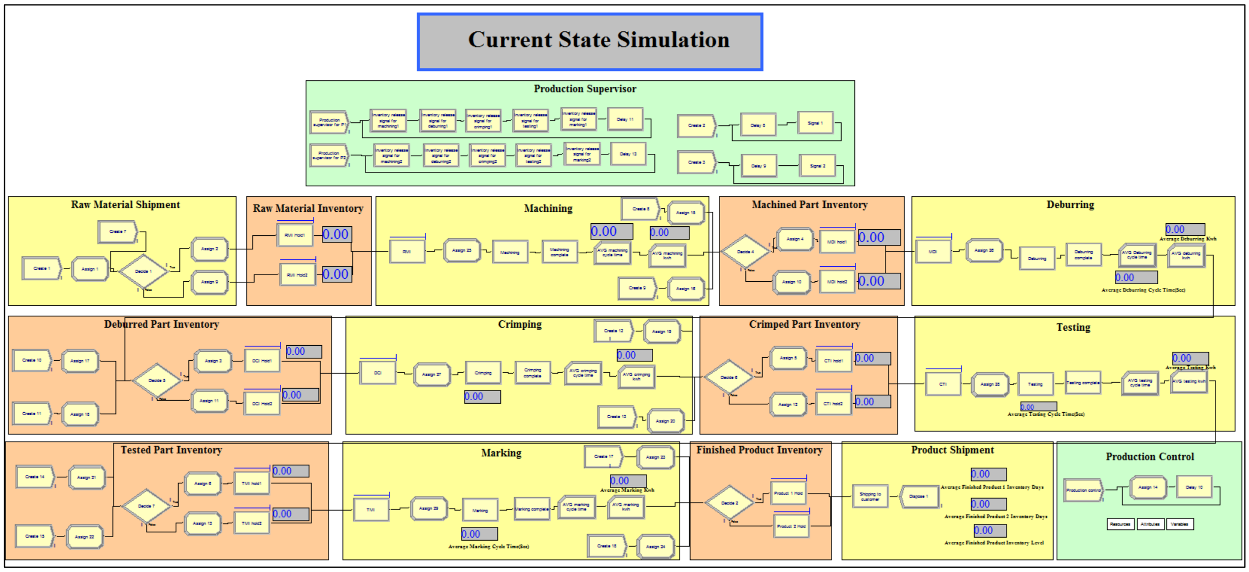
In order to construct a generic data structure in XML, we adopted Core Manufacturing Simulation Data (CMSD) for the translation from Visio file to XML file. Table 15 below shows one machining process data in CMSD.

Table 15: Process information in XML

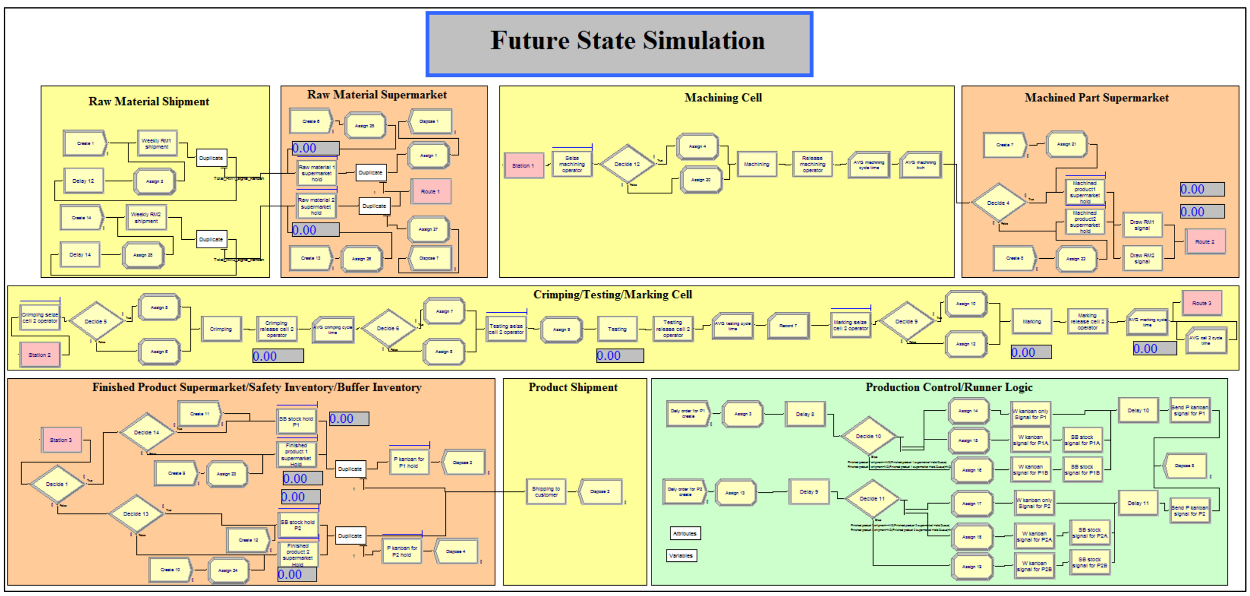
<Process>						
	<Identifier>	Machining	</Identifier>			
	<PredecessorProcess>	Inventory 1	</PredecessorProcess>			
	<SuccessorProcess>	Inventory 2	</SuccessorProcess>			
	<OperationTime>					
		<Unit>	second	</Unit>		
		<Value>	6	</Value>		
	</OperationTime>					
	<ResourceRequired>					
		<Description>	Operator	</Description>		
		<MinimumNumber>	1	</MinimumNumber>		
		<MaximumNumber>	1	</MaximumNumber>		
	</ResourceRequired>					
	<ResourceRequired>					
		<Description>	Machine 1	</Description>		
		<MinimumNumber>	1	</MinimumNumber>		
		<MaximumNumber>	1	</MaximumNumber>		
	</ResourceRequired>					
	<Property>					
		<Name>	Water usage	</Name>		
		<Unit>	gallon	</Unit>		
		<Distribution>				
			<Name>	Normal	</Name>	
			<DistributionParameter>			
				<Name>	mean	</Name>
				<Value>	6	</Value>
			</DistributionParameter>			

			<DistributionParameter>			
				<Name>	std	</Name>
				<Value>	2	</Value>
			</DistributionParameter>			
		</Distribution>				
	</Property>					
</Process>						

Based on the interface, we have developed a simulation model for the test case. The simulation model is developed in discrete event simulation software Arena®, and Figure 42 shows the snapshot of the simulation model involving the current state and future state.



(a) Simulation model for current state



(b) Simulation model for future state

Figure 42: Simulation model for the test case

8. Weather-dependent Energy Consumption Model

8.1. Regression Model with Historical Data

A typical manufacturing facility, the energy consumption by manufacturing processes and equipment is the largest contributor to the entire energy consumption of manufacturing facilities; and the energy consumed by the heating, ventilation, and air-conditioning (HVAC) system is considered the second largest contributor (EIA, 2002, Dababneh et al., 2016). The amount of energy consumption by HVAC system largely depends on outdoor air temperature. Especially, in the area with above-average temperatures like Tucson, the energy consumed by HVAC is highly related to the air conditioning system. Figure 43 shows the trends of the monthly energy consumption at Sargent and the average outdoor temperatures in 2 year period (2012 and 2013). They have similar tendency just except two months (April, 2012 and May, 2013) which are out of trend.

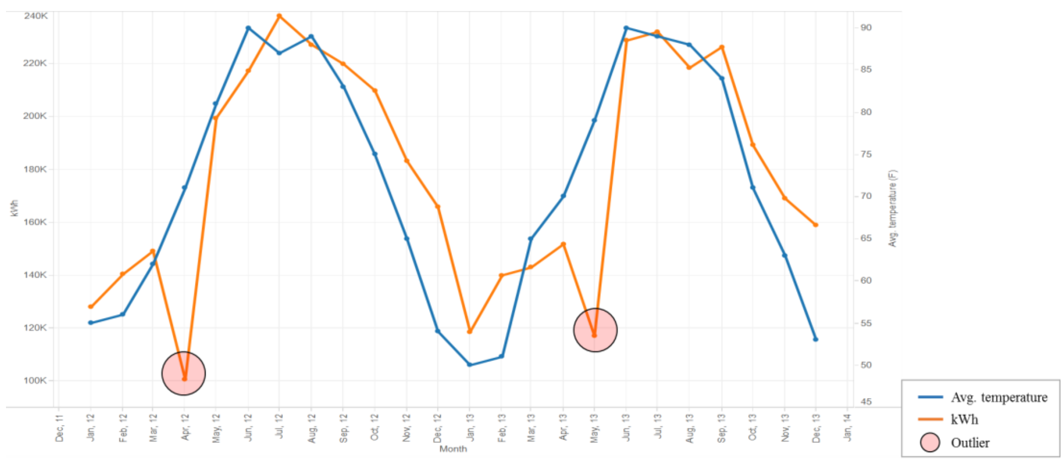


Figure 43: Monthly Energy Consumption Trends of Sargent (2012–2013)

Figure 44 presents the relationship between the electricity consumption and outdoor temperature during the same period. From this graph, the energy consumption of Sargent is closely affected by outdoor temperature, that is, electricity consumption is directly related to the ambient temperature.

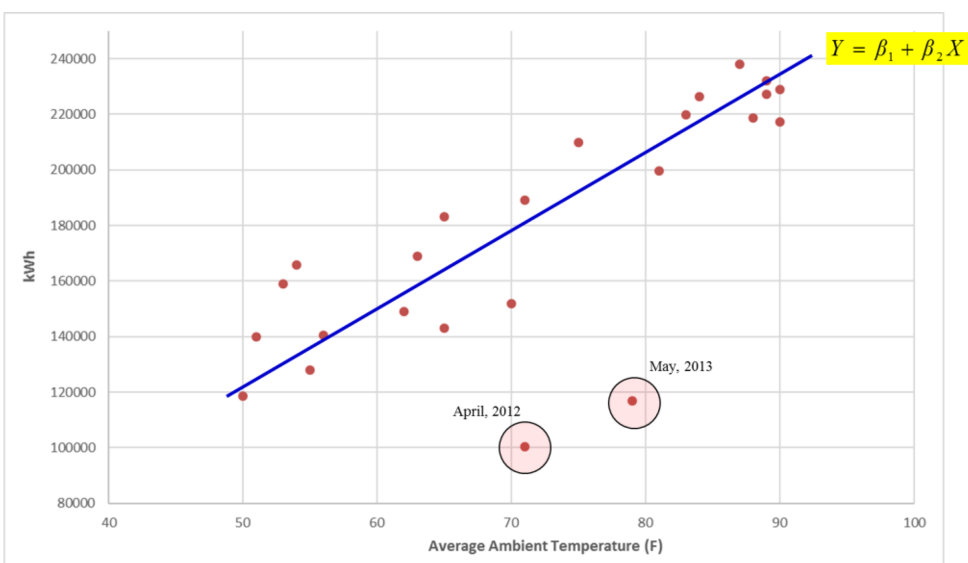


Figure 44: Relationship between the monthly energy consumption and trend of outdoor temperature

To figure out the linear relationship between energy consumption in Sargent and outdoor temperature, we applied a three-parameter cooling (3PC) change point model which is well known for describing weather dependency of energy use in typical industrial facilities (Kissock & Eger, 2008). Specifically, 3PC model is a regression model which can describe the common situation when cooling begins when the air temperature is more than some balance-point temperature (see Figure 45).

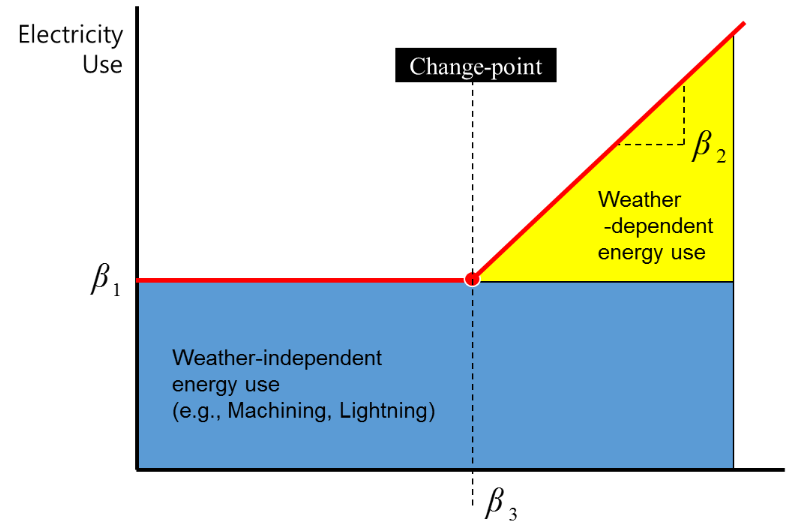


Figure 45: Three-parameter cooling (3PC) change point model

In this study, the cooling degree days (CDD)-based 3PC model has been adopted.

$$E = \beta_1 + \beta_2 CDD(\beta_3) \tag{8}$$

where β_1 is temperature-independent regression coefficient, β_2 is the rate of increment of electricity use with increasing temperature (i.e., slope of the regression model), β_3 is the change-point temperature where weather-dependent electricity use begins, and $CDD(\cdot)$ is the function of cooling degree days. The CDD function is as below:

$$CDD(\beta_3) = \sum_{i=1}^{n} (T_i - \beta_3)^+ \tag{9}$$

where T_i is the i^{th} average daily temperature.

To develop the weather-dependent energy consumption model by applying CDD-3PC model, two kinds of datasets are required: 1) monthly utility billing data at least 1 year period which had gathered during Year 1 project, 2) historical daily mean temperature during the billing period to calculate CDD. The billing data had gathered during Year 1 project, and the historical temperature data of Tucson area have collected from National Weather Service Forecast Office website. The general setting for this regression analysis has followed the standard from American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2002).
The procedure to identify the best fit model for daily power consumption are as follows:

1) Increase the base temperature (β_3) from 55ºF - 65ºF to calculate $CDD(\beta_3)$
2) Normalize the billing data to find an average kWh per day in each billing period
3) Normalize CDD to find an average CDD per day in each billing period
4) Find β_1 and β_2 to calculate R^2 and *CV-RMSE*
5) Choose the regression model with the highest R^2 and lowest *CV-RMSE*. If R^2 values for all models are very high (or low), *CV-RMSE* is to be given more consideration

Table 16 shows the result of the univariate regression analysis by following the aforementioned procedure.

Table 16: Result of the univariate regression analysis

Billing Month	Billing Duration	Billed kWh	Avg. kWh per Day	**CDD 55 (per Day)**	CDD 56 (per Day)	CDD 57 (per Day)	CDD 58 (per Day)	CDD 59 (per Day)	CDD 60 (per Day)	CDD 61 (per Day)	CDD 62 (per Day)	CDD 63 (per Day)	CDD 64 (per Day)	CDD 65 (per Day)
1/2012	31	127,940	4,127	**2.4**	2.1	1.9	1.7	1.5	1.3	1.1	1.0	0.8	0.7	0.6
2/2012	31	140,380	4,528	**3.5**	3.1	2.7	2.4	2.1	1.8	1.5	1.3	1.1	0.9	0.7
3/2012	29	149,160	5,143	**4.7**	4.2	3.8	3.4	3.0	2.7	2.3	2.0	1.8	1.5	1.3
5/2012	30	199,520	6,651	**18.2**	17.3	16.4	15.5	14.7	13.8	13.0	12.2	11.5	10.7	10.0
6/2012	31	217,280	7,009	**26.5**	25.5	24.5	23.5	22.5	21.6	20.6	19.7	18.7	17.8	16.9
7/2012	30	238,060	7,935	**33.3**	32.3	31.3	30.3	29.3	28.3	27.3	26.3	25.3	24.4	23.4
8/2012	31	227,280	7,332	**29.5**	28.5	27.5	26.5	25.5	24.5	23.5	22.5	21.5	20.5	19.5
9/2012	31	219,880	7,093	**31.5**	30.5	29.5	28.5	27.5	26.5	25.5	24.5	23.5	22.5	21.5
10/2012	30	209,940	6,998	**25.6**	24.6	23.6	22.6	21.6	20.6	19.6	18.6	17.6	16.6	15.6
11/2012	31	183,260	5,912	**16.7**	15.7	14.8	13.9	13.0	12.2	11.3	10.5	9.8	9.1	8.4
12/2012	30	165,800	5,527	**9.2**	8.5	7.8	7.2	6.6	6.1	5.6	5.1	4.6	4.1	3.7
1/2013	31	118,560	3,825	**2.2**	1.9	1.7	1.5	1.3	1.1	1.0	0.8	0.7	0.6	0.5
2/2013	31	139,980	4,515	**3.4**	3.0	2.6	2.3	2.1	1.8	1.6	1.3	1.1	1.0	0.8
3/2013	28	142,960	5,106	**3.5**	3.2	2.9	2.6	2.3	2.0	1.8	1.6	1.3	1.2	1.0
4/2013	31	151,740	4,895	**12.7**	11.9	11.1	10.4	9.7	9.0	8.3	7.7	7.1	6.5	6.0
6/2013	31	228,800	7,381	**26.4**	25.4	24.4	23.4	22.4	21.4	20.4	19.4	18.4	17.5	16.5
7/2013	30	232,100	7,737	**36.1**	35.1	34.2	33.1	32.1	31.1	30.1	29.2	28.1	27.1	26.1
8/2013	31	218,540	7,050	**31.7**	30.7	29.7	28.7	27.7	26.7	25.7	24.7	23.7	22.7	21.7
9/2013	31	226,380	7,303	**31.5**	30.5	29.5	28.5	27.5	26.5	25.5	24.5	23.5	22.5	21.5
10/2013	30	189,200	6,307	**26.6**	25.6	24.6	23.6	22.6	21.6	20.6	19.6	18.7	17.7	16.7
11/2013	31	169,060	5,454	**14.2**	13.3	12.5	11.7	10.9	10.2	9.4	8.7	8.1	7.4	6.8
12/2013	30	158,860	5,295	**8.2**	7.5	6.8	6.2	5.6	5.1	4.6	4.1	3.6	3.2	2.9
Gradient				**99.729**	101.836	104.161	106.687	109.416	112.399	115.628	119.138	122.986	127.218	131.860
Intercept				**4248.582**	4289.386	4327.870	4365.050	4401.609	4436.758	4471.462	4505.286	4537.810	4569.037	4599.281
RSQ				**0.910**	0.909	0.907	0.906	0.904	0.902	0.900	0.897	0.895	0.892	0.888
CV-RMSE (%)				**6.107**	6.144	6.188	6.239	6.300	6.362	6.435	6.514	6.604	6.696	6.791

The base temperature (i.e., β_3) for the best fit model is 55ºF, and the best-fit-model is:

$$E_{day} = 4248.582 + 99.729 * CDD(55) \tag{10}$$

However the outdoor temperature is not only independent variable as a predictor of energy consumption. Therefore Dr. Son's team has extend the regression analysis to the multi-variable case. Generally, humidity, wind speed, and the amount of cloud cover are well known independent variable which affect the energy consumption of the building (ASHRAE, 2002). In order to develop the more accurate regression model with multiple predictors, the historical weather data for the additional independent variables (i.e., humidity, wind speed, and cloud cover) have been collected from "Weather Underground" website (www.wunderground.com), and the correlation analysis has been implemented to find the significant predictors. Table 17 shows the correlation matrix for all of additional independent variables and the energy consumption of Sargent.

Table 17: The correlation matrix for the independent variables and the energy consumption

Variable	Humidity (%)	Wind Speed (*mph*)	Cloud Cover (*okta*)
kWh per Day	-0.4313**	0.444*	0.0847

**Correlation is significant at the 0.01 level (two-tailed)
*Correlation is significant at the 0.05 level (two-tailed)

Except the amount of cloud cover, both the humidity and the wind speed are very significant predictors of energy consumption in Sargent. Based on this result, the multi variable regression analysis has been implemented by varying the CDD (the base temperature: 55ºF - 65ºF), and Dr. Son's team has found that CDD 60 (i.e., the base temperature is 60ºF) is the most significant with other factors to predict the energy consumption in Sargent. Tables 18 shows ANOVA test results of the multi-variable regression for CDD 60 and other factors.

Table 18: ANOVA test of the multi-variable regression with CDD 60

Model	Sum of Squares	*df*	Mean Square	*F*	Significance
Regression	3.1214×10^{7}	3	1.0405×10^{6}	89.779	5.09×10^{-11}
Residual	2.0860×10^{6}	18	1.1589×10^{5}		
Total	3.3300×10^{7}	21			

And the weather-dependent daily (see Eq. (11)) and hourly (see Eq. (12)) energy consumption model of Sargent are as follows:

$$E_{day} = 8097.612 + 116.902 * CDD(60) - 19.991 * H - 415.971 * W \tag{11}$$

$$E_{hour} = 337.400 + 4.870 * CDD(60) - 0.833 * H - 17.332 * W \tag{12}$$

where *CDD*(60) is the value of CDD with the base temperature 60ºF, *H* is the humidity (%), and *W* is the wind speed (mph).
To complete development of the model and check the bias, the modeled values for kWh per day are multiplied by the number of days in the billing period. And then, the net determination bias error (NBE) has been calculated as below:

$$NBE = 100 * \frac{\sum_i \left(E_i - \hat{E}_i \right)}{\sum_i E_i} \tag{13}$$

From ASHRAE Guideline, only a model with bias>0.005% is accepted, and the NBE of the current model is 0.0008%. That is, this proposed model is very acceptable so that it can be utilized to estimate the weather-dependent energy consumption in Sargent.

8.2. What-If Analysis

To show the utility of the developed weather-dependent energy consumption model, Dr. Son's team has performed what-if analysis based on the historical weather data from "Weather Underground" website. Since the indoor thermostat setting of air conditioner determines the change-point in 3PC model, the team has analyzed how much energy can be saved by increasing the temperature-setting of AC in Sargent. Two extreme cases in weather, that is the middle of summer and the middle of winter, have been used in this analysis. Tables 19 and 20 respectively show the historical hourly weather data on June 16, 2015 (for midsummer case) and December 1, 2015 (for midwinter case).

Table 19: Historical weather data on June 16, 2015 for midsummer case

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm
Temperature (ºF)	90	92	95	98	100	101	103	104	105	104	103	102
Humidity (%)	23	19	19	16	15	13	12	11	10	9	8	8
Wind Speed (mph)	1	2	2	6	3	5	8	2	10	14	16	14
Time	8pm	9pm	10pm	11pm	12am	1am	2am	3am	4am	5am	6am	7am
Temperature (ºF)	100	92	90	88	83	83	82	79	79	76	77	82
Humidity (%)	11	24	26	28	27	32	35	39	39	41	38	33
Wind Speed (mph)	6	15	16	12	12	10	10	10	6	7	8	10

Table 20: Historical weather data on December 1, 2015 for midwinter case

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm
Temperature (ºF)	35	43	50	58	62	67	69	69	68	65	58	56
Humidity (%)	43	33	25	17	17	12	10	11	11	14	18	19
Wind Speed (mph)	3	1	2	5	5	7	5	9	3	6	6	6
Time	8pm	9pm	10pm	11pm	12am	1am	2am	3am	4am	5am	6am	7am
Temperature (ºF)	50	46	46	51	48	50	48	51	50	48	49	49
Humidity (%)	24	26	26	22	23	23	24	21	20	22	20	20
Wind Speed (mph)	7	7	13	10	15	14	12	15	13	12	12	13

In this experiment, the team compared the cost-saving effect between summer and winter season by changing the base temperature from 60ºF (current setting) to 61ºF. It was assumed that the amount of production is same in both cases (i.e., same amount of energy for production is used). For the electricity price, we adopted the summer and winter rate under TOU (see Table 21). Table 22 shows the electricity bills for both season under the temperature setting of 60ºF and 61ºF. Through an increase of on degree in the base temperature, Sargent can achieve $ 14.1 daily saving in summer and $ 2.8 in winter.

Table 21: Electricity rate for TOU

Time	Summer (May-Sep.)		Winter (Oct.-Apr.)	
	On-peak (2pm-8pm)	Off-peak (other times)	On-peak (6am-10am & 5pm-9pm)	Off-peak (other times)
Price ($/kWh)	0.1494	0.1112	0.1139	0.0916

Table 22: Daily electricity cost in midsummer and midwinter

Time	Midsummer (Jun. 16, 2015)		Midwinter (Dec. 1, 2015)	
	Setting = 60ºF	Setting = 61ºF	Setting = 60ºF	Setting = 61ºF
Electricity Cost ($)	953.4	939.3 (▼14.1)	438.6	435.8 (▼2.8)

Appendix A

Summary of Achievements

Item	Year 1	Year 2	Year 3
Knowledge-based Optimization Program		• Generic energy consumption prediction model developed	• Knowledge-based Optimizer developed • Implementation guide developed
Sensors	• Power meter installed at Sargent • Refractometer system developed	• Refractometer system installed at Sargent	• Thermal sensing system developed
Real-time data Acquisition & Monitoring System	• MySQL database and communication server program developed • Mobile application developed	• Mobile application delivered to Sargent	• Data acquisition and storing system with MTConnect standard developed - MTConnect Adapters for proposed sensors developed - Open-source MTConnect Agent customized and installed - MTConnect compatible database developed • Mobile application upgraded - Thermal sensor section added - Communication protocol added • Implementation guide developed
Simulation	• Shop operation simulation developed • Cost saving with optimized schedule and turn-on sequence demonstrated	• Simulation-based optimization tool with VSM developed	• Weather-dependent energy consumption model developed
Data Collection	• Machine shop layout • Equipment specification • Monthly utility bill • Coolant information & samples	• Samples for implemented power meter and refractometer system • Current and future state maps	

Appendix B

Implementation of MTConnect® Standard

Contents

Section I. General Features of MTConnect®

1. Overview: Why MTConnect?

MTConnect® is a set of Open, Extensible, and Royalty-free factory floor communications standards intended to foster higher interoperability between controls, devices and software applications by publishing data over networks using the Internet Protocol. **The Association for Manufacturing Technology** ("AMT") owns the copyright in this standard.

While there are various kind of communication platforms and solutions available for the shop floor, MTConnect offers one distinct difference: **It is the first standard to define a "Dictionary" for manufacturing data** (MTConnect Institute, 2011)**.** This means that data from various types of machines will have a common definition by the dictionary: name, units, values, and context.

Traditionally, the challenges in monitoring a shop floor has been that each vendor of a machine tool or piece of manufacturing equipment would speak a unique "language", so that we repeatedly make the efforts to define the data for each application even if we attempt to use same data for more than one application. This increases installation costs and time, increases long term costs to maintain, and introduces a level of complexity that leads to errors and system failures.
All of this problems can be resolved with the introduction of new shop floor standard called MTConnect. MTConnect is the tool that translates the information obtained from a given machine tool and equipment into a common language. Once the data is defined based on this Internet standard protocol, **it can then easily be used by all MTConnect compliant applications**. In common with the **"Bluetooth"**, MTConnect is not an application but rather a common translator that allows any machine in a plant to easily talk to any kinds of applications, so that users know that what is happening on their shop floor and can use such information to make changes to be more productivity (MTConnect Institute, 2013).

MTConnect standard is not a static document. A significant number of committees are continuing the development and extension of the standard to address new application areas for the shop floor. These committees are working on Robotics/Machine Loading, Sensors, Tooling, EDM machining, Machine Accessories, Alarming and Notification, and Software Application development. The availability of equipment and software applications based on MTConnect will continue to expand based on the level of demand for these products.

Some of the common uses of data obtained via MTConnect are as below:

- Production Dashboard or Monitor
- Alerts
- Availability/Usage of Equipment
- Overall Equipment Effectiveness
- Energy Conservation
- Quality and Statistical Process Control

2. Fundamental Components of MTConnect

2.1. Device

- Commonly a **machine tool**, but can be any piece of data source (e.g., sensors, human input devices)

2.2. Adapter

- A piece of **software** (and sometimes hardware) that **provides a link** or conversion from the data source (i.e., machine tool or sensor) and proprietary data definition in the Device to the MTConnect Data definition
- Working as a **translator**
  - ➔ If the devices use MTConnect as their native language, the adapter is NOT needed

2.3. Agent

- A piece of **software** that **collects, arranges, and stores data** from the adapter (or the device)
- It is a part of the communication system that is specifically defined by the MTConnect standard
- It contains MTConnect **data dictionary** (i.e., XML schemas)
- When the agent receives requests for data from applications (or users), it processes those requests and transmits them

2.4. Network

- The physical connection between a data sources and the data consumer (i.e., application).
- Typically, Ethernet network
- Communication on the network normally uses HTTP protocol standard

2.5. Application (or Client)

- Actual requester and consumer of MTConnect data
- Typical functions: request (from Agent), store, manipulate, and display data

3. General Types of Devices

3.1. MTConnect Native Devices

- Devices that are provided with MTConnect functions and the data dictionary
- They are capable to be connected to a network and MTConnect applications without additional components: they naturally communicate using MTConnect standard.

3.2. MTConnect Translation Dependent Devices → Thermometer

- Devices that require Translation unit (S/W and/or H/W) to translate data from the native language of the devices
- Adapter/Agent are needed: data needs to be translated into the MTConnect standard dictionary

3.3. MTConnect Data Connection Dependent Devices → Refractometer

- Devices that do not normally provide data
- Adapter/Agent are needed: data should be collected from the device and translated into the MTConnect standard dictionary

4. Data Model

MTConnect uses an XML data model to describe a piece of equipment and to provide relevance for each piece of data communicated using MTConnect standard.

4.1. Terminology

- **Component**: A part of a device that can have sub-components and data items. A component is a basic building block of a device
- **DataItem**: descriptive information regarding something that can be collected by Agent
- **Event**: A change in state that occurs at a point in time
- **Sample**: A data point from within continuous series of data points. (e.g., position of axis)
- **Socket**: When used concerning inter-process communication, it refers to a connection between two end-points (usually processes). Socket communication most often uses TCP/IP as the underlying protocol
- **Stream**: A collection of Events, Samples, and Condition organized by devices and components
- **XML Schema**: The definition of the XML structure and vocabularies used in the XML Document
- **XML Document**: An instance of an XML Schema which has a single root XML element and conforms to the XML specification and schema

4.2. Root Elements

4.2.1. MTConnectDevices

- Meta data about the device – changes very infrequently
- Specifying data items that are available from the device

4.2.2. MTConnectStreams

- Time-series of values from devices and their components – changes very frequently

4.2.3. MTConnectAssets

- Information pertaining to a machine tool asset – changes fairly frequently
- It provides a place to store and communicate rich domain models such as Cutting tools, Parts, Inspection/Verification, Coordinate system transformations, and so on

4.2.4. MTConnectError

- Information about an error that occurred in processing the request

4.3. Data Item Categories

4.3.1. SAMPLE (63 items)

- Data that represents a continuously changing or analog data value
- Scalar floating point number or Integers
- MUST have units (e.g., TEMPERATURE is Celsius, POSITION is Millimeters)
- Example:

```
<DataItem category="SAMPLE" coordinateSystem="WORK" id="pf“ name="Fact"
ativeUnits="FOOT/MINUTE“ subType="ACTUAL" type="PATH_FEEDRATE"
units="MILLIMETER/SECOND"/>
```

4.3.2. EVENT (58 items)

- State of a particular data item or a discrete message/count
- Does not have intermediated values
- When it provided at any specific point in time, it represents the current state of the device
- Example:

```
<DataItem category="EVENT" id="mode" name="mode" type="CONTROLLER_MODE"/>
<DataItem category="EVENT" id="pc1" name="pc" type="PART_COUNT"
representation="DISCRETE"/>
```

4.3.3. CONDITION (43 items)

- Data that represents a structural element's status or ability to operate
- MUST be reported as [*NORMAL*, *WARNING*, *FAULT*, or *UNAVAILABLE*]
  or [*LOW*, *NORMAL*, or *HIGH*]
- Some DataItems in SAMPLE and CONDITION category have associated CONDITION
  e.g., *TEMPERATURE*: 50 – 200 → *NORMAL*, 200 – 300 → *WARNING*
- Example:

```
<DataItem category="CONDITION" id="c1sc" name="spt_cond" type="TEMPERATURE">
<Source dataItemId="c1t" />
</DataItem>
…
<DataItem category="SAMPLE" id="c1t" name="c_temp" type="TEMPERATURE" units="CELSUIS"/>
```

4.4. XML Structure of Root Elements

4.4.1. MTConnectDevices

- XML structure:

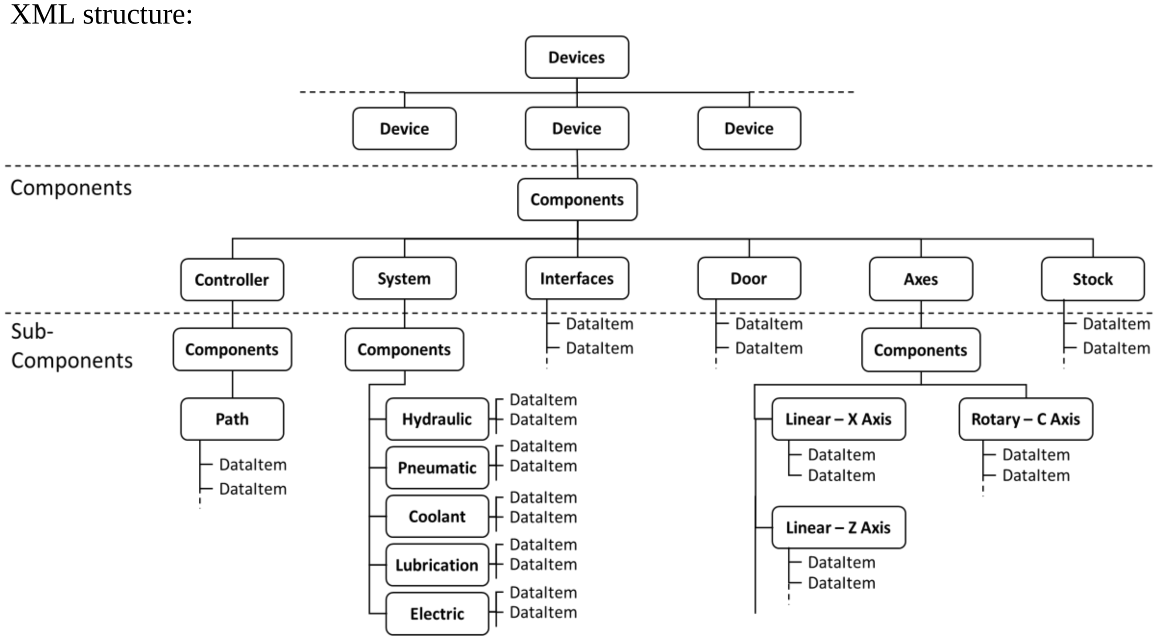


Figure B1: The structure of MTConnectDevice XML schema

- ***Devices***: the top level XML container element in MTConnectDevices document for organizing data from one or multiple devices into a single XML document. MUST always appear in the document and MUST contain at least one *Device* element.
- ***Device***: the primary container type element for holding all the elements associated with single device. At least one *Device* MUST always appear in the document.
- ***Components***: the container type element for organizing information representing each of the physical or logical parts of a *Device*. Only one *Components* container MAY appear for a *Device* element.
- ***Component***: the abstract type element (i.e., will never appear directly) for defining the structure of the physical parts of a *Device* and the association of the data.
    - ***Controller***: The intelligent or computational part of a *Device* which monitors and calculates information
    - ***Systems***: Structural elements describing the major sub-systems that provide services
    - ***Interface***: The information used to coordinate actions and activity between devices or sub-systems and a *Device*
    - ***Door***: Mechanisms or closures that can cover access portals into a *Device*
    - ***Axes***: Structural elements that perform linear or rotational motion.
    - ***Stock***: The material to which work is applied in a machine or piece of equipment to product to produce part(s).
- ***DataItem*** (for *Component*): the abstract type element for providing a detailed description for each piece of data collected from a *Device*.
- Example of **"MTConnectDevices"** document:


```
<MTConnectDevices xmlns:xsi='http://www.w3.org/2001/XMLSchemainstance'
  xmlns='urn:mtconnect.org:MTConnectDevices:1.3' xmlns:m='urn:mtconnect.org:MTConnectDevices:1.3'
  xsi:schemaLocation='urn:mtconnect.org:MTConnectDevices:1.3 /schemas/MTConnectDevices_1.3.xsd'>
  <Header creationTime='2015-02-10T10:04:55Z' assetBufferSize='1024' sender='localhost'
  assetCount='0' version='1.3' instanceId='0' bufferSize='524288'/>
    <Devices>
      <Device name='INDEX-200' uuid='ee44f744-0a4a-11e5-85ff-28cfe91a82ef' id='INDEX-200'>
      <Description model='C200' manufacturer='Index'>Index C200 - Machine #200</Description>
        <DataItems>
          <DataItem type='AVAILABILITY' category='EVENT' id='dtop_5001' name='avail'/>
          <DataItem type='EMERGENCY_STOP' category='EVENT' id='dtop_5002' name='estop'/>
          <DataItem type='SYSTEM' category='CONDITION' id='dtop_5003' name='alarm'/>
        </DataItems>
          <Components>
          <Axes name='axes' id='axes_5004'>
            <Rotary name='C4' nativeName='S4' id='C4_5007'>
              <DataItems>
                <DataItem type='x:MOTION' category='EVENT' id='C4_5008' name='s4_motion'
                subType='ACTUAL'/>
                <DataItem category="SAMPLE" id="c2" name="Sspeed" nativeUnits="REVOLUTION/
              MINUTE" subType="ACTUAL" type="SPINDLE_SPEED" units="REVOLUTION/MINUTE"/>
              </DataItems>
            </Rotary>
```

4.4.2. MTConnectStreams

- XML Structure:

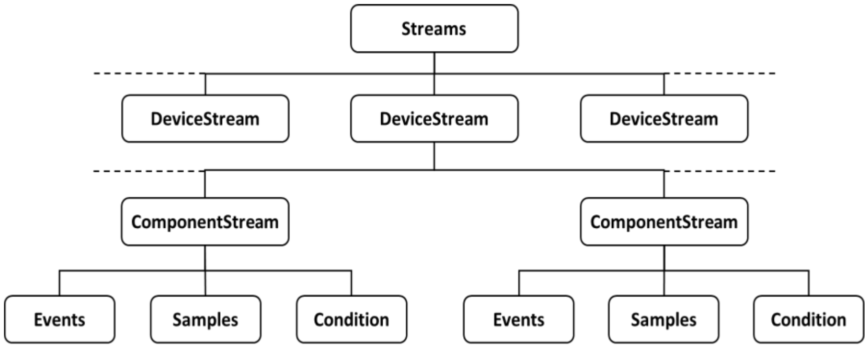


Figure B2: The structure of MTConnectStreams XML schema

- ***Streams***: the top level XML container element in MTConnectStreams document. MUST always appear in the document and MUST contain at least one *DeviceStream* element.
- ***DeviceStream***: the container type element which provides data from a device and the information. If data is provided for a device, it MUST be organized in a *ComponentStream* element. Even though there was no data available, an empty *DeviceStream* element MUST be created to indicate that the device exists.
- ***ComponentStream***: the container type element which organizes data for a specific structural element of a device. It MUST NOT be empty – at least one for each type of data item (i.e., SAMPLE, EVENT, and CONDITION) MUST be provided.
- Example of **"MTConnectStreams"** document:

```
<MTConnectStreams xmlns:m="urn:mtconnect.org:MTConnectStreams:1.3" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance" xmlns="urn:mtconnect.org:MTConnectStreams:1.3"
xsi:schemaLocation="urn:mtconnect.org:MTConnectStreams:1.3 ../../MTConnectStreams_1.3.xsd">
  <Header creationTime="2010-03-04T18:58:50+00:00" sender="localhost" instanceId="1267728234" bufferSize="131072"
  version="1.1" nextSequence="183806" firstSequence="52734" lastSequence="183805" />
    <Streams>
      <DeviceStream name="VMC-3Axis" uuid="000">
        <ComponentStream component="Rotary" name="C" componentId="c1">
          <Samples>
            <SpindleSpeed dataItemId="c2" name="Sspeed" sequence="135230" subType="ACTUAL" timestamp="2010-03-
            04T18:54:11.677212">3400.0000000000</SpindleSpeed>
          </Samples>
          <Events>
            <RotaryMode dataItemId="cm" name="Cmode" sequence="2" timestamp="2010-03-
            04T18:43:54.178023">SPINDLE</RotaryMode>
          </Events>
          <Condition>
            <Normal dataItemId="Cload" sequence="62" timestamp="2010-03-04T18:44:24.187733" type="LOAD" />
          </Condition>
        </ComponentStream>
        <ComponentStream component="Path" name="path" componentId="pth">
          <Samples>
            <PathFeedrate dataItemId="Fovr" sequence="55" timestamp="2010-03-
            04T18:44:24.187733">100.0000000000</PathFeedrate>
            <PathFeedrate dataItemId="Frt" sequence="183801" timestamp="2010-03-04T18:58:50.749116">0.4</PathFeedrate>
            <PathPosition dataItemId="Ppos" sequence="3" subType="ACTUAL" timestamp="2010-03-
            04T18:43:54.178023">UNAVAILABLE</PathPosition>
          </Samples>
          <Events>
            <Block dataItemId="cn2" name="block" sequence="183791" timestamp="2010-03-04T18:58:50.689112">X0.327005
            Y-0.359532</Block>
            <ControllerMode dataItemId="cn3" name="mode" sequence="53" timestamp="2010-03-
            04T18:44:24.187733">AUTOMATIC</ControllerMode>
            <Line dataItemId="cn4" name="line" sequence="183786" timestamp="2010-03-04T18:58:50.689112">764</Line>
            <Program dataItemId="cn5" name="program" sequence="52" timestamp="2010-03-
            04T18:44:24.187733">FLANGE_CAM.NGC</Program>
            <Execution dataItemId="cn6" name="execution" sequence="178023" timestamp="2010-03-
            04T18:58:27.319781">ACTIVE</Execution>
          </Events>
        </ComponentStream>
```

5. Communication Protocol

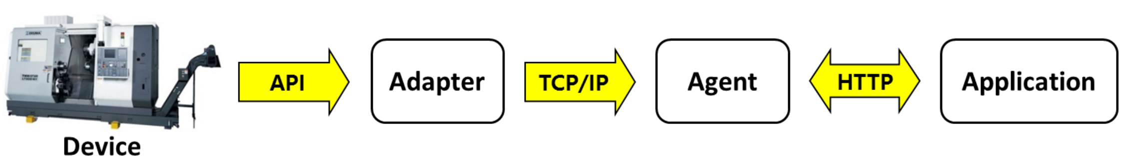
5.1. Fundamental of MTConnect Protocol

- The adapter is responsible for receiving the required data from devices and making it available for the agent. The agent grabs the structured data being relayed by the adapter and transforms and publishes it in the MTConnect standard (XML formatted) whenever required. The MTConnect compliant data thus output by the agent can then be utilized by external applications for further processing and analysis.
- MTConnect Agent is a special purpose HTTP server
- The MTConnect Agent has a responsibility to collect and deliver data from devices to applications
- MTConnect uses REST semantics

> **REST** (**RE**presentational **S**tate **T**ransfer) is web standards based architecture and uses HTTP Protocol for data communication. It revolves around resource where every component is a resource and a resource is accessed by a common interface using HTTP standard methods. A REST Server simply provides access to resources and REST client accesses and presents the resources. REST uses various representations to represent a resource like text, JSON and XML. The use of REST is often preferred over the more heavyweight SOAP (Simple Object Access Protocol) style because REST does not leverage as much bandwidth, which makes it a better fit for use over the Internet.

➔ Agent is unaware of the applications state: it is the responsibility of the application to maintain the current read position or next operation. This removes the Agent's burden of keeping track of application sessions.

- Communications between components



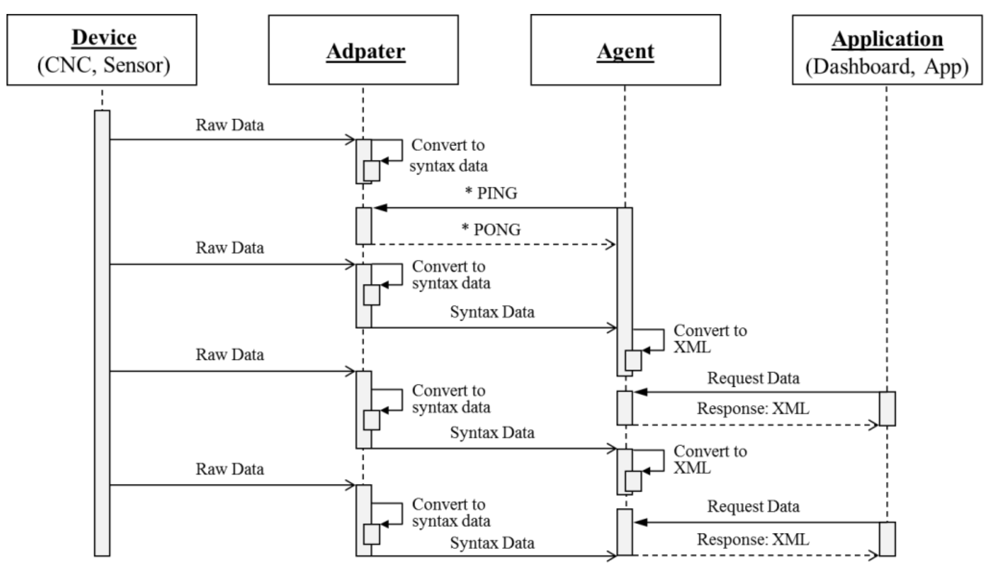


Figure B3: Time sequence diagram of the communication between MTConnect components

- Device continually sends raw data to Adapter through the proprietary or user-defined API
    - Adapter converts raw data to syntax data
    - After Adapter open its Socket, Agent connects to Adapter by “PING-PONG” communication
    - Agent continually check the connectivity with Adapter at pre-defined time interval (Heartbeats)
    - Agent converts syntax data to XML and store it
    - Application sends a request to Agent, which returns the data with XML

5.2. The requirements for Agent

- MUST support HTTP version 1.0 or greater
- MUST support **HTTP GET** verb
  ➔ If the HTTP GET is not used, Agent MUST respond with a “HTTP 400 Bad request”
- The response to a HTTP request MUST be with XML
- The only information the Agent MUST consider is the **URI** in the HTTP GET

> **URI** (**U**niform **R**esource **I**dentifier) is a string of characters used to identify a name or a resource on the Internet. A URI identifies a resource either by location, or a name, or both. A URI has two specializations known as URL and URN.

- HTTP requests to Agent SHOULD NOT include a body: if Agent receives a body, Agent ignores
- Agent ignores any cookies or additional information
- **Heartbeat**
    - Agent will automatically wait up to heartbeat interval for data to arrive from Adapter
    - When there is no data to send (SAMPLE only), an empty stream (Only includes Header) will be sent

5.3. Agent – Application Communication

5.3.1. Standard HTTP Requests from Application

5.3.1.1. *probe*

- to retrieve components and data items for the device
- Returns **“MTConnectDevices”** XML document
- All devices: http://[*domain*:*port*]/probe
  Single device: http://[*domain*:*port*]/[*device_name*]/probe
- Every time reconnect to the Agent, it is suggested *probe* first
- Use “***intanceId***” to detect the change of “MTConnectDevices”

```
<Header creationTime="2015-06-07T04:38:22Z" sender="mtcagent" instanceId="1425445166"
version="1.3.0.9" bufferSize="131072" />
```

5.3.1.2. *current*

- to retrieve the snapshot of the latest values of all the data items or the state of the device at a point in time
- Returns **“MTConnectStreams”** XML document. For a continuous stream of data, MUST use “**nextSequence**” number in XML Header

- All devices: http://[*domain*:*port*]/current
  Single device: http://[*domain*:*port*]/[*device_name*]/current
- SAMPLEs, EVENTs, and CONDITION returned from *current* request MUST have the **timestamp** and the **sequence number** that was assigned at the time the data was collected
- Allow rollback of history to view state at that point of time
- Parameters (optional) for filtering (use XPath standard from W3C)
  - *path*: specifies a component or sub-component (default: all components)
  - *at*: specifies MTConnect protocol sequence number (default: latest value)
  - *interval*: milliseconds time interval between requests
- Example:

  http://10.0.1.23:3000/mill-1/current?path=//Axes//DataItem[@type="POSITION"and @ subType="ACTUAL"]&at=1232

  ➔ retrieves all axes' actual positions at sequence number 1232

5.3.1.3. *sample*

- to retrieve the SAMPLEs, EVENTs, and CONDITION in time series
- Returns **"MTConnectStreams"** XML document. For a continuous stream of data, MUST use "**<u>nextSequence</u>**" number in XML Header
- All devices: http://*domain*:*port*/sample
  Single device: http://*domain*:*port*/*device_name*/sample
- By default, *sample* will start from the first item
- Parameters (optional) for filtering (use XPath standard from W3C)
  - *path*: same as *current*
  - *from*: beginning sequence number of stream
  - *count*: return at most this number of items at a time (default: 100)
- Example

  http://10.0.1.23:3000/mill-1/sample?path=//Axes//DataItem[@type="POSITION"and @ subType="ACTUAL"]&from=50&count=200

  ➔ retrieves all axes' actual positions from sample 50 to sample 250

5.3.1.4. *asset*

- to request the most recent state of an asset known to this device

5.3.2. Streaming

5.3.2.1. **Pull-based**: *probe* → *current* → *sample* → *sample* → …

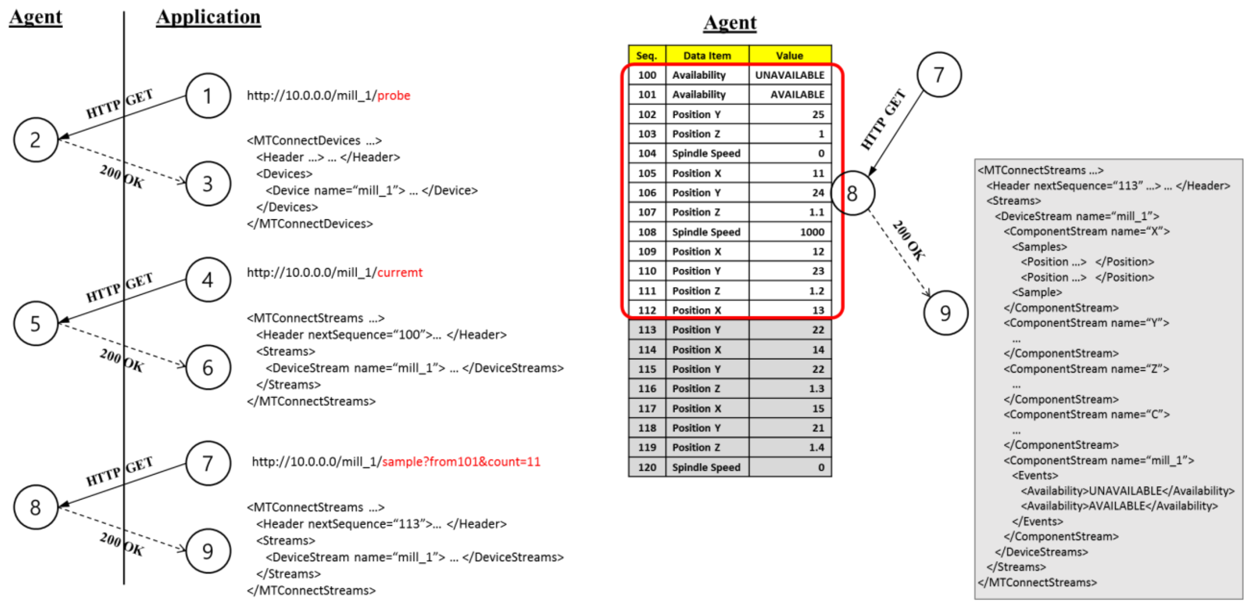


Figure B4: Pull-based streaming between Agent and Application

5.3.2.2. **Push-based**: *probe* → *current* → *sample* with <u>interval</u>

- Agent pushes data at a given interval to Application
- Request example

```
http://10.0.1.23:3000/mill-1/sample?count=1000&interval=1000
```

- Real-time updates
  - use **<u>interval=0</u>** ➔ the changes will be sent with no delay
  - To make this efficient, can use XPath filtering

5.4. Device-Adapter Communication

Figure B5: Communication between Device and Adapter

- Devices can be exposed various interfaces so that the connection between Device and Adapter can be over various communication protocol such as RS-232, RS-485, etc
- Most of the Adapter development time will be spent figuring out what data is required and how to access the data

5.5. Adapter-Agent Communication

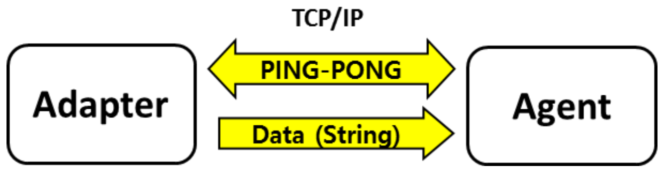


Figure B6: Communication between Adapter and Agent

- Adapter use **Socket** to communicate with Agent: Read and write to the Socket
  ➔ Open socket and wait for the access of Agent
- Heartbeat: Time interval for verifying the connection is open (PING-PONG)
  - Agent will automatically wait for the heartbeat until sending next PING
  - If Adapter becomes unresponsive (i.e., no PONG from Adapter), Agent can disconnect
- Write data to Agent as text
  - Samples and Events:
    Timestamp|name_1|value_1|name_2|value_2|…

    2016-03-07T00:00:00.000000|power|ON|execution|ACTIVE|line|412|Xact|-1.1761875153|Yact|1766618937

  - Conditions:
    <timestamp>|<data_item_name>|<level>|<native_code>|<native_severity>|<qualifier>|<message>

    2016-03-07T00:00:00.000000Z|htemp|WARNING|HTEMP|1|HIGH|Oil Temperature High

  - Messages: <timestamp>|<data_item_name>|<native_code>|<message>

    2016-03-07T00:00:00.000000Z|message|CHG_INSRT|Change Inserts

  - Time Series:
    <timestamp>|<data_item_name>|<count>|<sampleRate>|<message>

    2016-03-07T00:00:00.000000Z|current|10|100|1 2 3 4 5 6 7 8 9 10

Section II. Development and Implementation

1.   Overview of the Proposed System

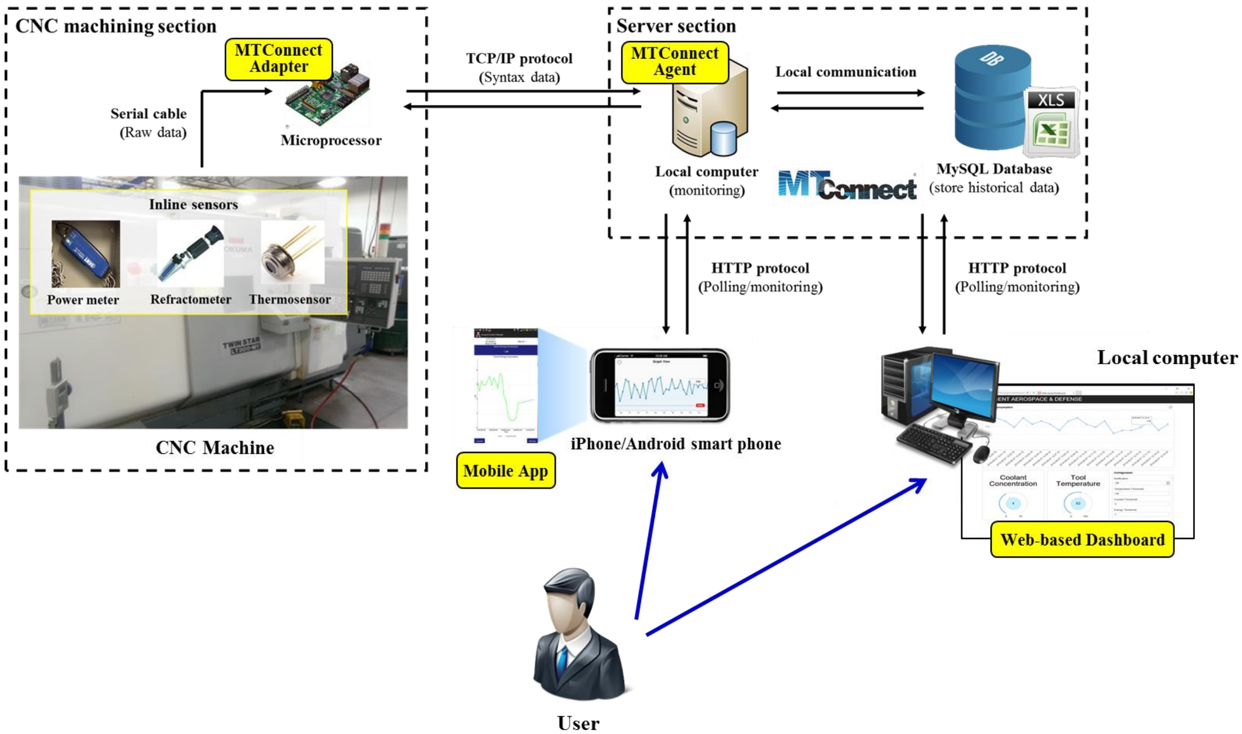


Figure B7: Overview of the proposed data acquisition system with MTConnect

The purpose of the automated data acquisition and monitoring system with MTConnect standard is to provide a live monitoring tool to the plant managers and CNC machine operators by collecting real-time machine status (i.e., tool temperature, process remaining time, etc.) and production status (at both machine level and shop floor level). This system includes six major objects: (1) CNC machine with inline sensors (e.g., power meter, refractometer, and thermal sensor), (2) Microprocessor with MTConnect Adapter, (3) Local computer with MTConnect Agent, (4) MySQL database, (5) Monitoring application (e.g., iPhone/Android smart phone app and Web-based dashboard), and (6) Shop floor manager. The output of the inline sensors embedded in the machine and parameters of CNC machine are gathered by microprocessor via serial cable. These raw data are converted to string format by MTConnect adapter and sent to a localhost computer via either USB communication or Wi-Fi communication. MTConnect agent installed in localhost computer gathers the data and temporarily store them in its buffer. MySQL database keep collecting the temporarily stored data from Agent by using push-based data streaming. Agent also sends the status data to iPhone/Android smart phone or computer so that a shop floor manager can monitor the status of CNC machines.

2. Development of Adapter

Since MTConnect Adapter should be customized to each machine and sensor, it is hard to define the standard procedure for developing. But common modules which should be included in Adapter are as below:

1) Socket communication module with Agent
2) Data sending module which can convert to the regulated string type to Agent

Adapters software for refractometer and thermal imaging sensor are written in Java.

2.1. Socket Communication Module

A socket is one end-point of a two-way communication link between two programs running on the network (Website reference 2). Socket modules are used to represent the connection between a client program and a server program. To write the socket program, four Java libraries are imported for developing the socket communication module: "java.io.DataInputStream", "java.io.DataOutputStream", "java.io.IOException", and "java.net.Socket."

Main functions of this module are 1) open the pre-defined socket, 2) wait until receiving "PING" stream, 3) send "PONG" stream with heartbeat, and 4) repeat 2) and 3). Since this module should be run simultaneously with the main data collection module, this module is developed as a runnable class (Java thread class).

2.2. Data Sending Module

Adapter reads raw data from individual machine or sensor and converts them to the Agent readable data format. The Agent readable data format means a pipe '|' delimited data stream that begins with a timestamp and then follows with a timestamp in ISO 8601 date time format with optional decimal places. In Java, the timestamp in ISO 8601 format can be written as below:

```
Date chkUpdate = new Date();
SimpleDateFormat sdf = new SimpleDateFormat("yyyy-MM-dd");
String chkDate = sdf.format(chkUpdate);
SimpleDateFormat sdf2 = new SimpleDateFormat("HH:mm:ss.SSSSSS");
String chkDate2 = sdf2.format(chkUpdate);
String TimeStamp = chkDate + "T" + chkDate2 + "Z";
```

And the sending data can be written as follow:

```
String mData = TimeStamp + "|coolant|" + Concentration + "\n";
byte[] cData = new byte[100];
cData = mData.getBytes();
```

The converted data (byte) is sent via opened socket as follow:

```
dos = new DataOutputStream(sk.getOutputStream());
dos.write(cData);
```

3. Implementation of Agent

Agent program should be run in "Command Prompt" of Windows. In Command Prompt, it is needed to change the directory where "agent.exe" file is located. The usage of "agent" command is as below:

```
agent [help|debug|run] [configuration_file]
   help           Prints this message
   debug          Runs the agent on the command line with verbose logging
   run            Runs the agent on the command line
   config_file    The configuration file to load
                  Default: agent.cfg in current directory
```

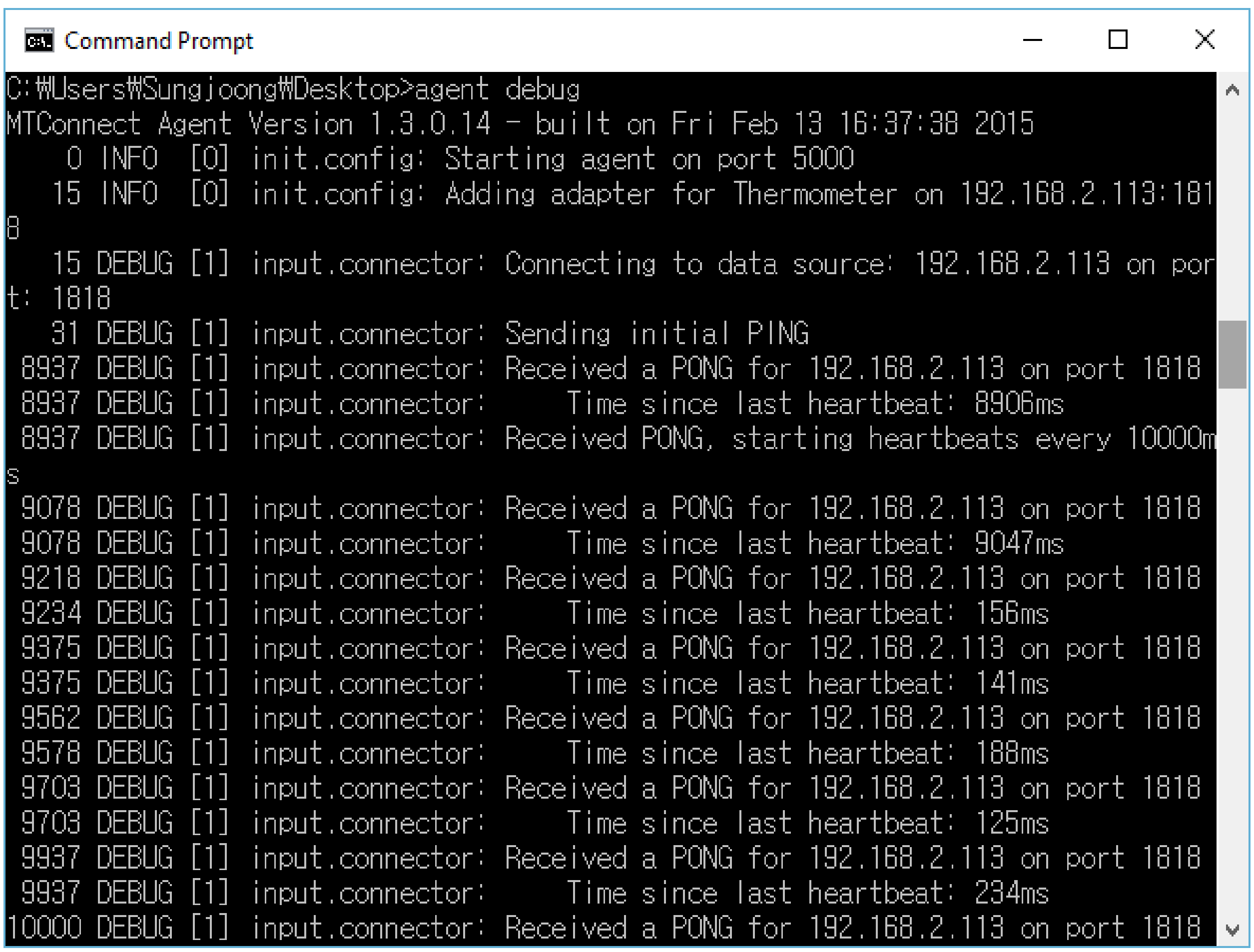
Before running "agent.exe" file, it is needed to set the configuration file, "agent.cfg." The format of configuration file is very strictly defined so that it can make errors if there are any typos. The general format of the configuration file is as follow:

```
Devices = Devices.xml
SchemaVersion = 1.3

logger_config{
  logging_level = info
  output = file ./agent.log
}

Files {
    schemas {
        Path = ./schemas
        Location = /schemas/
    }
    styles {
        Path = ./styles
        Location = /styles/
    }
}

StreamsNamespaces {
  e {
    Urn = urn:example.com:ExampleStreams:1.3
    Location = /schemas/ExampleStreams_1.3.xsd
  }
}

StreamsStyle {
  Location = /styles/Streams.xsl
}

DevicesStyle {
  Location = /styles/Devices.xsl
```

```
}


Adapters {
  Thermometer {
    Host = 127.0.0.1
    Port = 7879
  }
}
```

The first line of the “config.cfg” file indicates the xml schema which contains the information of devices and its data. The second line means what version of MTConnect schema will be used: the latest version is 1.3. The configuration file should specify at least one adapter. The adapters are contained within the very last block. In this block, it is needed to define the information of connection with adapter: adapter’s IP address and opened port should be presented.

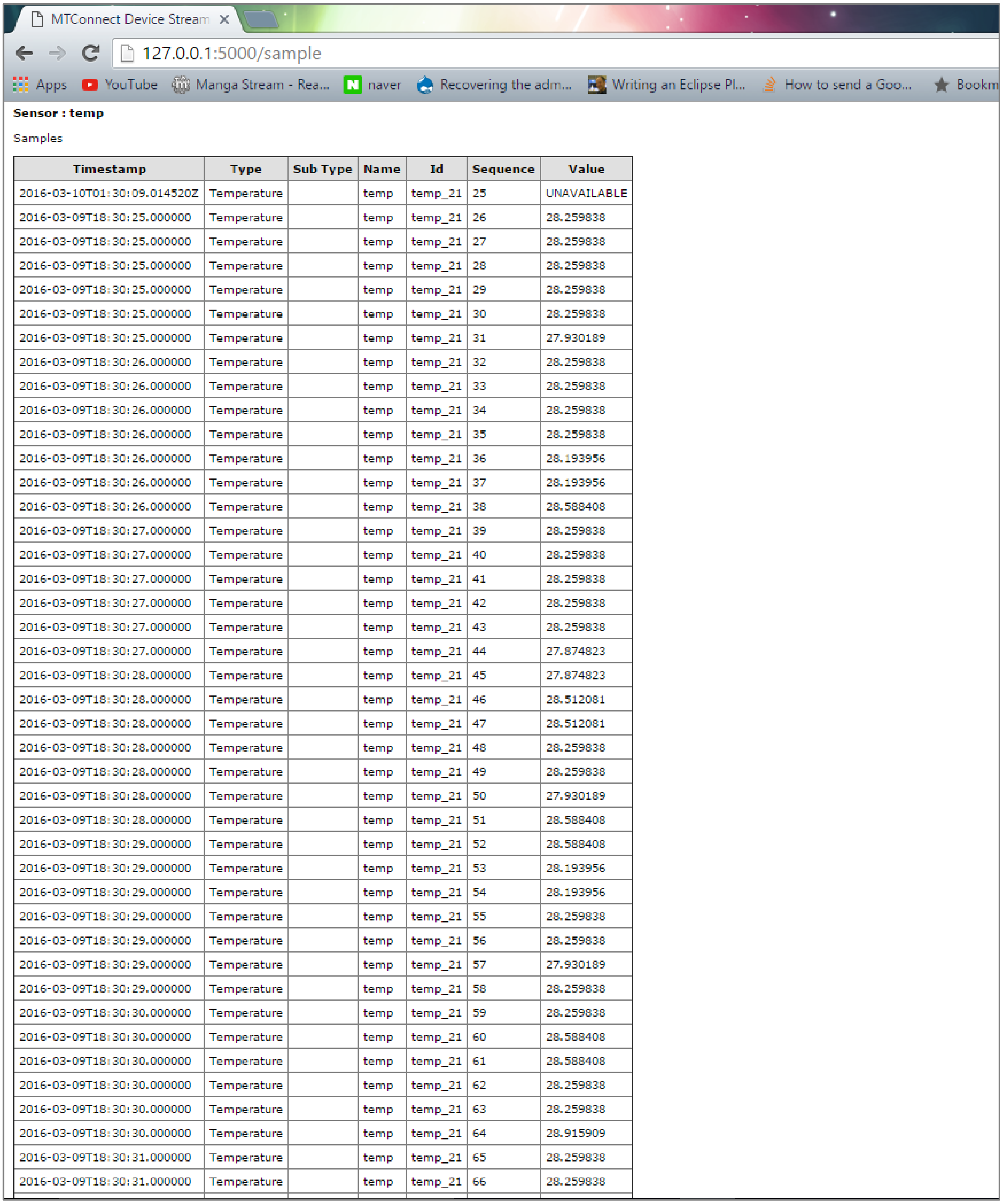
After running Agent in Command Prompt, “PING” – “PONG” communication is maintained until there is no response from Adapter as below:



```
Command Prompt
C:\Users\Sungjoong\Desktop>agent debug
MTConnect Agent Version 1.3.0.14 - built on Fri Feb 13 16:37:38 2015
    0 INFO  [0] init.config: Starting agent on port 5000
   15 INFO  [0] init.config: Adding adapter for Thermometer on 192.168.2.113:181
8
   15 DEBUG [1] input.connector: Connecting to data source: 192.168.2.113 on por
t: 1818
   31 DEBUG [1] input.connector: Sending initial PING
 8937 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 8937 DEBUG [1] input.connector:     Time since last heartbeat: 8906ms
 8937 DEBUG [1] input.connector: Received PONG, starting heartbeats every 10000m
s
 9078 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9078 DEBUG [1] input.connector:     Time since last heartbeat: 9047ms
 9218 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9234 DEBUG [1] input.connector:     Time since last heartbeat: 156ms
 9375 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9375 DEBUG [1] input.connector:     Time since last heartbeat: 141ms
 9562 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9578 DEBUG [1] input.connector:     Time since last heartbeat: 188ms
 9703 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9703 DEBUG [1] input.connector:     Time since last heartbeat: 125ms
 9937 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
 9937 DEBUG [1] input.connector:     Time since last heartbeat: 234ms
10000 DEBUG [1] input.connector: Received a PONG for 192.168.2.113 on port 1818
```

Figure B8: Snapshot of the running of Agent in Command Prompt

Through the *sample* request to Agent, the collected data by temperature can be shown as below:



Sensor : temp

Samples

Timestamp	Type	Sub Type	Name	Id	Sequence	Value
2016-03-10T01:30:09.014520Z	Temperature		temp	temp_21	25	UNAVAILABLE
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	26	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	27	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	28	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	29	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	30	28.259838
2016-03-09T18:30:25.000000	Temperature		temp	temp_21	31	27.930189
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	32	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	33	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	34	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	35	28.259838
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	36	28.193956
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	37	28.193956
2016-03-09T18:30:26.000000	Temperature		temp	temp_21	38	28.588408
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	39	28.259838
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	40	28.259838
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	41	28.259838
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	42	28.259838
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	43	28.259838
2016-03-09T18:30:27.000000	Temperature		temp	temp_21	44	27.874823
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	45	27.874823
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	46	28.512081
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	47	28.512081
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	48	28.259838
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	49	28.259838
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	50	27.930189
2016-03-09T18:30:28.000000	Temperature		temp	temp_21	51	28.588408
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	52	28.588408
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	53	28.193956
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	54	28.193956
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	55	28.259838
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	56	28.259838
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	57	27.930189
2016-03-09T18:30:29.000000	Temperature		temp	temp_21	58	28.259838
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	59	28.259838
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	60	28.588408
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	61	28.588408
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	62	28.259838
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	63	28.259838
2016-03-09T18:30:30.000000	Temperature		temp	temp_21	64	28.915909
2016-03-09T18:30:31.000000	Temperature		temp	temp_21	65	28.259838
2016-03-09T18:30:31.000000	Temperature		temp	temp_21	66	28.259838

Figure B9: Snapshot of the *sample* request to Agent

Section III. Lists of MTConnect® Data Items

Sample

type/subtype	Description	Units
ACCELERATION	Rate of change of velocity	MILLIMETER/SECOND^2
ACCUMULATED_TIME	The measurement of accumulated time associated with a Component	SECOND
ANGULAR_ACCELERATION	Rate of change of angular velocity	DEGREE/SECOND^2
ANGULAR_VELOCITY	Rate of change of angular position	DEGREE/SECOND
AMPERAGE	The measurement of AC Current or a DC current	AMPERE
ALTERNATING	The measurement of alternating current. If not specified further in statistic, defaults to RMS Current	AMPERE
DIRECT	The measurement of DC current	AMPERE
ANGLE	The angular position of a component relative to the parent	DEGREE
ACTUAL	The angular position as read from the physical component	DEGREE
COMMANDED	The angular position computed by the Controller	DEGREE
AXIS_FEEDRATE	The feedrate of a linear axis	MILLIMETER/SECOND
ACTUAL	The actual federate of a linear axis	MILLIMETER/SECOND
COMMANDED	The feedrate as specified in the program	MILLIMETER/SECOND
JOG	The feedrate specified by a logic or motion program, by a pre-set value, or set by a switch as the feedrate for a linear axis when operating in a manual state or method (jogging)	MILLIMETER/SECOND
PROGRAMMED	The feedrate specified by a logic or The feedrate specified by a logic or motion program or set by a switch for a linear axis	MILLIMETER/SECOND
RAPID	The feedrate specified by a logic or motion program, by a pre-set value, or set by a switch as the feedrate for a linear axis when operating in a rapid positioning mode.	MILLIMETER/SECOND
CLOCK_TIME	The reading of a timing device at a specific point in time. Clock time MUST be reported in W3C ISO 8601 format	YYYY-MM-DDThh:mm:ss.ffff
CONCENTRATION	Percentage of one component within a mixture of components	PERCENT
CONDUCTIVITY	The ability of a material to conduct electricity	SIEMENS/METER
DISPLACEMENT	The displacement as the change in position of an object	MILLIMETER
ELECTRICAL_ENERGY	The measurement of electrical energy consumption by a component	WATT_SECOND
FILL_LEVEL	The measurement of the amount of a substance remaining compared to the planned maximum amount of that substance	PERCENT
FLOW	The rate of flow of a fluid	LITER/SECOND
FREQUENCY	The measurement of the number of occurrences of a repeating event per unit time	HERTZ
LENGTH	The length of an object	MILLIMETER
STANDARD	The standard or original length of an object	MILLIMETER
REMAINING	The remaining total length of an object	MILLIMETER
USEABLE	The remaining useable length of an object	MILLIMETER
LINEAR_FORCE	The measure of the push or pull introduced by an actuator or exerted on an object	NEWTON
LOAD	The measurement of the percentage of the standard rating of a device	PERCENT
MASS	The measurement of the mass of an object(s) or an amount of material	KILOGRAM
PATH_FEEDRATE	The feedrate of the tool path	MILLIMETER/SECOND
ACTUAL	The three-dimensional feedrate derived from the Controller	MILLIMETER/SECOND
COMMANDED	The feedrate as specified in the program	MILLIMETER/SECOND
JOG	The feedrate specified by a logic or motion program, by a pre-set value, or set by a switch as the feedrate for a linear axis when operating in a manual state or method (jogging)	MILLIMETER/SECOND
PROGRAMMED	The feedrate specified by a logic or The feedrate specified by a logic or motion program or set by a switch for a linear axis	MILLIMETER/SECOND
RAPID	The feedrate specified by a logic or motion program, by a pre-set value, or set by a switch as the feedrate for a linear axis when operating in a rapid positioning mode.	MILLIMETER/SECOND
PATH_POSITION	The current program control point or program coordinate in WORK coordinates. The coordinate system will revert to MACHINE coordinates if WORK coordinates are not available	MILLIMETER_3D
ACTUAL	The position of the Component as read from the device	MILLIMETER_3D
COMMANDED	The position computed by the Controller	MILLIMETER_3D
TARGET	The target position for the movement	MILLIMETER_3D
PROBE	The position provided by a probe	MILLIMETER_3D

type/subtype	Description	Units
PH	The measure of the acidity or alkalinity	PH
POSITION	The position of the Component. Defaults to MACHINE coordinates	MILLIMETER
ACTUAL	The position of the Component	MILLIMETER
COMMANDED	The position as given by the Controller	MILLIMETER
TARGET	The target position for the movement	MILLIMETER
POWER_FACTOR	The measurement of the ratio of real power flowing to a load to the apparent power in that AC circuit	PERCENT
PRESSURE	The force per unit area exerted by a gas or liquid	PASCAL
RESISTANCE	The measurement of the degree to which an object opposes an electric current through it	OHM
ROTARY_VELOCITY	The rotational speed of a rotary axis	REVOLUTION/MINUTE
ACTUAL	The rotational speed the rotary axis is spinning at. ROTARY_MODE MUST be SPINDLE	REVOLUTION/MINUTE
COMMANDED	The rotational speed as specified in the program	REVOLUTION/MINUTE
SOUND_LEVEL	Measurement of a sound level or sound pressure level relative to atmospheric pressure	DECIBEL
NO_SCALE	No weighting factor on the frequency scale	DECIBEL
A_SCALE	A Scale weighting factor. This is the default weighting factor if no factor is specified	DECIBEL
B_SCALE	B Scale weighting factor	DECIBEL
C_SCALE	C Scale weighting factor	DECIBEL
D_SCALE	D Scale weighting factor	DECIBEL
STRAIN	Strain is the amount of deformation per unit length of an object when a load is applied	PERCENT
TEMPERATURE	The measurement of temperature	CELSIUS
TILT	A measurement of angular displacement	MICRO_RADIAN
TORQUE	The turning force exerted on an object or by an object	NEWTON_METER
VOLT_AMPERE	The measure of the apparent power in an electrical circuit, equal to the product of root-mean-square (RMS) voltage and RMS current (commonly referred to as VAR)	VOLT_AMPERE
VOLT_AMPERE_PEACTIVE	The measurement of reactive power in an AC electrical circuit (commonly referred to as VAR)	VOLT_AMPERE_PEACTIVE
VELOCITY	The rate of change of position	MILLIMETER/SECOND
VISCOSITY	A measurement of a fluid's resistance to flow	PASCAL_SECOND
VOLTAGE	The measurement of electrical potential between two points	VOLT
ALTERNATING	The measurement of alternating voltage. If not specified further in statistics, defaults to RMS voltage	VOLT
DIRECT	The measurement of DC voltage	VOLT
WATTAGE	The measurement of power consumed or dissipated by an electrical circuit of device	WATT

Event

type/subtype	Description
ACTUATOR_STATE	The state of the Actuator - ACTIVE or INACTIVE.
ACTIVE_AXES	The set of axes associated with a Path that the Controller is controlling. If this DataItem is not provided, it will be assumed the Controller is controlling all axes.
AVAILABILITY	Represents the ability of a Component to communicate. This MUST be provided for a Device and MAY be provided for any other Component. AVAILABLE or UNAVAILABLE.
AXIS_COUPLING	Describes the way the axes will be associated to each other. This is used in conjunction with COUPLED_AXES to indicate the way they are interacting. The possible values are: TANDEM, SYNCHRONOUS, MASTER, and SLAVE. The coupling MUST be viewed from the perspective of the axis, therefore a MASTER coupling indicates that this axis is themaster of the COUPLED_AXES.
Axis_FEEDRATE _OVERRIDE	The value of a signal or calculation issued to adjust the feedrate of an individual linear type axis. The value provided for AXIS_FEEDRATE_OVERRIDE is expressed as a percentage of the designated feedrate for the axis. When AXIS_FEEDRATE_OVERRIDE is applied, the resulting commanded feedrate for the axis is limited to the value of the original feedrate multiplied by the value of the AXIS_FEEDRATE_OVERRIDE. There MAY be different subtypes of AXIS_FEEDRATE_OVERRIDE, each representing an override value for a designated subtype of feedrate depending on the state of operation of the axis. The states of operation of an axis are currently defined as PROGRAMMED, JOG, and RAPID.
JOG	The value of a signal or calculation issued to adjust the feedrate of an individual linear type axis when that axis is being operated in a manual state or method (jogging).
PROGRAMMED	The value of a signal or calculation issued to adjust the feedrate of an individual linear type axis that has been specified by a logic or motion program or set by a switch.
RAPID	The value of a signal or calculation issued to adjust the feedrate of an individual linear type axis that is operating in a rapid positioning mode.
AIX_INTERLOCK	An indicator of the state of the axis lockout function when power has been removed and the axis is allowed to move freely. The values MUST be ACTIVE or INACTIVE.
AXIS_STATE	An indicator of the controlled state of an Axis. The value MUST be on of HOME, TRAVEL, PARKED, or STOPPED.
BLOCK	The block of code being executed. Block contains the entire expression for a line of program code.
CHUCK_INTERLOCK	An indication of the state of an interlock function or control logic state intended to prevent the associated CHUCK component from being operated. The values MUST be ACTIVE or INACTIVE.
MANUAL _UNCLAMP	An indication of the state of an operator controlled interlock that can inhibit the ability to initiate an unclamp action of an electronically controlled chuck. The values MUST be ACTIVE or INACTIVE. When MANUAL_UNCLAMP is ACTIVE, it is expected that a chuck cannot be unclamped until MANUAL_UNCLAMP is set to INACTIVE.
CHUCK_STATE	An indication of the operating state of a mechanism that holds a part or stock material during a manufacturing process. It may also represent a mechanism that holds any other mechanism in place within a device. The value MUST be one of OPEN, CLOSED, or UNLATCHED.
CONTROLLER_MODE	The current mode of the Controller. AUTOMATIC, MANUAL, MANUAL_DATA_INPUT, or SEMI_AUTOMATIC.
COUPLED_AXES	Refers to the set of associated axes. The value will be a space delimited set of axes names.
DIRECTION	The direction of motion. CLOCKWISE or COUNTER_CLOCKWISE
ROTARY	The rotational direction of a rotary device using the right hand rule convention as defined in Appendix B. CLOCKWISE or COUNTER_CLOCKWISE
LINEAR	The direction of motion of a linear device. POSTIVE or NEGATIVE
DOOR_STATE	The opened or closed state of the door. OPEN, UNLATCHED, or CLOSED.
END_OF_BAR	An indication of whether the end of a piece of bar stock being feed by a bar feeder has been reached. The value MUST be expressed as a Boolean state of YES or NO.
PRIMARY	Specific applications MAY reference one or more locations on a piece of bar stock as the indication for the End_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_BarEnd_of_Bar. The main or most important location MUST be designated as the PRIMARY indication for the End_of_Bar.
AUXILIARY	When multiple locations on a piece of bar stock are referenced as the indication for the End_of_Bar, the additional location(s) MUST be designated as AUXILIARY indication(s) for the End_of_Bar.
EMERGENCY_STOP	The current state of the emergency stop actuator. ARMED (the circuit is complete and the device is operating) or TRIGGERED (the circuit is open and the device MUST cease operation).
EXECUTION	The execution status of the Controller. READY, ACTIVE, INTERRUPTED, FEED_HOLD, or STOPPED
FUNCTIONAL_MODE	The current intended production status of the device or component. Typically, the FUNCTIONAL_MODE SHOULD be modeled as a data item for the Device Element, but MAY be modeled for any Structural Element in the XML document. The value MUST be PRODUCTION, SETUP, TEARDOWN, MAINTENANCE, or PROCESS_DEVELOPMENT.
INTERFACE_STATE	The current functional or operational state of an Interface type element indicating whether the interface is active or not currently functioning. The values MUST be ENABLED or DISABLED. When the INTERFACE_STATE is DISABLED, the state of all other data elements associated with that Interface MUST be set to NOT_READY.

type/subtype	Description
LINE	The current line of code being executed
MAXIMUM	The maximum line number of the code being executed.
MINIMUM	The minimum line number of the code being executed.
MESSAGE	An uninterpreted textual notification.
OPERATION_ID	The identifier of the person currently responsible for operating the device.
PALLET_ID	The identifier for the pallet currently in use for a given Path
PART_COUNT	The current count of parts produced as represented by the Controller. MUST be an integer value.
ALL	The count of all the parts produced. If the subtype is not given, this is the default.
GOOD	Indicates the count of correct parts made.
BAD	Indicates the count of incorrect parts produced.
TARGET	Indicates the number of parts that are projected or planned to be produced
PERMAINING	The number of parts remaining in stock or to be produced.
PART_ID	An identifier of the current part in the device
PATH_FEERATE _OVERRIJOGDE	The value of a signal or calculation issued to adjust the feedrate for the axes associated with a Path component - may represent a single axis or the coordinated movement of multiple axes. The value provided for PATH_FEEDRATE_OVERRIDE is expressed as a percentage of the designated feedrate for the path. When PATH_FEEDRATE_OVERRIDE is applied, the resulting commanded feedrate for the path is limited to the value of the original feedrate multiplied by the value of the PATH_FEEDRATE_OVERRIDE.
JOG	The value of a signal or calculation issued to adjust the feedrate of the axes associated with a Path component when the axes (axis) are being operated in a manual mode or method (jogging). When the JOG subtype of PATH_FEEDRATE_OVERRIDE is applied, the resulting commanded feedrate for the axes(axis) associated with the path are limited to the value of the original JOG subtype of the PATH_FEEDRATE multiplied by the value of the JOG subtype of PATH_FEEDRATE_OVERRIDE.
PROGRAMMED	The value of a signal or calculation issued to adjust the feedrate of the axes associated with a Path component when the axes (axis) are operating as specified by a logic or motion program or set by a switch. When the PROGRAMMED subtype of PATH_FEEDRATE_OVERRIDE is applied, the resulting commanded feedrate for the axes(axis) associated with the path are limited to the value of the original PROGRAMMED subtype of the PATH_FEEDRATE multiplied by the value of the PROGRAMMED subtype of PATH_FEEDRATE_OVERRIDE.
RAPID	The value of a signal or calculation issued to adjust the feedrate of the axes associated with a Path component when the axes (axis) are being operated in a rapid positioning mode or method (rapid). When the RAPID subtype of PATH_FEEDRATE_OVERRIDE is applied, the resulting commanded feedrate for the axes(axis) associated with the path are limited to the value of the original RAPID subtype of the PATH_FEEDRATE multiplied by the value of the RAPID subtype of PATH_FEEDRATE_OVERRIDE.
PATH_MODE	The operational mode for this Path. SYNCHRONOUS, MIRROR, or INDEPENDENT. Default value is INDEPENDENT if not specified.
POWER_STATE	The ON or OFF status of the Component. DEPRECATION WARNING: MAY bedeprecated in the future.
LINE	The state of the high voltage line.
CONTROL	The state of the low power line.
PROGRAM	The name of the program being executed
PROGRAM_EDIT	An indication of the Controller component's program editing mode. On many controls, a program can be edited while another program is currently being executed. The value MUST be: ACTIVE(The controller is in the program edit mode.), READY(The controller is capable of entering the program edit mode and no function is inhibiting a change of mode.), NOT_READY(A function is inhibiting the controller from entering the program edit mode.)
PROGRAM_EDIT _NAME	The name of the program being edited. This is used in conjunction with PROGRAM_EDIT when in ACTIVE state.
PROGRAM_CONNECT	A comment or non-executable statement in the control program.
PROGRAM_HEADER	The non-executable header section of the control program.
ROTARY_MODE	The mode for the Rotary axis. SPINDLE, INDEX, or CONTOUR.
ROTARY_VELOCITY _OVERRIDE	A command issued to adjust the programmed velocity for a Rotary type axis. This command represents a percentage change to the velocity calculated by a logic or motion program or set by a switch for a Rotary type axis. ROTARY_VELOCITY_OVERRIDE is expressed as a percentage of the programmed ROTARY_VELOCITY.
SPINDLE_INTERLOCK	An indication of the status of the spindle for a device when power has been removed and it is free to rotate. The value MUST be: ACTIVE(if power has been removed and the spindle cannot be operated(, INACTIVE(if power to the spindle has not been deactivated)
TOOL_ASSET_ID	The identifier of an individual tool asset.
TOOL_NUMBER	The identifier of a tool provided by the device controller.
WORKHOLDING_ID	The identifier for the workholding currently in use for a given Path

Condition

type/qualifier	Description
ACCELERATION	Rate of Change of Velocity
ACCUMULATED_TIME	The measurement of accumulated time associated with a Component
ACTUATOR	An actuator related condition.
AMPERAGE	A high or low condition for the electrical current.
ANGLE	The angular position of a Component.
ANGULAR_ACCELERATION	Rate of change of angular velocity.
ANGULAR_VELOCITY	Rate of change of angular position
COMMUNICATIONS	A communications failure indicator.
CONCENTRATION	Percentage of one ingredient within a mixture of ingredients
CONDUCTIVITY	The ability of a material to conduct electricity
DATA_RANGE	Information provided is outside of expected value range
DIRECTION	The direction of motion of a Component
DISPLACEMENT	The change in position of an object
ELECTRICAL_ENERGY	The measurement of electrical energy consumption by a Component
FILL_LEVEL	Represents the amount of a substance remaining compared to the planned maximum amount of that substance
FLOW	The rate of flow of a fluid
FREQUENCY	The number of occurrences of a repeating event per unit time
HARDWARE	The hardware subsystem of the Component's operation condition.
LINEAR_FORCE	The measure of the push or pull introduced by an actuator or exerted by an object
LOAD	The measure of the percentage of the standard rating of a device
LOGIC_PROGRAM	An error occurred in the logic program or PLC (programmable logic controller).
MASS	The measurement of the mass of an object(s) or an amount of material
MOTION_PROGRAM	An error occurred in the motion program.
PATH_FEEDRATE	The federate of the tool path
PATH_POSITION	The current control point of the path
PH	The measure of acidity or alkalinity
POSITION	The position of a Component.
POWER_FACTOR	The ratio of real power flowing to a load to the apparent power in that AC circuit.
PRESSURE	The measurement of the force per unit area exerted by a gas or liquid.
RESISTANCE	The measurement of the degree to which an object opposes an electric current through it
ROTARY_VELOCITY	The rotational speed of a rotary axis
SOUND_LEVEL	The measurement of sound pressure level
STRAIN	Indicates the amount of deformation per unit length of an object when a load is applied
SYSTEM	A condition representing something that is not the operator, program, or hardware. This is often used for operating system issues.
TEMPERATURE	Indicates the temperature of a Component.
TILT	The measure of angular displacement
TORQUE	The measured of the turning force exerted on an object or by an object

Appendix C

Implementation of Energy Consumption Estimation Program

Contents

Section I. Major Features of Knowledge Based Energy Optimization Program

1. Overview: Why Knowledge Based Optimization Program needed?

Manufacturing converts a wide range of raw materials, components, and parts into finished goods that meet market expectations. As an end-use sector, manufacturing is the most diverse in the U.S. economy in terms of its energy sources, foundational technologies, and the products manufacturing produces. In 2012, U.S. manufacturing was responsible for 12.5% [1] of GDP, direct employment for about 12 million people [1], and 70% [2] of all business R&D performed (in 2010 and 2011); and close to 75% [3] of U.S. exports of goods; production of 17% [4] of the world's manufacturing output, and 25% [5] of U.S. energy use. Therefore, energy plays a vital role in manufacturing industries.

The major goal of this project is to reduce the energy consumption for machine shops by improving the energy efficiency of the CNC machine. To achieve high energy efficiency, appropriate machining parameters like cutting speed, depth of cut, feed etc. need to be optimized toward the minimization of energy consumption. Since the existing CAM software MasterCAM (used by Sargeant) cannot provide any estimation of energy consumption priori, a post processing tool is needed to get some idea about the energy consumption which allows the designer to change the machining parameter accordingly in order to minimize the energy consumption. The Energy Consumption Estimation Program is one such tool that can be used to calculate the machining parameter (spindle speed, feed rate) which yields minimum energy consumption during production. Therefore, designer can easily change the parameter of the NC code before production.

2. Main Features of Knowledge Based Optimization Program

Main features of the Energy Consumption Estimation Program are listed below

- Provide diverse selection of part materials such as Aluminum, Copper, Brass, Mild Steel, Stainless Steel, Cast Iron, Wax etc.
- Two major types of tool materials are included, one is High Speed Steel (HSS) and the other is Carbide
- Includes major tool diameter used in small manufacturing facilities. Tool Diameter ranges from 1/16” to 1/4”
- Extensible tool information database
- Provide 4 different selection of number of teeth of the tool
- Recommended surface feet per minute and inch per tooth for various combination of part material and tool materials are considered
- Program can be upgraded easily to add new features with little modification

Section II. Development and Implementation

1. Proposed System

The proposed system contains the following algorithm shown in Figure C1 to calculate the minimum energy consumption and to find the optimum parameters

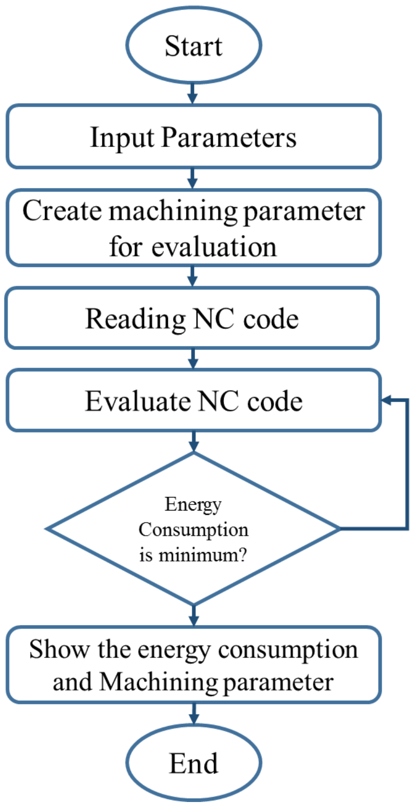


Figure C1: Algorithm to find the minimum energy and optimum machining parameter

Here the input parameters are as follows

- Feed rate
- Part Material
- Tool Material
- Tool Diameter
- Number of teeth
- NC code

After taking all these input the program retrieve the recommended parameter from the excel database based on the input parameters. The database provides the recommended range of surface feet per minute (SFM) and inch per tooth (IPT) for specific combination of part and tool material. An example of database is shown in Figure C2. After retrieving the parameter from the database the program generates hundred different combination of spindle speed and feed rate. Based on each combination of spindle speed and feed rate, the program evaluates the NC code to calculate the energy consumption based on the regression model described in the main report. When the evaluation is over the program shows the parameters for which the energy consumption is minimum.

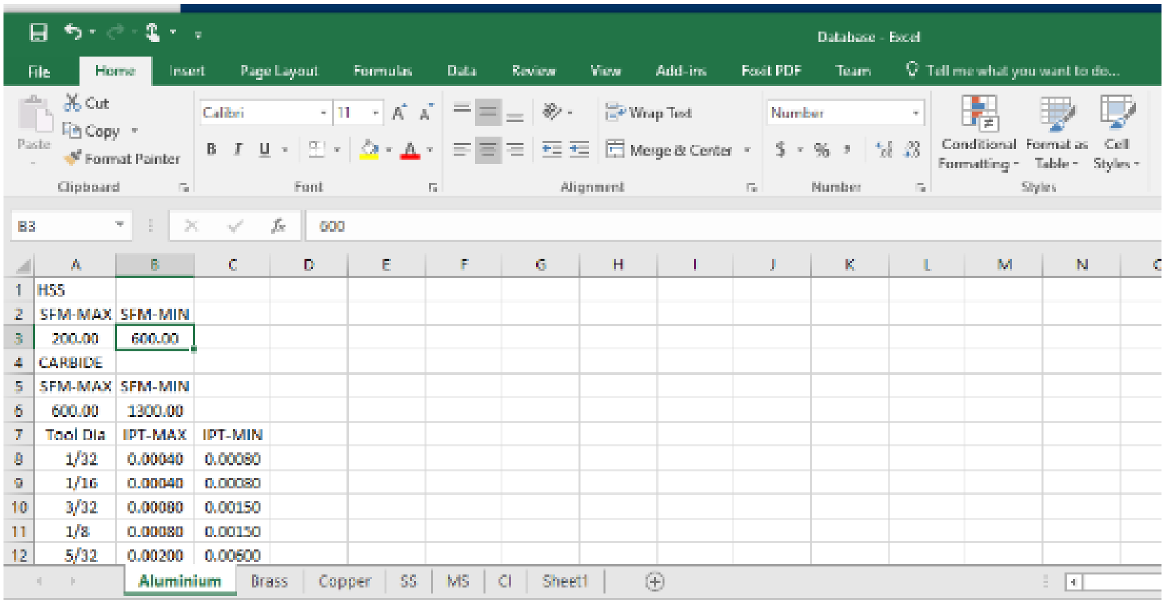


Figure C2: Excel Database of the recommended SFM and IPT

2. Development of the program

The program is developed using java which contains six different classes and seven different input files. The classes are as follows

- NC code parsing
- NC code reader
- Regression model
- Regression Input
- Database reader

The input files are the Excel database of the machining parameter (see Figure 2) and text files contains the coefficients of the regression model for each part material.

Section III. How to use the program?

1. Installing Java

Since the estimation program developed using java, the user needs to install the java development kit (jdk) first. The installation steps are shown below

- Step 1

Go to the following website and click on the icon showed by arrow

http://www.oracle.com/technetwork/java/javase/downloads/index.html

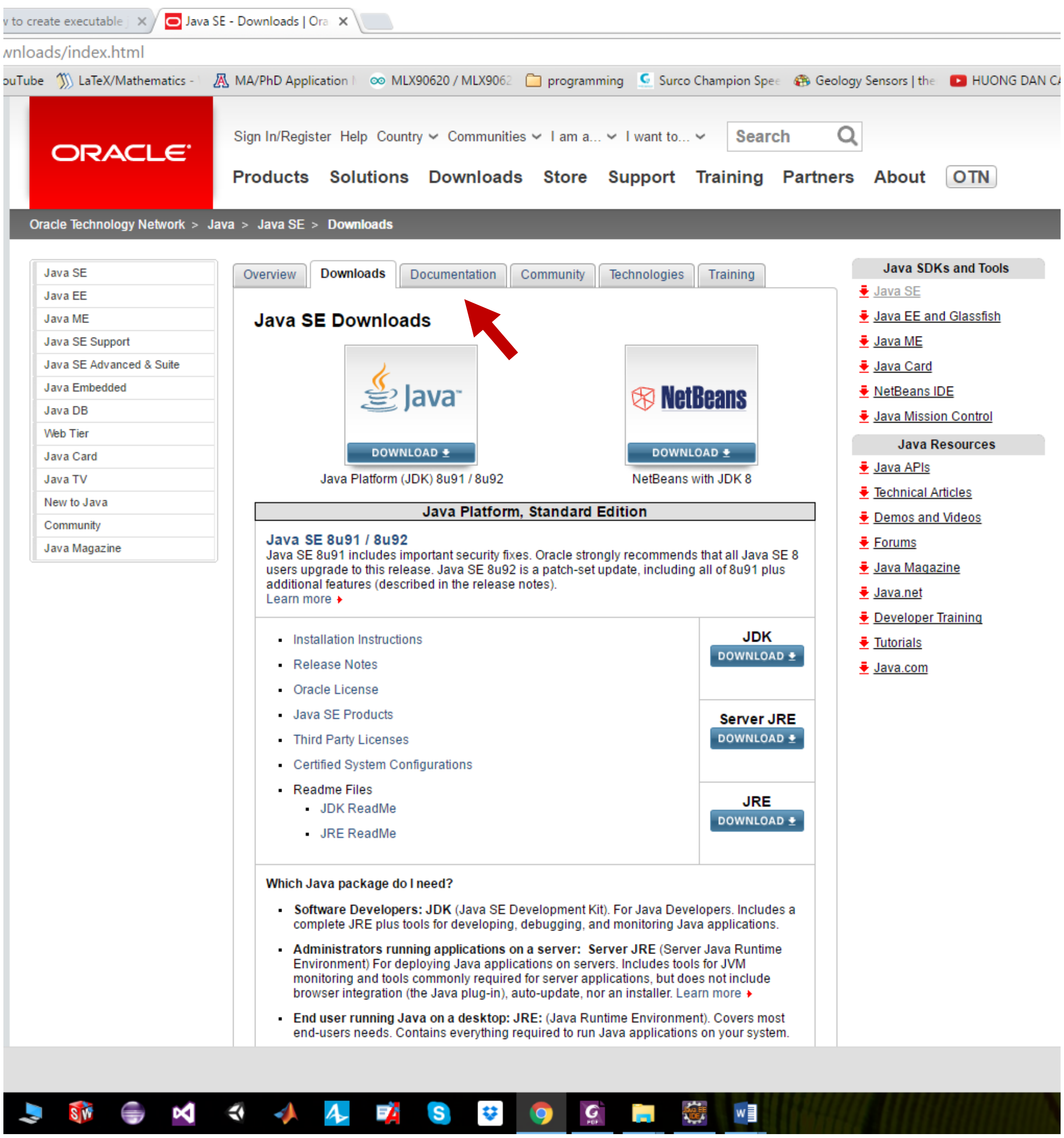


Figure C3: The website to download and install the java development kit (1)

- Step 2

Accept the license agreement and download the appropriate jdk version for the computer operating system

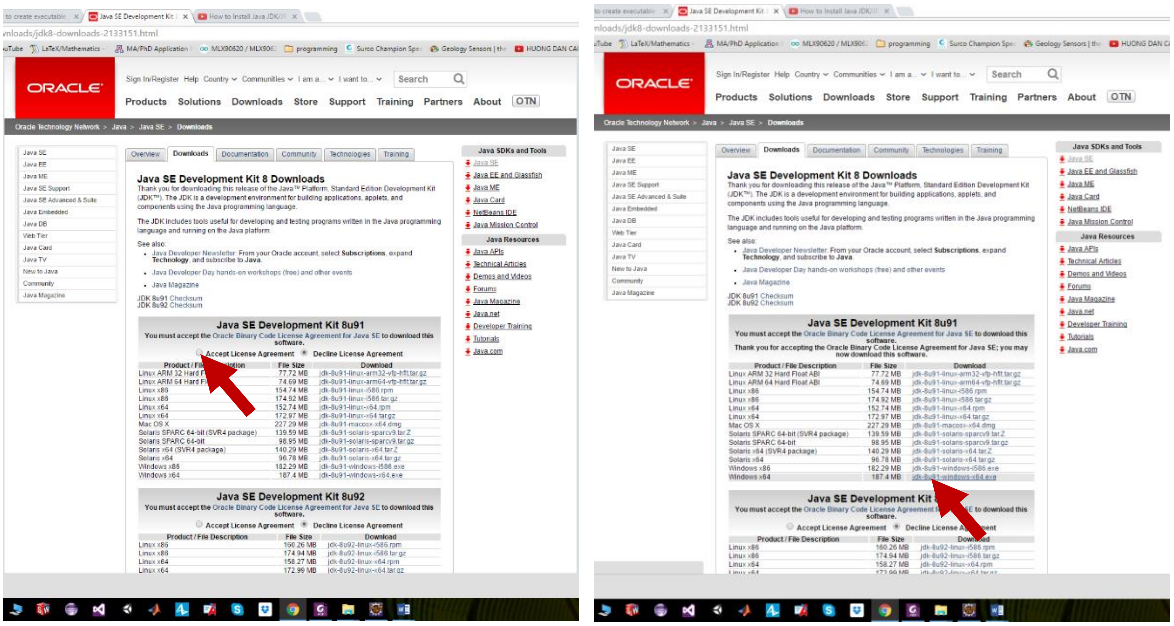


Figure C4: The website to download and install the java development kit (2)

- Step 3

After finishing the download run the downloaded file and follow the instruction on each step and finish the installation

2. Using the Energy Estimation Program

To use the energy estimation program user need to follow the following steps

- Step 1

Run the Energy Estimation .jar file which begins the estimation program

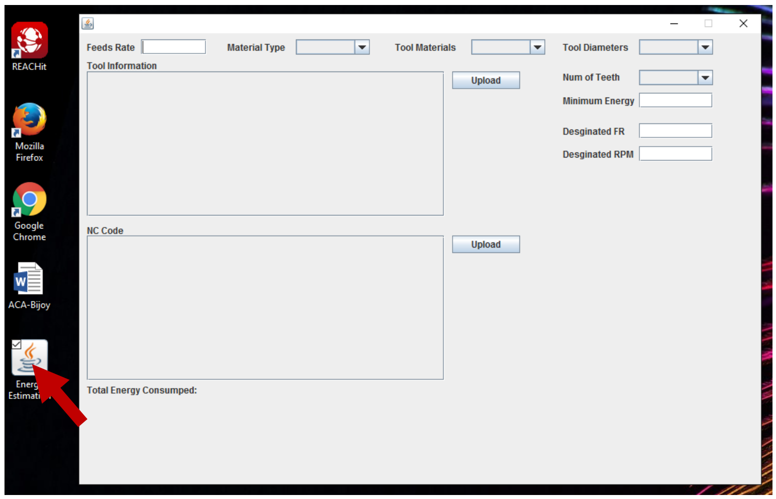
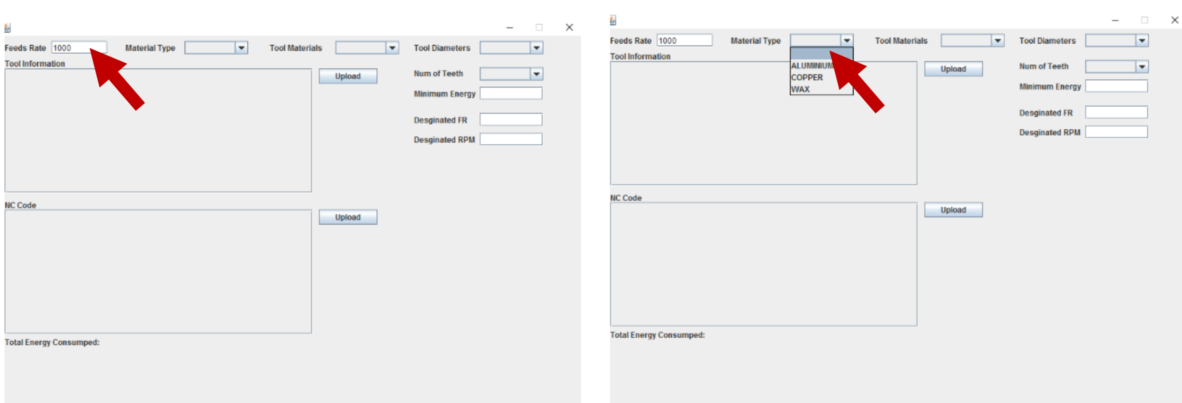


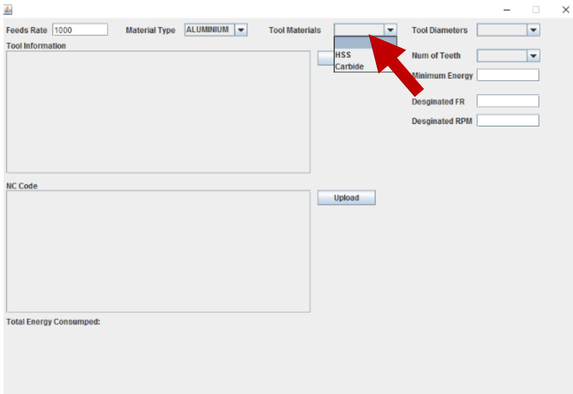
Figure C5: Start-up screen of the program

- Step 2

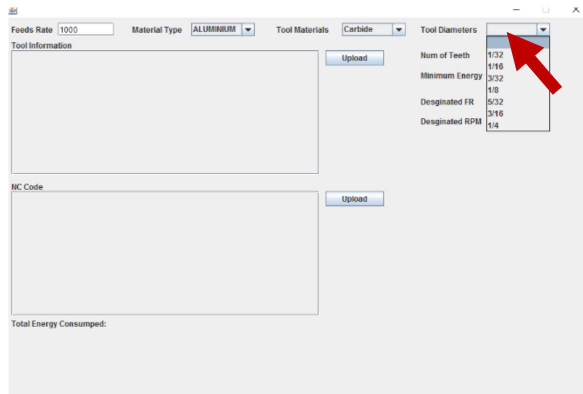
Enter the feed rate and select different parameters from the dropdown menu one by one as shown below



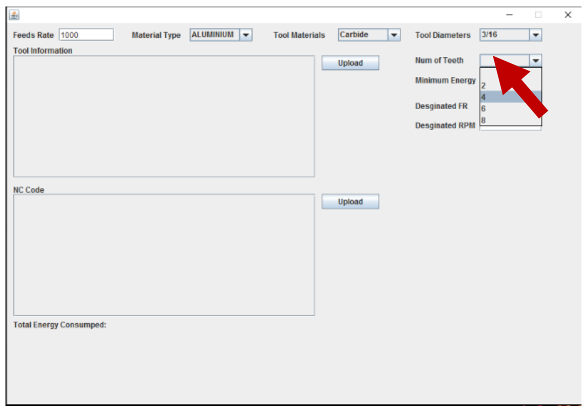
(a)Feed Rate entering box (b) Part Material Selection dropdown menu



(c) Tool Material Selection dropdown menu



(d) Tool Diameter Selection dropdown menu



(e)Tool Teeth Number Selection dropdown menu

Figure C6: Selecting different parameters in Step 2

- Step 3

Upload the NC code to evaluate

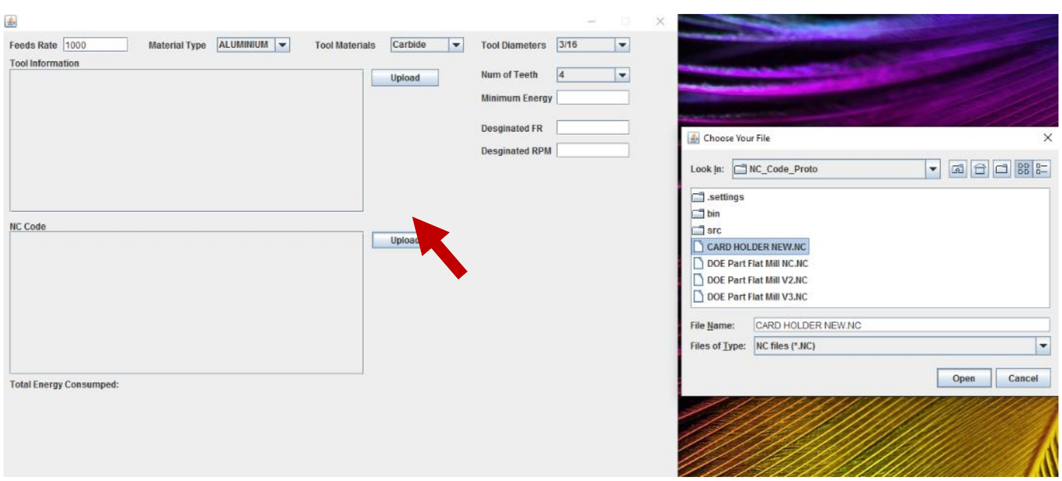


Figure C7: Uploading NC code from the directory in Step 2

- Step 4

The output appears in the box of Minimum Energy, Designated FR and Designated RPM

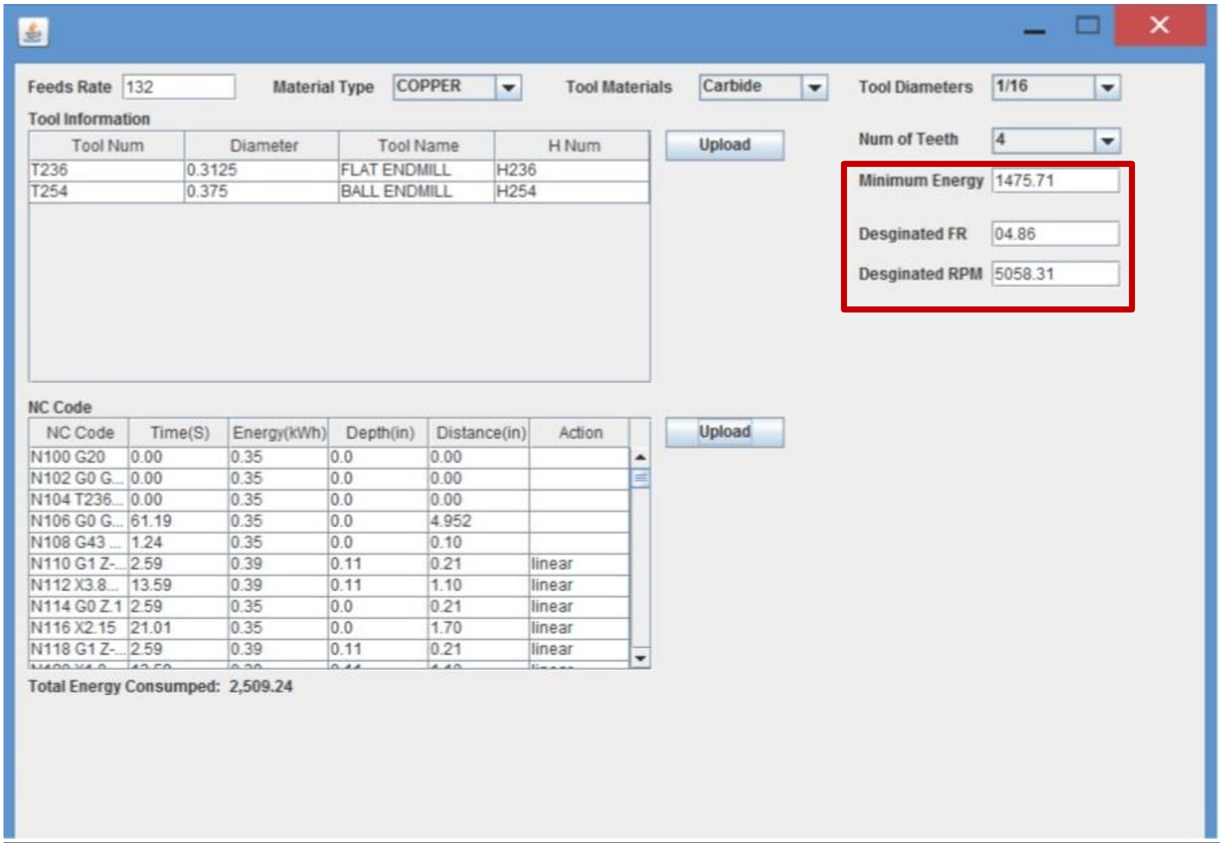


Figure C8: Output of the Energy Consumption Estimation Program

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Arizona Commerce Authority

FINAL REPORT

2014 Innovation in Advanced Manufacturing Grant Competition

Lean Advisors USA and Industrial Tool Die & Engineering

PREPARED BY:

Intersol

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Background

In 2014, the Arizona Commerce Authority conducted an Advanced Manufacturing Grant Competition to support and grow southern and central Arizona's Aerospace and Defense industry and its supply chain.

The grant funded projects that develop innovative new tools and technologies for integrated approaches that both improve productivity and reduce energy consumption of older generation machine tools. The grant was also aimed at fostering better relationships between manufacturing companies looking to improve their cost competitiveness with solution providers interested in developing new "out of the box" continuous improvement tools and technologies.

Lean Advisors USA and Industrial Tool Die & Engineering partnered up to address the following topic area:

Topic Area 1: Integrated Lean & Green Energy Improvement Tools

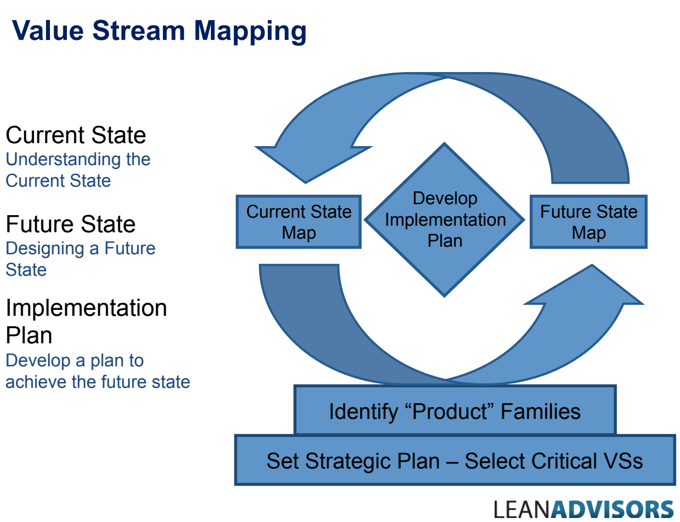
Next-gen lean tools and rapid response Kaizen events to help identify integrated productivity and energy use improvement opportunities using data driven tools and methods developed and supplied by a training partner that link proposed improvement ideas to bottom line financial savings and energy use impact

The purpose of this report is to share the findings of our project. This report will provide an overview of the approach taken, the results found, areas of focus for the future kaizens and next steps.

Approach

Value Stream Methodology

The Lean Methodology and in particular Value Stream Mapping is based on following a proven transformation cycle as outlined in the diagram.



Current State Mapping
A Current State map is a picture of what is happening in the process. With the data on the map, you can determine all of the following:

- health of process,
- bottlenecks, constraints are, system lead time reflective of the work in process and unnecessary delays,
- what people are doing,
- how the process actually works

The purpose of the Current State map is to give you the basis to analyze with a Lean lens in order to identify significant Kaizens or improvement activities necessary to improve Service, Quality and Efficiencies. It is important to understand that the intent is not to over burden the organization with initiatives but rather to indentify the critical few that will have the greatest impact with respect to supporting the Future vision.

Future State Mapping
A Lean Future State map envisions what your process will look like once you have effected improvements in all the areas identified. It should be aligned with the broader strategic objectives and vision reflective in the Lean Value Stream Charter.

Lean Implementation Plan
The Lean implementation plan is the most important document in the Value Stream Mapping process. This plan outlines what you will work on in order to create the vision you captured in the future-state map. A Lean plan typically includes the following elements:

- Kaizens
- Associated activities for each Kaizen if necessary to provide greater clarity
- Measure of Success. Ideally this is identified throughout the mapping activity although when the data is unavailable, then it is determined by the process owners prior to commencing with the actual Kaizen
- Timeline and sequencing of the identified Kaizens to ensure that changes is introduced in the right order from an end to end system perspective. Timeline also recognizes resourcing constraints and the change plan is spread out sufficiently to maintain momentum while not over burdening the organization.

Energy Value Stream Mapping
Energy Value Stream Mapping takes traditional VSM to the next level in order to capture energy and environmental waste and to quantify it. It captures all energy waste within a process or Value Stream and highlights the environmental impacts associated with and /or caused by that energy waste. Total Energy Waste is identied and reduced systematically through a Future State Waste Reduction Plan.

The EnVSM team measures and uses energy usage data of each process while collecting data from the current state of the process such as; cycle time, change over time and up time. The objective being to have both data from the value added actions alongside energy usage or waste, in order to fully analyze and improve the future state from an ***Energy*** perspective and focus.

The Energy Value Stream Mapping allows us to:

- Visualize the Energy usage within machining processes (both value added and non value added), in order to identify Energy waste;
- Highlight the stations which need further energy analysis;
- Identify greatest opportunities for energy reduction / efficiency in order to target Energy Kaizen events.

Deliverables & Outcomes

Task 1.0: Project Kick-off

The kick-off meeting took place with the project team on January 6th 2015.
The purpose of this meeting was to meet with the project team to review the project work plan and ensure project scope and deliverable expectations were clear.

The following deliverables were accomplished during this meeting:

- Lean Advisors provided an overview of the Scope of work, our approach, timeframes and deliverables pertaining to the Energy Reduction Grant project;
- ITDE identified data sources available for use by LA consultant;
- ITDE identified key personnel to be engaged;
- ITDE Identified past Lean training and initiatives.

Task 2.0: Lean Energy Training

Lean energy training was provided in order to Train the ITDE Lean team to recognize energy usage and impacts. We discussed Lean and it's application to Energy reduction including the various tools that would be applied throughout the project (Recognizing Energy Waste, EnVSM, Kaizen Energy Events and Hierarchal process mapping for Energy reduction).

Task 3.0: Energy Current State Mapping; Task 4.0: Energy Hierarchal Process Mapping

Energy Current State Mapping and hierarchal process mapping began January 7 & was completed week Feb 9 of 2015. Marcus Engineering conducted electrical measurements on Lathes, Mills and EDMS in order to capture current state electricity consumption measurements for our Energy Current State Map.

Figure 1: Snapshot of Energy Current State Value Stream Map (VSM)

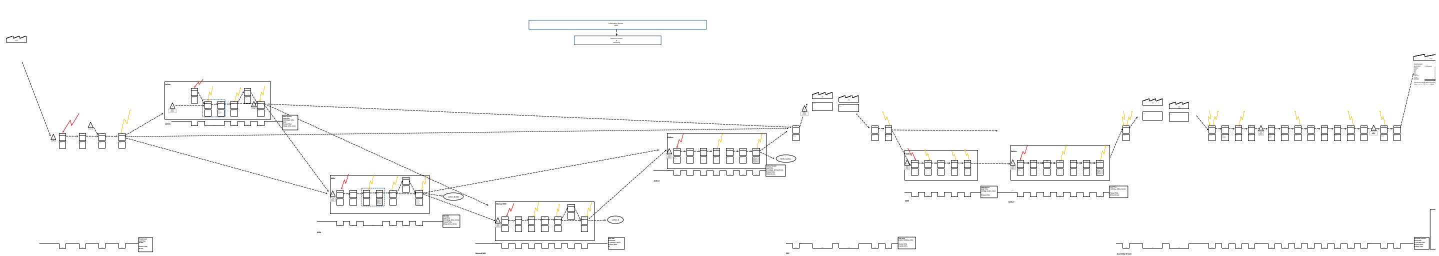


Table 1: Energy Use Hidden in Lean Wastes	
Waste Type	**Energy Use**
Overproduction	• More energy consumed in operating equip-ment to make unnecessary products
Inventory	• More energy used to heat, cool, and light inventory storage and warehousing space
Transportation and Motion	• More energy used for transport • More space required for work in process (WIP) movement, increasing lighting, heating, and cooling demand and energy consumption
Defects	• Energy consumed in making defective products • More space required for rework and repair, increasing energy use for reprocessing, as well as heating, cooling, and lighting
Over Processing	• More energy consumed in operating equipment related to unnecessary processing • Use of right-sized equipment often results in significant reductions in energy use per unit of production
Waiting	• Wasted energy from heating, cooling, and lighting during production downtime

Energy Use Hidden in Lean Wastes - Source: EPA Lean Energy Climate Toolkit

Energy Current State Analysis: The above Lean wastes were analyzed from an energy perspective in order to find hidden wasted energy within the current state. "*Significant energy savings are typically related to a manufacturing company's involvement in Lean activities—even without explicit consideration of energy use.* The greatest benefits for lean implementation can be understood by thinking about energy in the context of Lean's "deadly wastes" (source: EPA Lean Energy Climate Toolkit).

It was discovered during our Current State Analysis, that ITDE had significant hidden energy waste in Overproduction, Transportation and Motion, Inventory, Defects, Over Processing and Waiting.

Data Collection - Order Prep

Process / Data	Generate Traveller	Issue Material	Pull Material	Serialize
Process Time 1st Article	NA	NA	NA	NA
Process Time Production	15 MIN	15 MIN	30 MIN	15 MN
Lot Size (Production)	NA	NA	NA	NA
Setup	8 HRS	NA	NA	NA
Unload / Load Time	NA	NA	NA	NA
ReWork % 1st Article	NA	NA	NA	NA
REWork % Production	NA	NA	NA	NA
Scrap at this Process	NA	NA	NA	NA

Data Collection - Mill Operations

Process / Data	Mill (Machines) Setup	First Off Inspect	Buy Off	Mill Production
Process Time 1st Article	1.5 HR	6 HR	NA	NA
Process Time Production	NA	NA	5 MIN	4 DAY
Lot Size (Production)	1	1	NA	NA

Setup	4 HR	15 MIN	NA	NA
Unload / Load Time	5 MIN	NA	NA	5 MIN
ReWork % 1st Article	39% YTD	NA	NA	NA
REWork % Production	NA	NA	NA	32% YTD
Scrap at this Process	20% YTD	NA	NA	68% YTD
% time Machine is Producing during shift	NA	NA	NA	60%
Mach Startup Time	NA	NA	NA	12 MIN
Machine Shut down Time	NA	NA	NA	5 MIN

Data Collection Lathe Ops

Process / Data	Lathe Setup	First Off Inspect	Buy Off	Lathe Production
Process Time 1st Article	1.5 HR	1 HR	NA	NA
Process Time Production	NA	NA	5 MIN	2 DAYS
Lot Size (Production)	1	1	NA	NA
Setup	3 HR	15 MIN	NA	NA
Unload / Load Time	30 MIN	NA	NA	30 MIN
ReWork % 1st Article	27% YTD	NA	NA	NA
REWork % Production	NA	NA	NA	31% YTD

Scrap at this Process	20% YTD	NA	NA	69% YTD
% time Machine is Producing during shift	NA	NA	NA	60%
Mach Startup Time	NA	NA	NA	NA
Machine Shut down Time	NA	NA	NA	NA

Data Collection DeBurr

Process / **Data**	DeBurr First Article	Buy Off First Article	De Burr Production	Clean Production	Product Audit Production
Process Time 1st Article	45 MIN	10 MIN	NA	NA	NA
Process Time Production	NA	NA	10 HR	30 MIN	8 HR
Lot Size (Production)	NA	NA	NA	NA	NA
Setup	15 MIN	NA	NA	10 MIN	1 HR
Unload / Load Time	NA	NA	NA	NA	30 MIN
ReWork % 1st Article	2%	NA	NA	NA	NA
REWork % Production	NA	NA	3%	0	30%
Scrap at this Process	0.05%	NA	0	NA	4%

Data Collection OSP

Process	Ship	Outside Process	Outside Process	Receive	Inspect

Data		Spline	Heat Treat		
Process Time 1st Article	NA	NA	NA	NA	NA
Process Time Production	30 MIN	2 WEEKS	1 WEEK	30 MIN	1 HR
Lot Size (Production)	NA	NA	NA	NA	NA
Setup	15 MIN	NA	NA	NA	15 MIN
Unload / Load Time	NA	NA	NA	30 MIN	30 MIN
ReWork % 1st Article	NA	NA	NA	NA	NA
REWork % Production	NA	NA	NA	NA	NA
Scrap at this Process	NA	NA	NA	NA	NA

Ship	Outside Process NDT	Outside Process Anondize Passivate	Receive	Inspect OSP	Buy Off OSP	Issue Inventory Components
NA	NA	NA	NA	NA	NA	NA
30 MIN	1 DAY	3 DAYS	30 MIN	2 HR	5MIN	1 HR
NA	NA	NA	NA	NA	NA	NA
15 MIN	NA	NA	NA	30 MIN	NA	NA
NA	NA	NA	30 MIN	30 MIN	NA	NA
NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA

Data Collection - Order Prep

Process / Data	Generate Traveller	Issue Material	Pull Material	Serialize
Process Time 1st Article	NA	NA	NA	NA
Process Time Production	15 MIN	15 MIN	30 MIN	15 MN
Lot Size (Production)	NA	NA	NA	NA
Setup	8 HRS	NA	NA	NA
Unload / Load Time	NA	NA	NA	NA
ReWork % 1st Article	NA	NA	NA	NA
REWork % Production	NA	NA	NA	NA
Scrap at this Process	NA	NA	NA	NA

Data Collection Assemble & Bag n Tag

Process / Data	Assembly First Article	First Article Inspect	Buy Off Assembly	Assembly Production	Bag n Tag First Article	First Article Inspect Bag n Tag	Complete Bag n Tag	Final Inspection	Place in F/G Inventory
Process Time 1st Article	30 MIN	15 MIN	NA	NA	15 MIN	15 MIN	NA	NA	NA
Process Time Production	NA	NA	5 MIN	8 HR	NA	NA	2 HR	1.5 HR	15 MIN

Lot Size (Production)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Setup	30 MIN	NA	NA	NA	15 MIN	10 MIN	NA	15 MIN	NA
Unload / Load Time	NA	NA	NA	NA	NA	NA	NA	NA	NA
ReWork % 1st Article	2%	NA	NA	NA	0.50%	0.50%	NA	NA	NA
REWork % Production	NA	NA	NA	4%	NA	NA	NA	NA	NA
Scrap at this Process	0.05%	NA	NA	0.05%	NA	NA	NA	NA	NA

Lead Time Calculations

Prep Stream
Lead Time
75 Min
Process Time
75 min

Lathe Stream
Lead Time
3 3/4 Days, 3 hrs, 5min
Process Time
2 Days, 3 hrs, 5 min

De Burr Stream
Lead Time
1 1/4 days, 19 hrs, 25 min
Process Time
19 hrs 25 min

CNC Mill
Lead Time
6 1/2 Days, 8 hrs, 10 min
Process Time
4 Days, 8 hrs, 10 min

Man Mill
Lead Time
1 1/2 Days + PT ??
Process Time
??

EDM Stream
Lead Time
1/4 Day, 23 hrs, 5 min
Process Time
23 hrs 5 min

OSP
Spline / Heat Treat
Lead Time
3 Weeks
Process Time
??

OSP NDT / Passivate / Anondize
Lead Time
3 Weeks
Process Time
??

Assembly Stream
Lead Time
7 1/2 days 6 hrs
Process Time
5 Days, 6 hrs

Power Analysis: Machine Energy Consumption Readings

Voltage Baselines			
	208V 3Ph	**480V 3Ph**	
Ph1-3	207	485	
Ph 2-3	207.4	485	
Ph 1-2	207.4	483	

Machine: Mazak QT 100 + SMW Spacesaver 2200
Machine Type: Lathe
Machine ID: CL04
Voltage: 480 3Ph

Currents	**Idle(A)**	**Run(A)**	**Cut(A)**	
Ph1	2.6	4.2	4.4	
Ph2	2.6	4.3	4.4	
Ph3	2.4	4.4	4.4	
power	**2125.593333**	**3607.915**	**3691.82**	**Watts**

Notes

Setup: Had SMW Spacesaver 2200 bar feeder connected
Idle: Power and lights on, no pumps or motors running
Running: Main spindle running 1400RPM no load, coolant and feed chute on
Cutting: 1400RPM spindle, no load, servos running program, coolant+chute
Other:

Machine: Mazak QT 250
Machine Type: Lathe
Machine ID: CL02
Voltage: 208 3Ph

Currents	**Idle(A)**	**Run(A)**	**Cut(A)**	
Ph1	N/A	9.4	14.7	
Ph2	N/A	9	13.4	
Ph3	N/A	9	14.4	
power	**#VALUE!**	**3270.738**	**5073.225**	**Watts**

Notes

Setup:

Idle: Not Available during test
Running: 327RPM, No load, coolant and conveyor running
Cutting:
Other:

Machine: Fadal VMC4020HI
Machine Type:
Machine ID: C3
Voltage: 208 3Ph

Currents	**Idle(A)**	**Run(A)**	**Cut(A)**	
Ph1	2.2	3.7	4.6	
Ph2	3.4	6.1	7.3	
Ph3	4.9	6.1	7.1	
power	**1253.385**	**1897.983**	**2268.03**	**Watts**

Notes
Setup:
Idle: Power on, no coolant pumps
Running: Motors on, coolant on
Cutting: Under load and coolant
Other: CM012 XTREME Cool 250C

Machine: Fadal VMC6030HT
Machine Type:
Machine ID: C-1
Voltage: 208 3Ph

Currents	**Idle(A)**	**Run(A)**	**Cut(A)**	
Ph1	1.9	2.2	8	
Ph2	3.9	4.4	13	
Ph3	4.6	5	11	
power	**1241.448**	**1384.692**	**3819.84**	**Watts**

Notes
Setup:
Idle: On, no pumps, no spindle

Running:	3154 RPM on spindle plus coolant pumps
Cutting:	
Other:	

Machine: Haas SL-40L
Machine Type:
Machine ID: F-3
Voltage: 208 3P

Currents	Idle(A)	Run(A)	Cut(A)	
Ph1	4.6	7.9	N/A	
Ph2	6	11.5	N/A	
Ph3	6.5	12.5	N/A	
power	**2041.227**	**3807.903**	**#VALUE!**	**Watts**

Notes

Setup:	
Idle:	Power on, lights on, no pumps running
Running:	No load, coolant and spindle running
Cutting:	
Other:	Machine broke down before we were able to get cutting measurements

Machine: Mitsubishi FX10K
Machine Type: EDM
Machine ID: F-5
Voltage: 208 3Ph

Currents	Idle(A)	Run(A)	Cut(A)	
Ph1	17	N/A	N/A	
Ph2	16.6	N/A	N/A	
Ph3	13	N/A	N/A	
power	**5562.642**	**#VALUE!**	**#VALUE!**	**Watts**

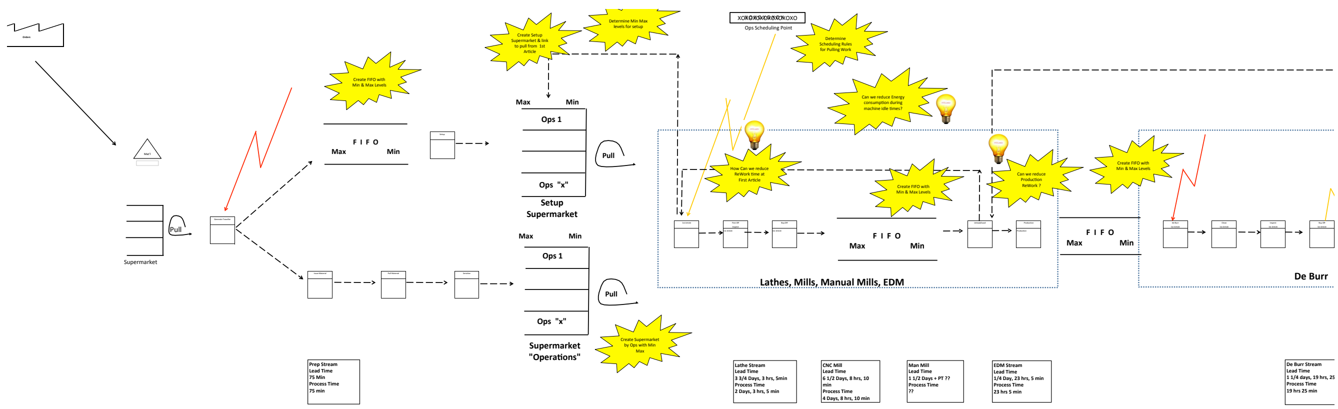
Notes

Setup:	
Idle:	Computers and lights on, coolant bath pump running
Running:	

Cutting:
Other: Machine was not avaible to run

Task 5.0: Future State Energy Reduction Map Task

Future State Energy Reduction Mapping took place in April 2015. Lean Advisors facilitated a workshop to develop and review the Future State Energy Reduction Map. Lean Advisors conducted a report out to communicate findings to ITDE management team.



Snapshot of Future State Energy Reduction Map

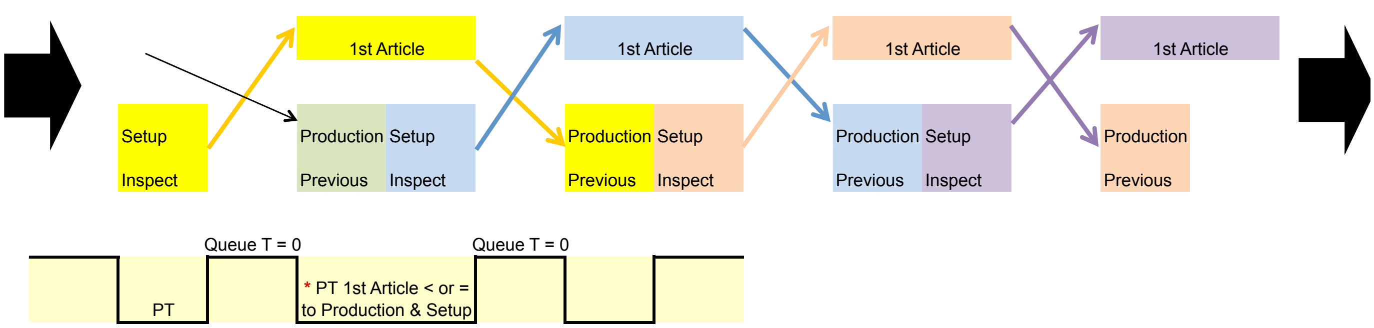
- Energy Future State Design Guidelines and considerations: Manufacturing at an optimum operating point, reducing energy demand of resources by technical improvements, minimizing energy consumption of resource during stand-by operation, minimizing energy consumption during turn-on and turn-off, leveling energy consumption, laying down energy efficient processing sequences, synchronizing energy supply and energy consumption.
- The Future state map included energy kaizen starbursts for energy improvement opportunities and Impact analysis

Task 6.0: Energy Reduction Implementation Plan

Lean Advisors created an Implementation Plan (multi year roadmap) and details for how each part of the recommended changes would be carried out. The implementation plan includes methods for improving energy performance and efficiency in operations and training, methods for promoting energy efficiency at ITDE. Each identified improvement opportunity was documented with expected benefits with respect to linking to the Energy consumption metrics. Lean Advisors is currently developing a go-forward plan to be used by ITDE to apply Value Stream Mapping and kaizen events to additional production lines.

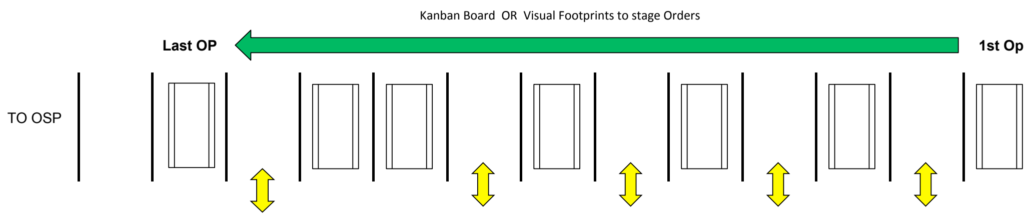
Improvement (Kaizen) Event	Activity	Lean Concept	What does Success look like? Measurable Goal	
			Current	Required
Set pace of production to TAKT time (Customer Demand Rate)	Set pace based on Weekly Demand	Client Pull	unknown	52 weekly
	Determine number of Lathe,Mill, Man and EDM Ops required weekly to meet weekly shipments (51 Shipments)	Reduce Over Production	unknown	59 Daily
	Establish Visual Control "dashboard" to show on / off production		Go See	
Determine "scheduling rules" to PULL work forward	pull next operation based on the completion of an operation	Reduce WIP		
Create a 1st Article Supermarket and stage work by the operation step not by type of operation	establish min / max levels for each	Flow & Pull		
	locate space			
Create FIFO Lanes 1st Article to Production	Establish min / max level	Flow		
	locate space			
Create FIFO Lanes Production to Deburr	Establish min / max level			
	locate space			
Creatte FIFO Lanes from OSP to Assembly	Establish min / max level			
	locate space			
How can we reduce Process Time at 1st Article?		Rework Over Processing		
How can we reduce production re-work		Rework Over Processing		
How can we reduce Energy consumption during idle time		Over processing		

Kaizen Activity Plan



* This three step process does not allow for queue time between operations. It does design in wait time as Production must wait for Previous Production Order Run and Setup for Next Order Run. Quality must complete 1st Article Inspection within this window.

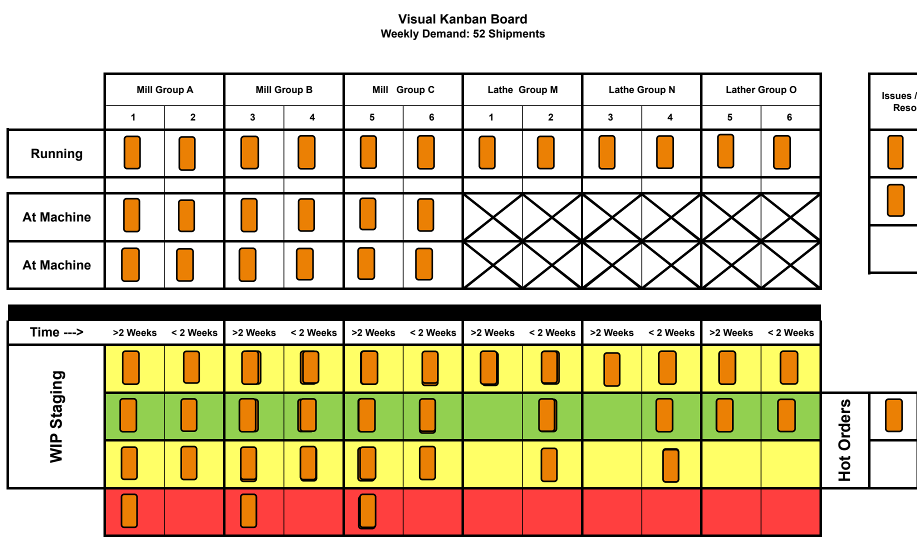
Mill Flow Scenario



-- Must be simple / no effort to advance orders from initial op to final op
-- Must limit the number of orders allowed to be in process at any one time
-- Must know at a glance that we are in control or out of control - is it the plan / actual board??

Floor inspection on floor - **1st article** on floor (for Lathes at this time) -- frees up equipment inside to do more Finals on days
No lathe work on the CMM -- prevents CMM from becoming a bottleeneck
3rd CMM is on the table to purchase
Certifed program - approve 1st article -- lock it PLUS with SPC CPk we should be good ------is part of Sampling Plan that Honeywell must approve -->>>> what can we do in a long term
Product Audit ongoing throughout (internal processing) the Order mfg.
Staff in Quality to work extra hours to eliminate backlog in Product Audit

Kanban Visual Management



Quality Inspection Demand 1st Article, Final & Product Audit			
Plan	Plan	Actual	Variance
Monday	59		
Tuesday	59		
Wed	59		
Thurs	59		
Fri	59		
Sat	59		
Sun	59		
Total	**416**		

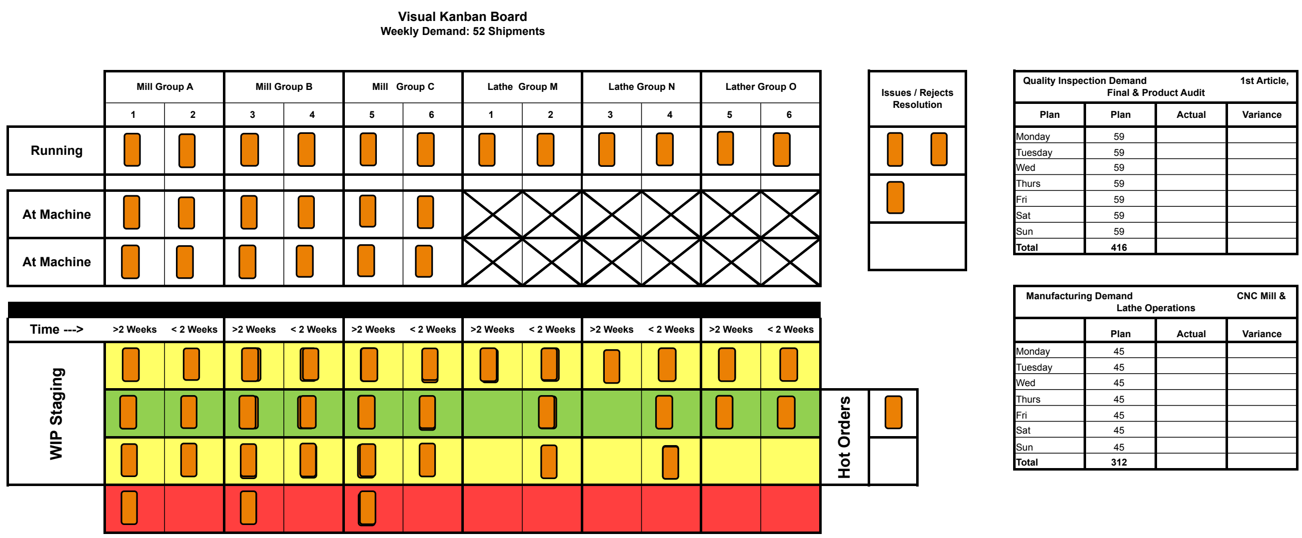
Manufacturing Demand CNC Mill & Lathe Operations			
	Plan	Actual	Variance
Monday	45		
Tuesday	45		
Wed	45		
Thurs	45		
Fri	45		
Sat	45		
Sun	45		
Total	**312**		

Visual Kanban Board

Task 7.0: Implementation Support (Energy Kaizen)

Lean Advisors began facilitation of Energy Kaizen / Rapid Improvement Events. Kaizens focused on the reduction of processing times by creating a Kanban Pull system through the CNC Mill and Lathe Operations. This in turn significantly reduces machine run times, resulting in significant reduction of energy consumption

Outcomes from Kaizen:



- Team identified need fro effort to support improved flow / pull to reduce Lead Time through the CNC Mill & Lathe operations requires improvement in Quality inspection and re-work
- Team identified need to move Quality inspection out onto the work floor to support operators and identify issues earlier in the process ---earlier detection to reduce re-work of rejects
- Quality to complete on floor inspection for Lathe Ops – Mill inspection will continue to be completed in Quality room within a controlled environment ---- reduce Lead-time by coordinating inspection to work in real time, in conjunction with operations
- Introduce Operator certification for inspection to improve and standardize operator inspection practices and methods. ----Improve measurement accuracy to reduce lead time and unnecessary duplication of effort
- Quality to complete Full Product in concurrence with the order flowing through the operation ---- allows for earlier detection/correction and reduces backlog and lead time at final inspection to shipping
- Introduce a Heijunka board or alternative Scheduling tool that will
    - Fix amount of WIP within operations at any one time
    - Introduce the concept of Pull by ensuring new orders are inducted based on the pull of a completed order

   - Provide a visual management system that allows all staff, supervisors and managers with real time status in terms of whether or not manufacturing is on or off production at any time
- Purchase of a manual CMM: ITDE has purchasd a manual CMM machine as a result of the kaizen event. This piece of equipment will allow Quality inspectors and trained staff to take critical part measurements in less than 10% of the time that they currently spend. This is a tremendous processing time improvement (resulting in energy reduction) BUT more importantly from a Lean perspective it represents a significant opportunity to reduce backlog - orders waiting to be inspected. As a result of orders that are trapped waiting to be inspected, scheduling often introduces new work, new orders into the process in order to keep people and machines busy. This results with increased Work in Process and as a result the total Lead -time increases which means the machines are running longer for each order. By reducing backlog at inspection / Quality inspection with a manual CMM, the right orders at the right time are available to operations and they are able to reduce total turnaround time to complete the end to end process resulting in less energy being used to complete each part.

Savings:

Operation	Production Run Processing Time*	Machine Idle*	Rework / Reject Rate*	Energy Consumption Rate (Idle)	Energy Consumption Rate (Run)	Energy Consumption Rate (Cut)
	Hrs	%	%	Watts	Watts	Watts
CNC Mills**	80 hrs	40%	32%	1253.385	1897.983	2268.03
Lathes**	20 hrs	40%	31%	2125.593	3607.915	3691.82
EDM**	20 hrs	20%	11%	5562.642	NA	NA

Current Consumption per Order	Energy Consumption Savings Per Order with Rework / Reject % Improvement			Annual Energy Savings Watts ~2600 orders annually		
Watts	20%	30%	40%	@20% improvement	@30% improvement	@40% improvement
181442.4	36288.48	54432.72	72576.96	94350048	141525072	188700096
73836.4	14767.28	22150.92	29534.56	38394928	57592392	76789856

**Based on CSData*

** Based on Machines Operating at time of Sampling

Based on completion of the initial Kaizen, Re-work reduction and inspection delays will have significant Lead time reductions and increasing throughput, meaning more orders will becompleted within a specific timeframe. From an energy perspective this is reflected in an estimated % improvement in energy consumption per order produced.

Next Steps

Project Plan for Next Steps

The above noted implementation plan represents areas of focus to provide a potential path forward for future activities that could aid in further identifying and alleviating the current bottlenecks and non-value-add-activities that are increasing unnecessary energy usage at ITDE.

The main areas of opportunity that Lean Advisors is proposing to focus on for next steps include:

Yellow Belt Training – In order to both lay the foundation and set the stage for true sustainability, we are proposing online Yellow Belt Training for ITDE operational staff (up to 12 participants). The Yellow Belt training will be accompanied with workbooks that will focus each module on the energy component of continuous improvement. Our Lean Yellow Belt Program is designed primarily to provide a practical Introduction to Lean principles tailored specifically for individuals directly involved in continuous improvement activities within a manufacturing environment. At the conclusion of the workshop, participants will have an understanding of Lean as a client-centered philosophy that combines a proven methodology to lead continuous improvement teams to improve energy efficiency at ITDE. Participants will have the understanding of how to successfully select and engage the appropriate team to properly identify and improve processes within your area of responsibility. Lean will support efforts to effectively optimize process flow, increase energy efficiency and ultimately decrease costs.

Energy Kaizen Event #1| Reducing Process Time at 1st Article

Currently, a significant amount of time is being used to set up for 1st Article. Parts are being reworked multiple times. Meanwhile, the machines are running at full capacity while adjustments are made to parts. It can easily take from 2 hours to 1 day to get the part correct. Our objective is to facilitate an energy kaizen event with the goal being to reduce processing time at 1st article, so that we may reduce machine run time and save considerable amounts of energy.

Energy Kaizen Event #2| Energy Treasure Hunt - Currently, there is considerable wasted energy in ITDE operations. The Energy Treasure Hunt is a structured and collaborative event – driven by the employees that work in the facility. Rooted in team-based problem-solving, this multi-day project draws upon the experience of a cross-functional team to find and eliminate wasted energy in facility operations, as well as identifying upgrade opportunities to push efficiency performance even further.

END OF DOCUMENT

Final Report: 2015 Innovation in Advanced Manufacturing Grant Competition

Arizona Commerce Authority

Lean Advisors USA and Industrial Tool Die & Engineering

Intersol

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Background

- In 2015, the Arizona Commerce Authority conducted an Advanced Manufacturing Grant Competition that funded projects that develop innovative new tools and technologies that both improve productivity and reduce energy consumption of older generation machine tools.

- Lean Advisors USA and Industrial Tool Die & Engineering partnered up to address the following topic area: **Topic Area 1: Integrated Lean & Green Energy Improvement Tools.** Rapid response Kaizens help identify integrated productivity and energy use improvement opportunities using data driven tools and methods developed and supplied Lean Advisors USA that link proposed improvement ideas to bottom line financial savings and energy use impact at ITDE.

Approach

- **Yellow Belt Training andCertification** In order to both lay the foundation and set the stage for true sustainability, we provided Lean Yellow Belt Training for 12 ITDE operational staff. Participants now have the understanding of how to successfully select and engage the appropriate team to properly identify and improve processes within their area of responsibility.

- **Lean Energy Training**Lean energy training will provided allowed Lean teams to recognize energy usage and impacts. The training discussed Lean and it's application to Energy reduction including the various tools that were applied (Recognizing Energy Waste, Ends, Kaizen Energy Events).

- **Energy Kaizen Events** Lean Advisors facilitated Energy focused kaizen events, in order to analyze and eliminate energy waste from focused areas. The Kaizen Events involved a cross functional team and implemented process changes to reduce energy waste. Kaizen events allow the team to better understand how energy is used and brainstorm opportunities to reduce energy use.

Approach

- **5S Workplace Organization** 5S often is where continuous improvement in a particular area begins. The five terms, which all begin with S, describe an action used to create and maintain a safe, organized, clean, high-performance workplace: sort, set, shine, standardize, and sustain. Front- line employees will not be able to effectively implement energy-management / improvement techniques without these characteristics. Through regular use, 5S trains minds and eyes to see waste and provides an easy-to-understand and universally applicable methodology to eliminate and prevent it. Eliminating waste at ITDE means reducing equipment idle time and reducing energy consumption.

Approach

- **Visual Management** refers to the concept of conveying pertinent knowledge of an environment's processes and conditions to everyone working in that environment using visual signals. It enables employees to differentiate between a normal and an abnormal situation immediately.

- Visual Management is an integral part of energy efficiency continuous improvement programs. These tools enable operational efficiency, which in turn supports efficient use of energy.

RESULTS

Need to celebrate…

- Have dedicated over 900 hrs in Kaizen/lean activities
- 12 members of the lean team have completed on-line lean six sigma training and trained in kaizen event methodology. ITDE has now a train team to facilitate change and conduct energy kaizens.
- QC area was transformed through visual management, 5S and muda/waste elimination, providing better organization, and improving work flow to reduce energy
- 80% of 5's activities defined by the team have been closed
- Two VSM were performed for QA and First Article representing benefits to **reduce 6.28 hrs in QA time, 4.1 hrs in equipment idle time per batch** and cutting **50 hrs in queue time waiting** for QA for prototypes
- Improvements will be scaled up and deployed to rest of the production part numbers representing a significant impact in production lead time and energy efficiency.

- Visual management techniques were implemented and ITDE saving them significant time on waiting and reducing equipment idle time. this allows for a more continuous flow and more effective anticipation of potential problems and debug.
- Improved sequential processing flow. This also optimized equipment utilization resulting in energy reduction.
- ITDE is cutting (depending on prototype) an average of 58 hours on lead time for prototype, reducing equipment idle time.T his also reduces rework and increases process effectiveness by 20-30%.
- Certified operators now do their own inspections providing continuous flow to operations, reducing machine idle time, and reducing QC time for inspections.

Challenges that need to be overcome to sustain kaizen/lean efforts to improve energy efficiency

Premises:

- Management is the ultimate driver of the transformation:
  - Make employees accountable to stick to new changes
  - Ask daily for direct reports about kaizen and 5S activities
  - Assigned time for kaizen/lean activities based on proposed plans
- Everyone is responsible for kaizen activities and sustainment
- Lean team is responsible for transformation plans, providing training, guidelines and standards for Kaizen processes and monitoring adherence

Set clear accountability

- Make kaizen a priority
- Do a 15 min Gemba/shop floor walk every day and challenge people on Kaizen activities, improvement ideas, adherence
- Align performance review and compensation to kaizen expectations
- Enable resources that will make things better (people's time)

HOLD FIRM TO KAIZEN PRINCIPLES

Next Steps - key actions need to be completed to capture all benefits

- **Roll out 5S** to every section/area of the organization

- **Close VSM actions plans**:
  - Define criteria and curriculum for **Certified operators**
  - Approve and execute new procedures to enable proposed changes (QC for Opck, work instructions)
  - Continue to test new VSM on new prototypes
  - Continue to hold and roll out **stand up** meetings involving operators and front line

- Spread benefits to all part numbers

KAIZEN EVENT : Increasing Work Flow to Reduce Idle Machine time and Reduce Energy

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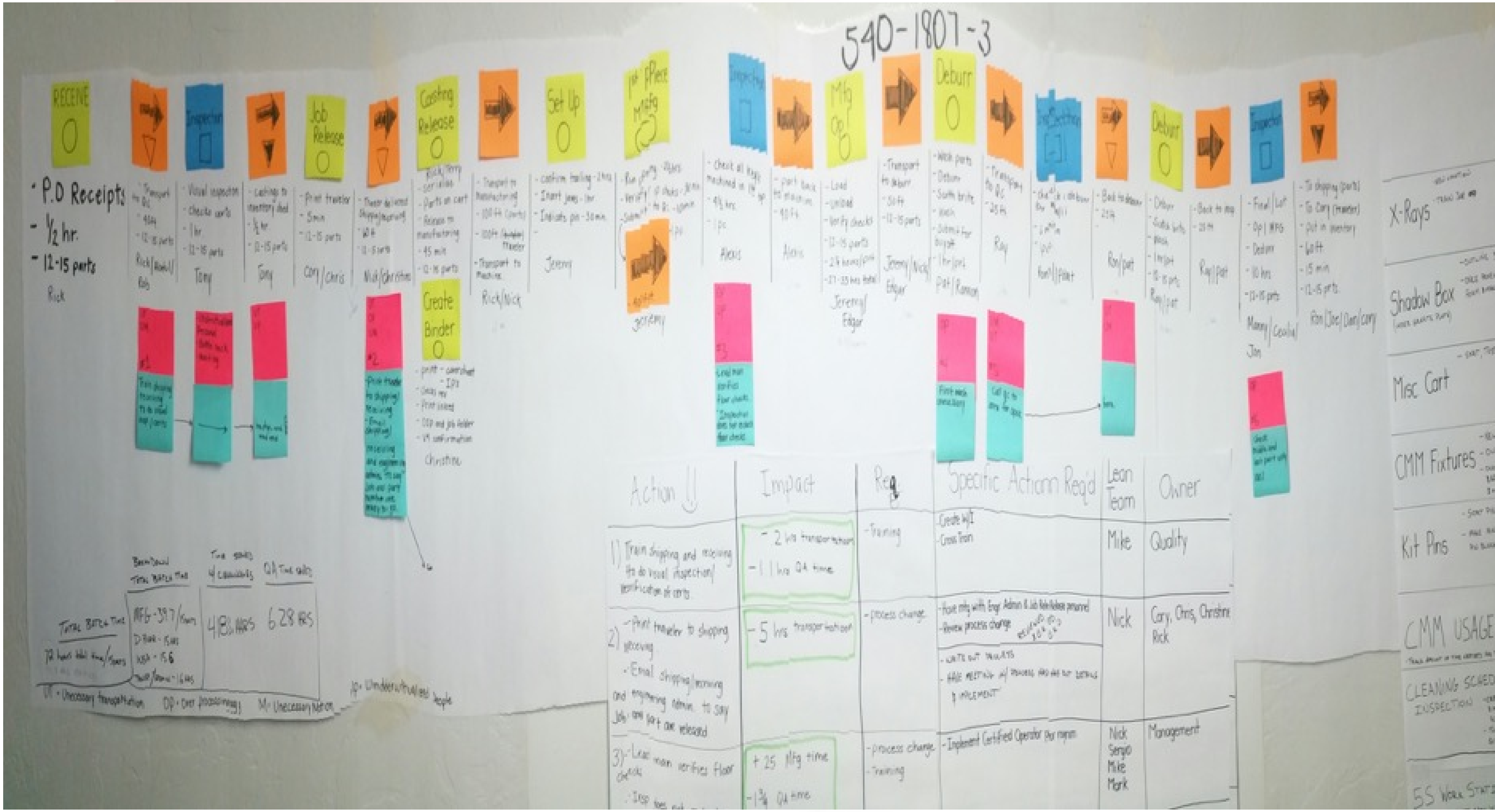
Cover Page, Team picture and objectives

LEAN TEAM:

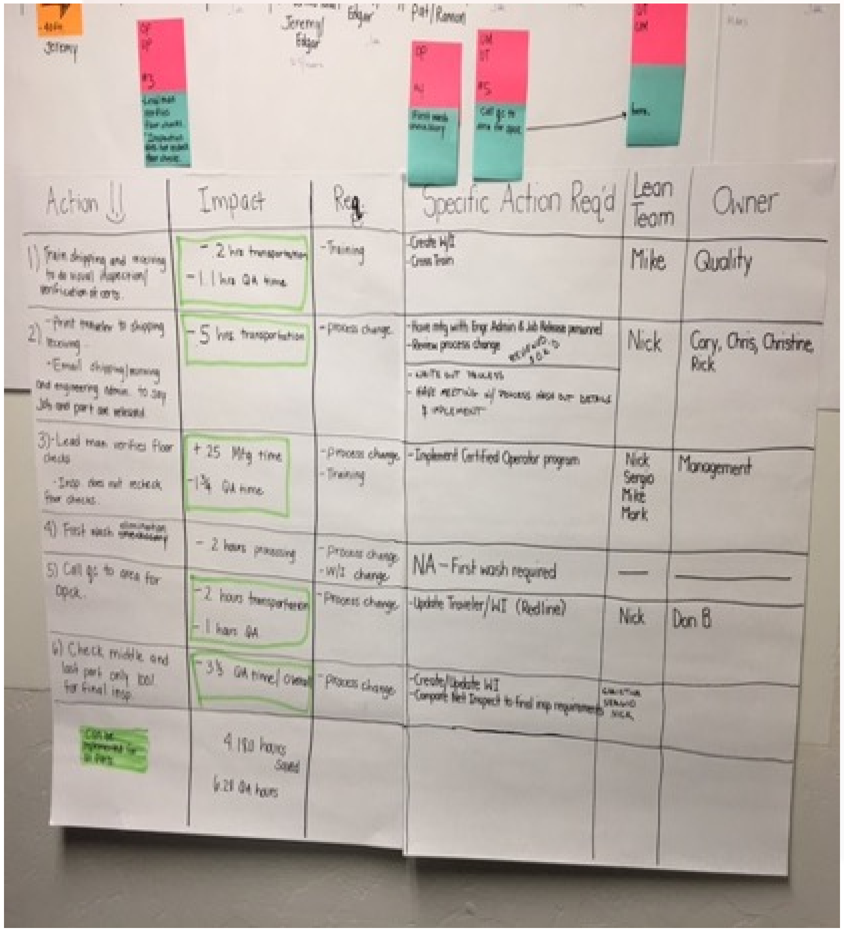
- Alexis
- Jesus
- Nick
- Christine
- Todd
- Sergio
- Jake
- Teresa
- Matt
- Mark
- Dwight
- Mike
- James

Objectives:
Increase work flow, decrease FA times, and decrease the amount Of time a part spends in QC resulting in lead time and energy reduction

VSM for regular production (picture and findings)



Action plan and Impact



Action plan

- Step 1: Training Shipping and Receiving.
- Step 2: Job release procedure.
  - Reached agreement with all involved.
  - Nick to write procedure.
  - Doing this will save .5 hours of transportation.
  - This can be done with 90% of jobs.
- Step 3: Certified Operator. Presented in Prototype section.
- Step 4: Eliminate first wash in review.
- Step 5: OPCK
  - Redlines have ben signed and submitted to change FA's to OPCK's
  - This process change will save .2 hours in the transportation of parts & people.
- Step 6: Integrate Net-Inspect into final inspection
  - still in review.

Impact:
These steps will save 4.18 hours in production time Resulting in less Equipment running time and less Energy usage. In addition, the steps save an additional 6.28 hours in QA per part number.

Annual projection savings for part #540-1807-3 is aprox $9,000 USD . This can be deployed to 90% of total Volume.

5's Activity in QA area (pictures before and after)

Removed the clutter and created away to track CMM fixtures.
(Red totes will be removed once fixtures have AAITD numbers)

5’s Activity in QA area (pictures before and after)

Moved Surface plate table between the CMM’s so both operators have access to it. Allows for better work flow.

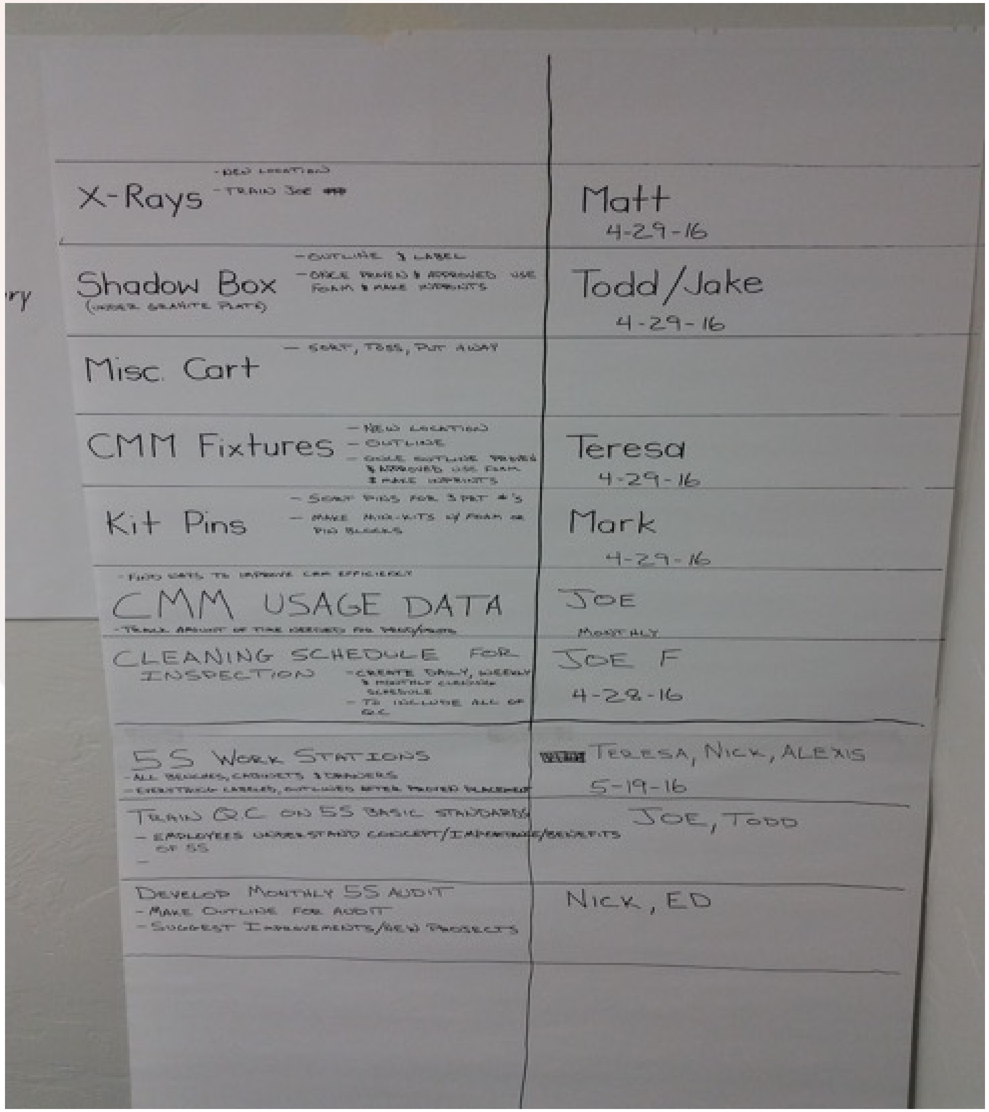
5's Activity in QA area (pictures before and after)

Removed all of the items that were not waiting for First article.
(Picture on the left is of FA are yesterday. Picture on the right is of FA area today)

5's Activity in QA area (pictures before and after)

QA Future lay out

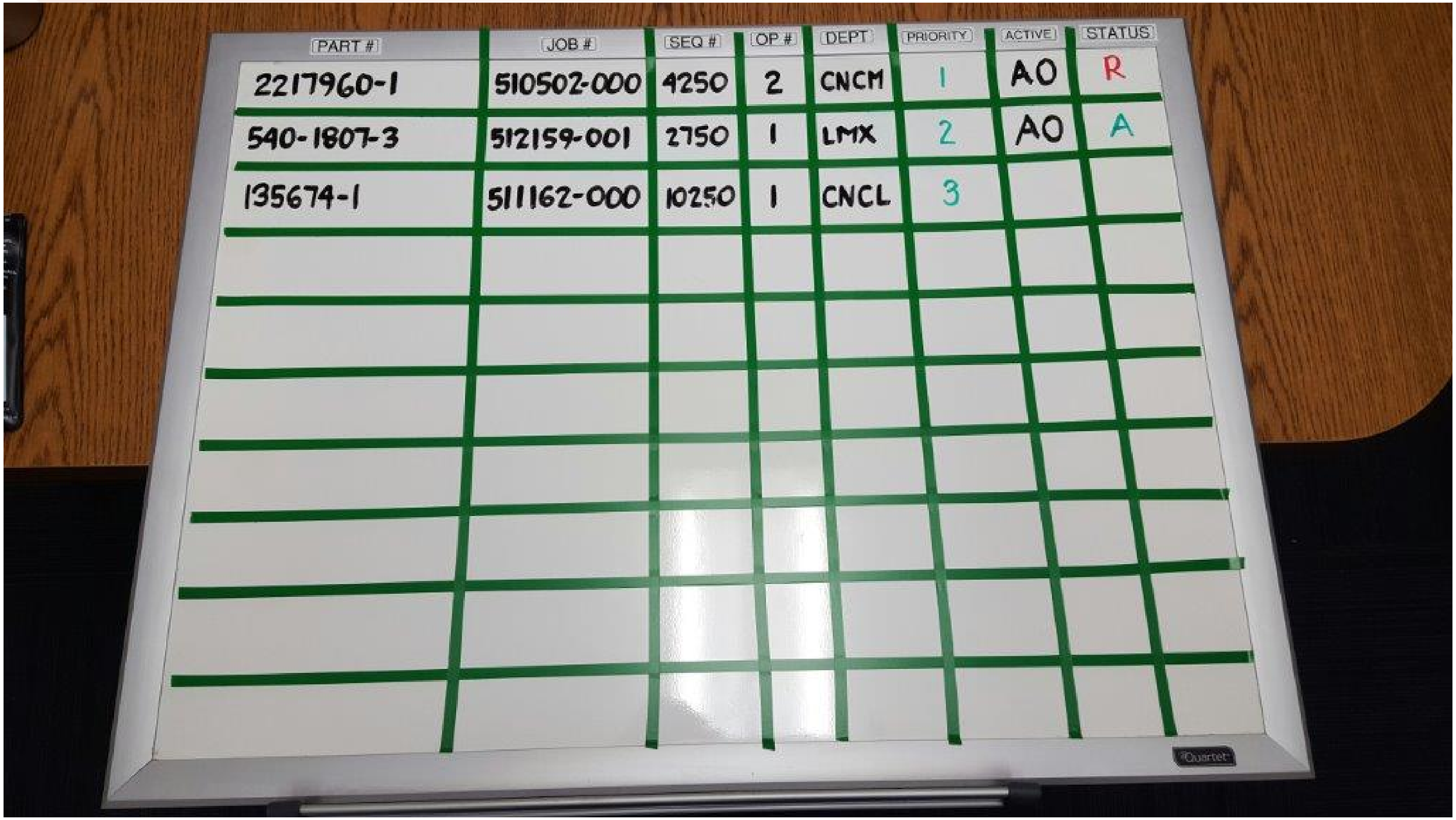
5's Deployment plan



QC Priority List

Part Number	Job Number	QTY	Process	Date Arrived	Date Needed	Days in QC	Total Days Needed	Worker
3233561-901	511366-004	9	Insp for OSP	4/4/2016	4/4/2016	18.00	18.00	
25039-1007-1	512443-000	29	Insp for OSP	4/6/2016	4/6/2016	16.00	16.00	
3826232-1	51214-006	121	Final Insp	4/11/2016	4/11/2016	11.00	11.00	
3233561-901	511365-004	9	Insp for OSP	4/12/2016	4/12/2016	10.00	10.00	
4244821-2	512429-000	62	Final Insp	4/13/2016	4/13/2016	9.00	9.00	
3233561-901	511785-004	9	Insp for OSP	4/13/2016	4/13/2016	9.00	9.00	
3233561-901	511786-004	8	Insp for OSP	4/13/2016	4/13/2016	9.00	9.00	
3237672-4	511111-002	9	Insp for OSP	4/15/2016	4/15/2016	7.00	7.00	
4245374-1	511850-000	30	Insp for OSP	4/16/2016	4/16/2016	6.00	6.00	
3184976-1-FAB2	512116-001	30	Insp for OSP	4/16/2016	4/16/2016	6.00	6.00	
3798693-1	510963-000	40	Receiving Insp	4/18/2016	4/18/2016	4.00	4.00	
2208753-3	512108-001	6	Final Insp	4/18/2016	4/18/2016	4.00	4.00	
23100-1180-901	PO 27810	1	Receiving Insp	4/18/2016	4/18/2016	4.00	4.00	
25039-1000-1	511465-100	12	Receiving Insp	4/18/2016	4/18/2016	4.00	4.00	
7205556-1	511756-000	33	Insp for OSP	3/28/2016	4/19/2016	25.00	3.00	
540-1806-6	510906-002	65	Final Insp	4/20/2016	4/20/2016	2.00	2.00	
5810045-1	511720-001	15	Insp for OSP	4/20/2016	4/21/2016	2.00	1.00	
3237673-3	511111-001	12	Final Insp	4/14/2016	4/21/2016	8.00	1.00	
5810078-1	510906-100	7	Final Insp	4/22/2016	4/22/2016	0.00	0.00	
886015-901	511365-002	9	Final Insp	1/28/2016	4/22/2016	85.00	0.00	
540-1807-3	512157-001	12	Final Insp	4/19/2016	4/22/2016	3.00	0.00	
540-1807-3	512158-001	12	Final Insp	4/18/2016	4/22/2016	4.00	0.00	
21068-1011-1	511986-000	12	Insp for OSP	4/6/2016	4/22/2016	16.00	0.00	
2050203-1	511338-100	270	Final Insp	4/14/2016	5/1/2016	8.00	-9.00	
3169571-6	512334-000	67	Insp for OSP	3/22/2016	5/10/2016	31.00	-18.00	
2712713-1	512441-000	280	Insp for OSP	4/14/2016	5/10/2016	8.00	-18.00	
4245307-902	510098-002	20	Final Insp	7/20/2015	5/16/2016	277.00	-24.00	
2050203-1	511388-000	370	Final Insp	4/15/2016	6/13/2016	7.00	-52.00	
21314-800-2	511500-000	9	Final Insp	3/13/2016	12/12/2016	40.00	-234.00	
21068-1010-1	511934-000	12	Insp for OSP	11/25/2015	12/12/2016	149.00	-234.00	

Daily stand up meeting



Next Steps & Concerns

- Next Steps:
  - A weekly meeting until further notice.
  - Co Training program is to be developed by Joe Foss.
  - A 3 day event follow up near the end of May to discuss the impact of the event.
  - A company meeting to inform all employees of changes.
- Concerns:
  - Push back from quality personnel on all shifts.
  - Night shift not following procedures.
  - Management not standing behind the changes made and the LEAN team.

Prototype VSM

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PROTOTYPE VSM

Identifying Waste

- After careful evaluation of the prototype value stream map, we identified multiple forms of waste.
- As a team, it was important to note that some of the waste items/processes could be eliminated or reduced by simple means of process changes. However, some of these changes will require long term efforts.
- As a positive outlook, this leads us to an infinite path of continuous improvement.

Waiting.....

- Waiting....
- Waiting sucks right?
- Waiting is anytime parts are stuck in “The Que”.
- Waiting is pure waste, and adds zero value to parts
- Waiting causes wasted ENERGY from heating, cooling, and lighting during production downtime
- In the prototype VSM we’ve identified energy waste in the form of waiting

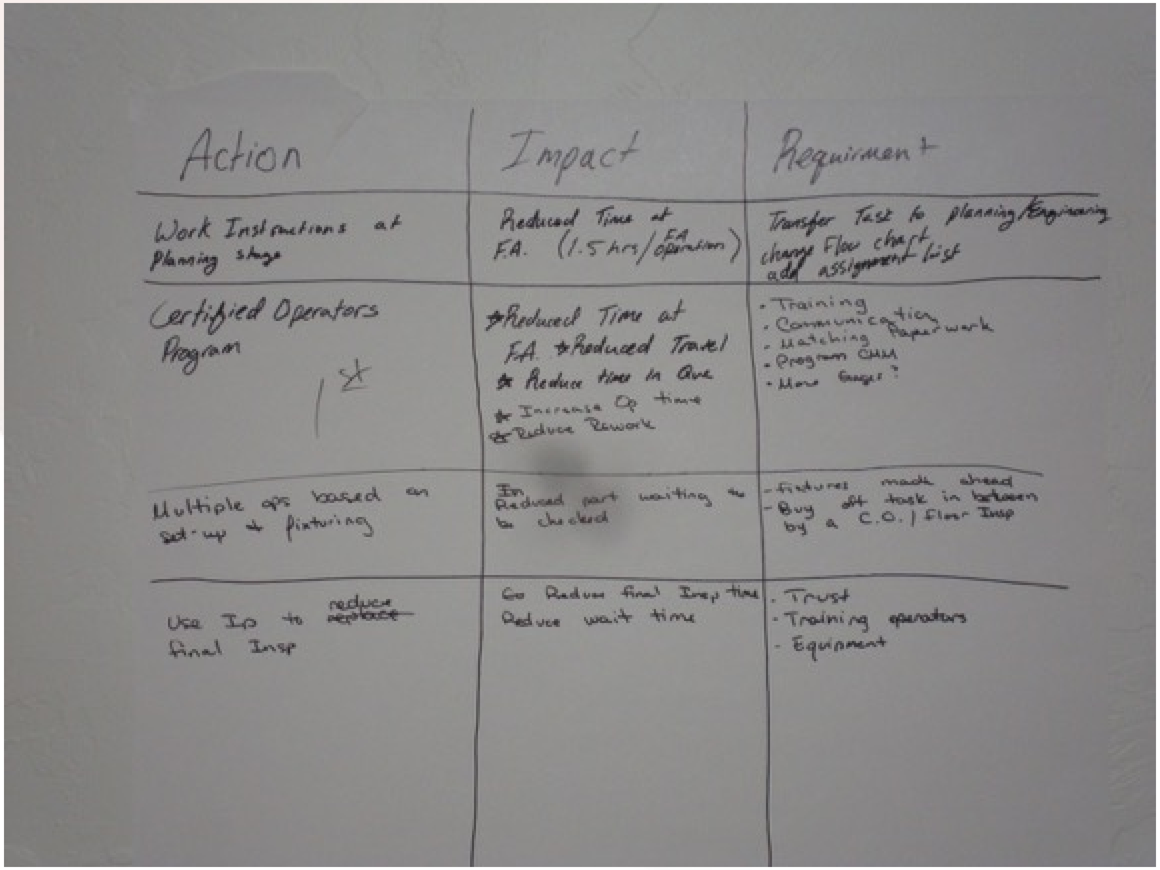
Under utilized personal

- Under utilized personal is also pure waste
- Utilizing all personal can help to alleviate other departments, retain some value lost in que time.
- In the example VSM we've identified waste in the form of UNDER UTILIZED PERSONALE.

Que time in the prototype vsm

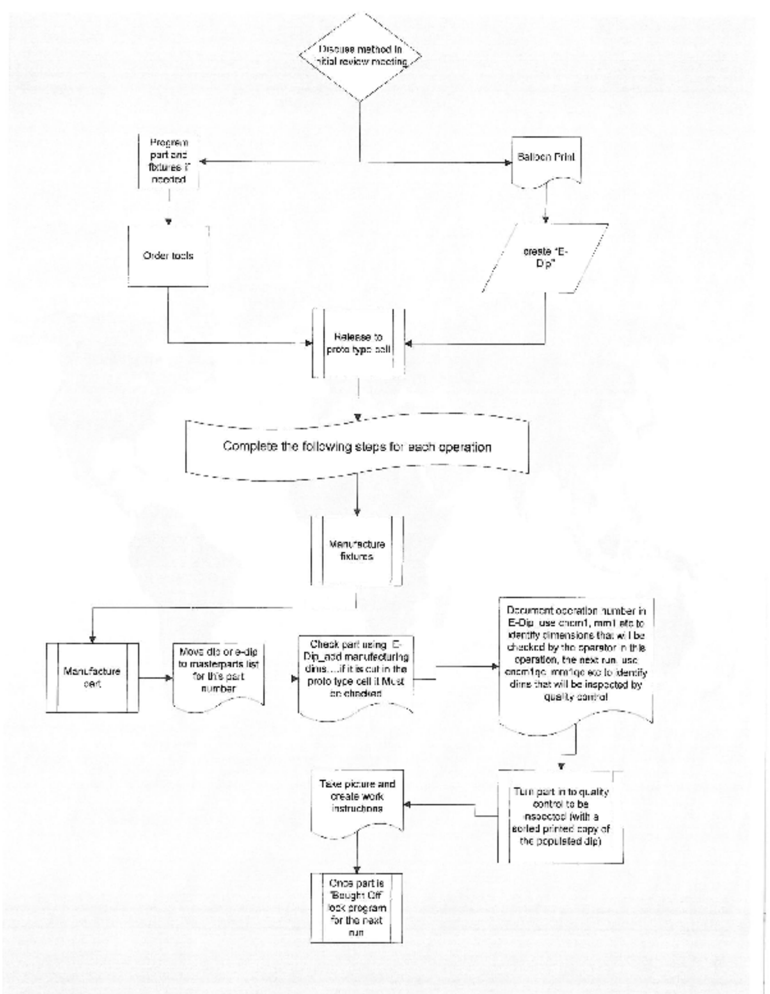
- Notice the orange sections on the VSM, these represent travel time and also “queue” time.
- Notice that every time parts go into Inspection there is queue time.
- The queue time can vary, and is often influenced by inspections backlog. We’ve seen this que time range from 1hr to sometimes 3DAYS!!
- In the example VSM, we see the that the product gets set up in the CNC mill then goes to inspection for FA, at this point the part is in que awaiting FA….
- ….waiting 1hr….to possibly three days… then, if the part is bought off, the operator is allowed to run the rest of the batch. (Note: the time in the que is not time the part is being inspected but rather time the part is waiting to be inspected)
- For every operation we see this process repeat…. Thus, every operation will likely have a possible que time of 1hr to 3 days causing WASTED ENERGY!!!

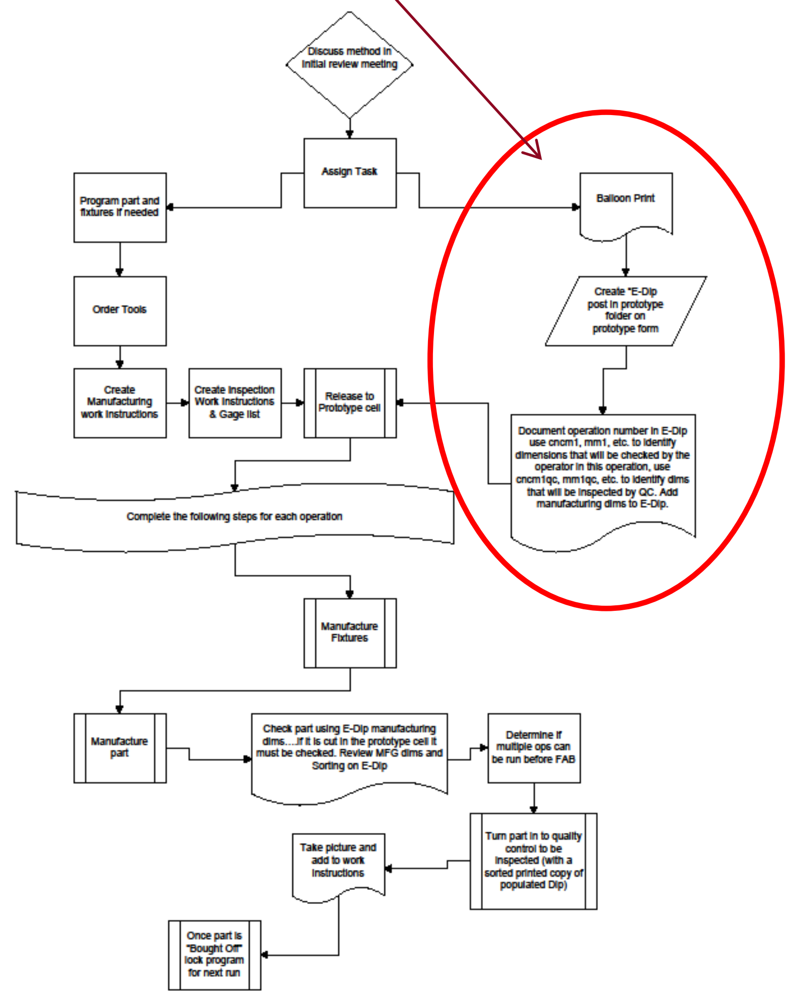
Action / impact / requirements



Developing work instruction at planning stage will reduce defects while cutting prototype lead time

Process was changed to develop work instructions during planning stage





Improvement actions & Impact

- Savings were achieved through to process of:
  - RUNNING MULTIPLE OPERATIONS in CNCs before submission for first article providing continuous flow in operations while reducing unnecessary change overs and wait time on QA inspections
  - USE OF CERTIFIED OPERATORS in both Deburr and Part Marking departments
- By eliminating the amount of times the part is submitted to inspection, we've reduced the queue time significantly.
- Though it is important to note that this process is not always feasible, it is wise to utilize this method when it's appropriate.

Impact

- Reduction of 5 hrs in QA Queue time waiting for inspections. This will cut total prototype lead time by 16-20% resulting in significant energy reduction

Certified operators

- Certified operators (CO) can perform the tasks normally completed in inspection to lighten the load on the QA department.

- In our example we implemented using CO's in only the deburr and part marking departments due to the lower training level needed to implement this change.

As a long term goal:

- The certified operator program outlined in the "Certified Operator Training Document" is designed to produce operators with the skill to check their own parts and alleviate the burden on QA for 100% inspection of first article and final inspection. This includes not only mechanical checks but also the use of the advanced height gage and shop floor CMM and

In conclusion

- We save time and ENERGY by eliminating the use of inspection department between multiple operations, reducing equipment idle time.

2214409																													
ENGINEERING/ PRE-PROD		WATER JET	RECEIVING	CUE	MAT CERTS	FA	CUE	CNC OP1	CUE	FA	CNC OP1	CUE	CNC OP2	CUE	FA	CNC OP2	CUE	DEBURR	CUE	FA	DEBURR	CUE	PART MARK	CUE	FA	PART MARK	CUE	FINAL INSPECT	FAIR
0		10	10		0	10		1		1	9		1		1	9		1			9		1			9		10	0
2 WKS		50	0.5	2	1				24			24		24			24		1			24		0.5			1 WK	5	3
0			20	30			120		60			20		60			100		50			20		30			30		

ENGINEERING/ PRE-PROD		WATER JET	RECEIVING	CUE	FA	CUE	CNC OP1	CNC OP2	CUE	FA	FA	CNC OP1	CNC OP2	CUE	DEBURR	CO FA	DEBURR	CUE	PART MARK	CO FA	PART MARK	CUE	FINAL INSPECT	FAIR	CUE	INVENT			
0		10	10		10		1	1		1	1	9	9		1		9		1		9		10	0					
2 WKS		50	0.5	2					24					24				24				1 WK	5	3		0.5			TOTAL
0			20	30		120			60					100				20				30			50FT				

Notice time saved !!

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To: The Arizona Commerce Authority

From: InterLink Engineering, LLC

Re: 2014 Innovation in Advanced Manufacturing Grant Competition Topic Area 2

Date: September 15, 2015

Overview

In response to the Arizona Commerce Authority's Advanced Manufacturing Grant Competition for *Topic Area 2: "Bolt-On" CNC Machine Tool Sensing & Control Technologies* as described in the ACA supplied document titled; *2014 Innovation in Advanced Manufacturing Grant Competition Southern & Central Arizona Aerospace & Defense Region*, InterLink Engineering is submitting this final report.

InterLink Engineering was awarded a grant to integrate new technology to an existing older generation press at Pilgrim Screw Company, and has now designed, built and installed a custom automation system, referred to as the HSAM in this document, to improve the energy and efficiency on one hot forging press at Pilgrim Screw Company.

Method and Calculations

The HSAM has been implemented and tested on one hot forging press, and at one company. In order to calculate the energy reduction for the HSAM, and to be able to translate it to other hot forging operations, we have separated the press energy requirement from the induction heating energy requirement.

In order to calculate the HSAM press energy requirement, we eliminated the set-up operations for both the die and the heating coil. The result will be the energy requirement for the press only.

Set-up times will vary from part to part, and from shop to shop. However, regardless of what size of press, or what type of hot headed part is being manufactured, or where it is being manufactured, the steps in Table 1 are common to the process. These steps represent the time that the press is running at steady state, and from the time we can calculate the total energy required.

Method and Calculations (continued)

Table 1

Energy Impact Based on Equipment Run Time

Operation	Prior Method Time (s)	HSAM Time (s)
Pick and place a cold slug into the (induction heating) coil.	3	3
Activate the induction heater.	1	1
Heat cycle occurs (part dependent & not part of this calculation)	*	*
React to the timer alarm indicating the heating cycle is complete (operator dependent).	1	0
Remove the slug from the coil.	2	0
Flip the slug upside down.	1	0
Place the inverted hot slug into the die.	2	0
Activate the press.	1	1
Remove the part from the die	3	3
Total time	**14**	**8**

As noted, the heating time and the energy required for the heat cycle is not included in this calculation. The heating cycle varies from part to part due to material, slug diameter, slug length, shape and style of head. Various sizes of heaters are also used, and each will have a different amperage draw and power setting. The heating energy requirement is estimated below, and in the conclusion section, we note the energy savings opportunity available for the heating process.

* Although the heating process requires a significant amount of energy to complete a cycle, it was not part of the scope of work for the HSAM Phase 1 grant.

<u>Method and Calculations (continued)</u>

The following calculations show the HSAM press energy requirement, and the induction heating energy requirement per cycle (for each part produced).

1. HSAM Press Energy (45 ton Minster press)
   1.1. The press runs at 6.7 amps and 460 volts, requiring 3,100 watts of energy to operate at steady state.
   1.2. The time the press runs is typically 14 seconds (not including the heating time), or 3,100 watts x 14 seconds = 43,400 Watt-seconds.
2. Induction heater
   2.1. The heater used in the HSAM can run at a maximum of 40 amps and 220 volts, for a maximum of 8,800 watts.
   2.2. We were able to achieve several production runs at 50% maximum power, or 4,400 watts.
   2.3. Many parts at Pilgrim run at below 12 seconds; but we do not know the power settings used. We believe that it is closer to maximum power based on observations, (and therefore at least 50%) or 4,400 watts x 12 seconds = 52,800 W-s are being consumed for heating.

Using the table to calculate the difference between the initial, manual process, and the HSAM process, we can conclude that the total energy required to operate the press can be reduced by a factor of 6/14 seconds, or 43% of the *non-heating* portion of the production time.

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Conclusions:

1. Implementation of the HSAM reduced the energy used by a hot forging press by 40%.
2. Productivity was increased by reducing the cycle time by six seconds per part.
3. The consistency of the forged parts is improved.
4. The heating cycle time can be reduced significantly with improved coil design and fabrication.

Lessons Learned:

1. The original design provides for X & Y adjustment of the induction coil in relationship to the part to be forged. Since it has proved difficult for Pilgrim Screw to make induction coils that are dimensionally consistent, the design could be improved by having an XY adjustment directly on the end effector, which would allow the operator to more easily compensate for variations in the fabrication of the coil.
2. Matching the design of the coil to the part to be heated is extremely critical especially when heating non-ferrous metals. Design features such as inner diameter, number of turns in the coil, overall coil height and single vs. double coil must be considered when selecting the correct coil for any given part.
3. The position of the part in the coil is also critical. The manual process caused the parts to be heated in a non-optimum position, and it was also not repeatable or adjustable. With the HSAM, this issue has been eliminated by repeatedly positioning the heating coil. Also, the ability to adjust the part height within the coil during the heating process allows for greater control, resulting in better forging results.

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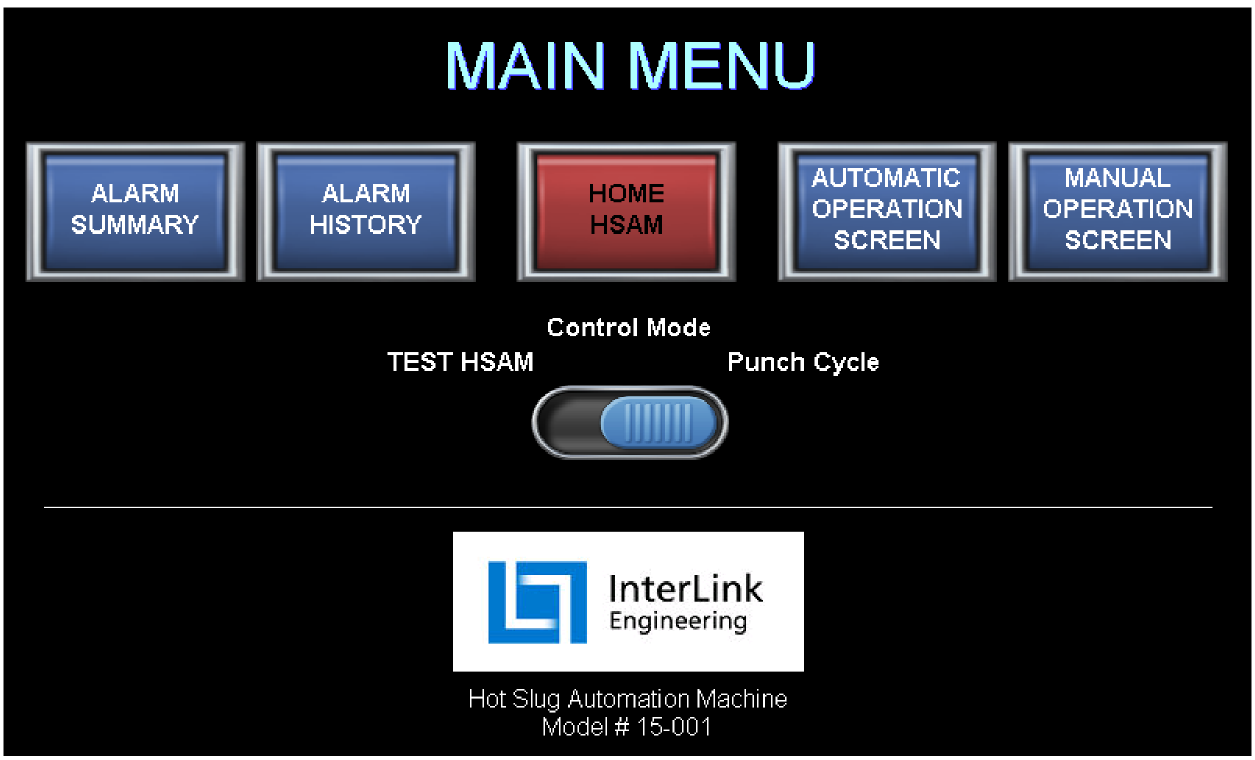
Software

The HSAM has software that was written specifically for the application. It provides the end user the ability to set specific parameters during the set up process to be used during the production runs. The HSAM has an integrated touch screen or (HMI or Human Machine Interface). This allows the inputs to the program to be set by the user without the need to use additional computer hardware. The HMI also provides direct and immediate feedback to user on the current machine conditions and settings. The HMI also has a feature designated as a recipe function that allows the user to save machine settings when desired. All of the machine functions of the machine are controlled or monitored thru 6 different screens.

Screen images and descriptions follow.

Main Menu Page: This is the main screen and allows the user to switch between manual and automatic mode along with providing access to the specific screen the user want to use.



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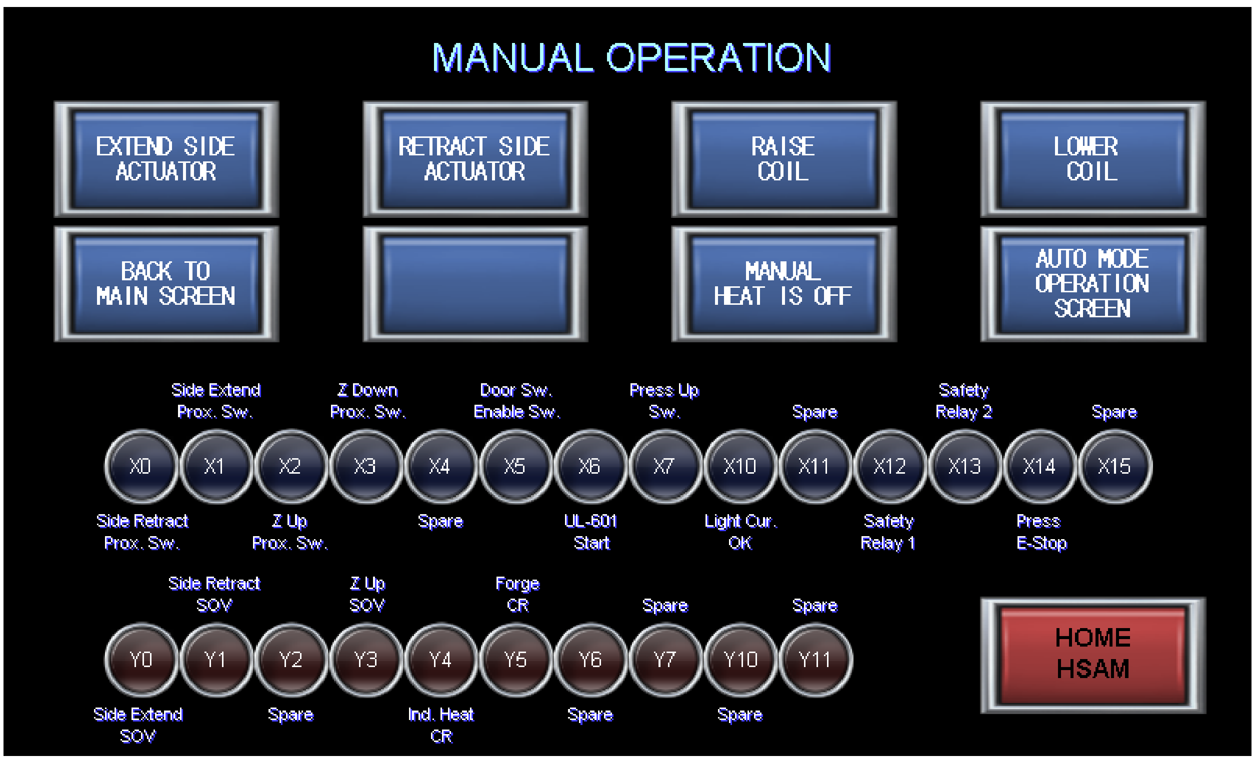
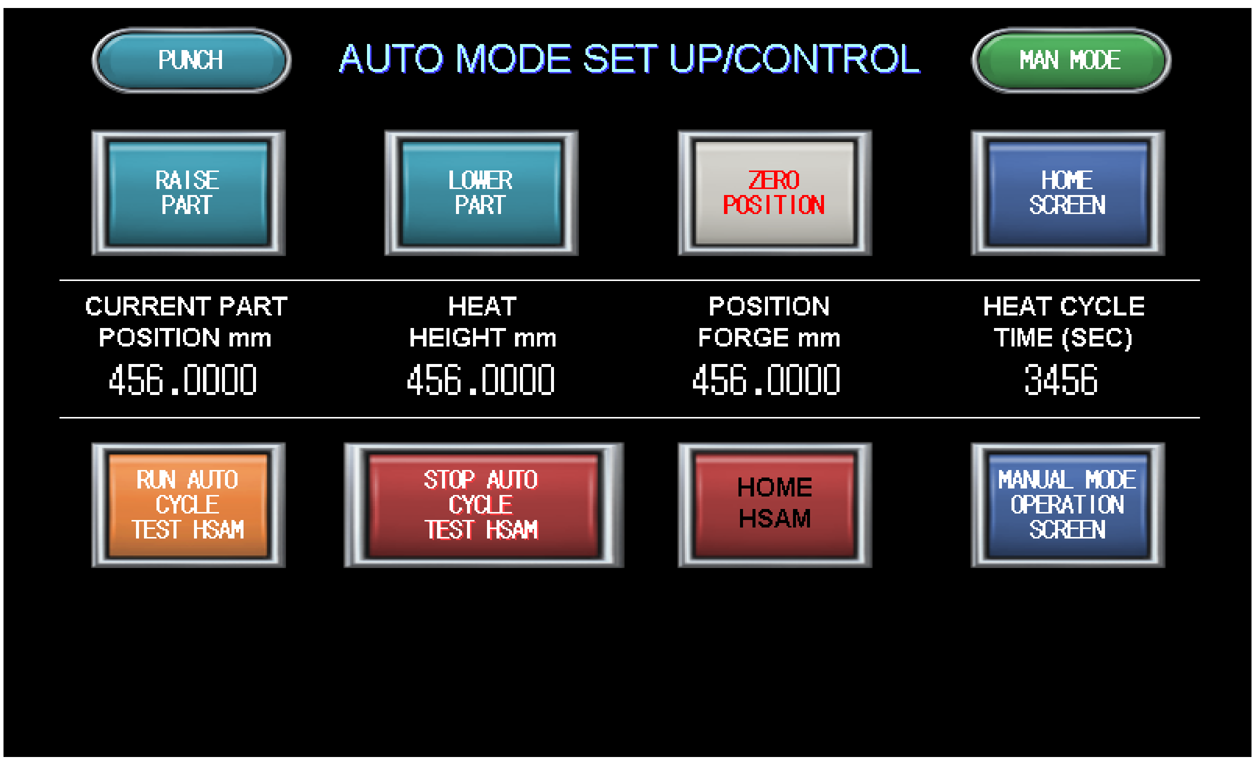
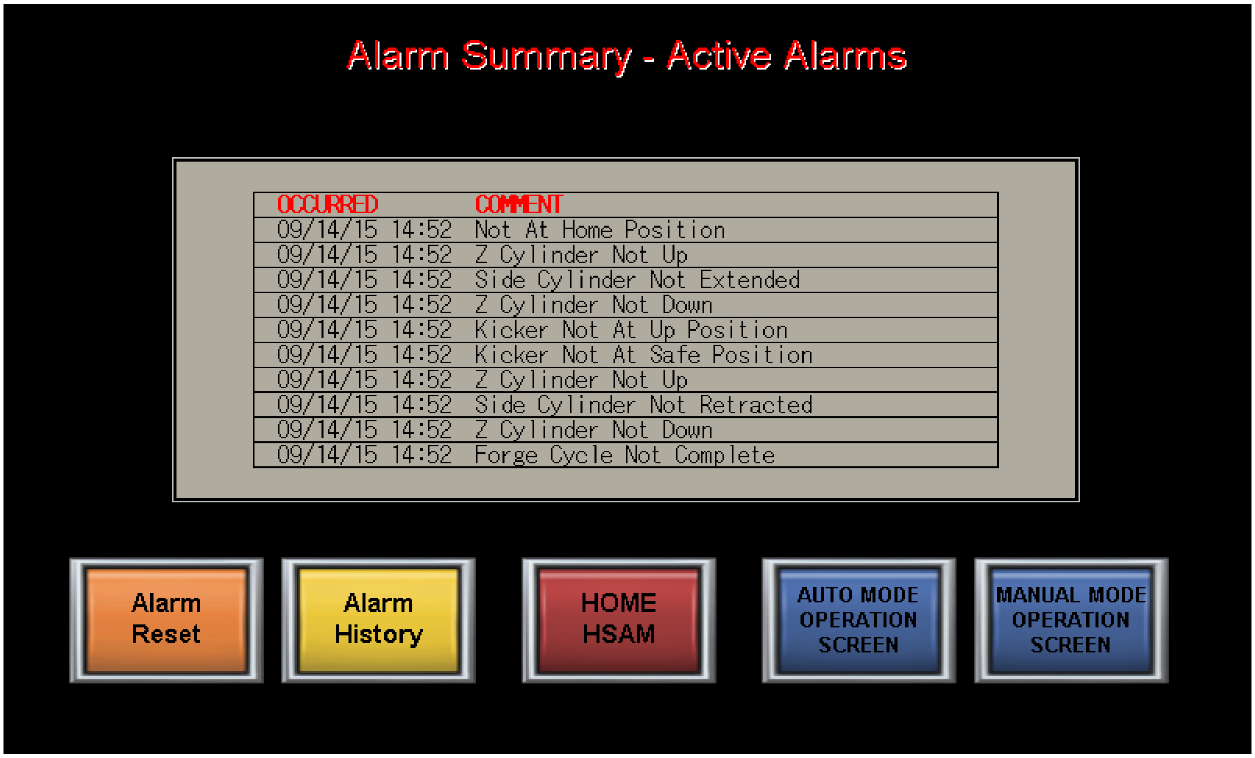
Manual Operation Mode: This page allows the user to function the HSAM manually during the tooling set up. All three of the actuators can be moved to the desired location independently and also has lamp indicators to give feedback to user on the condition of all input and outputs.



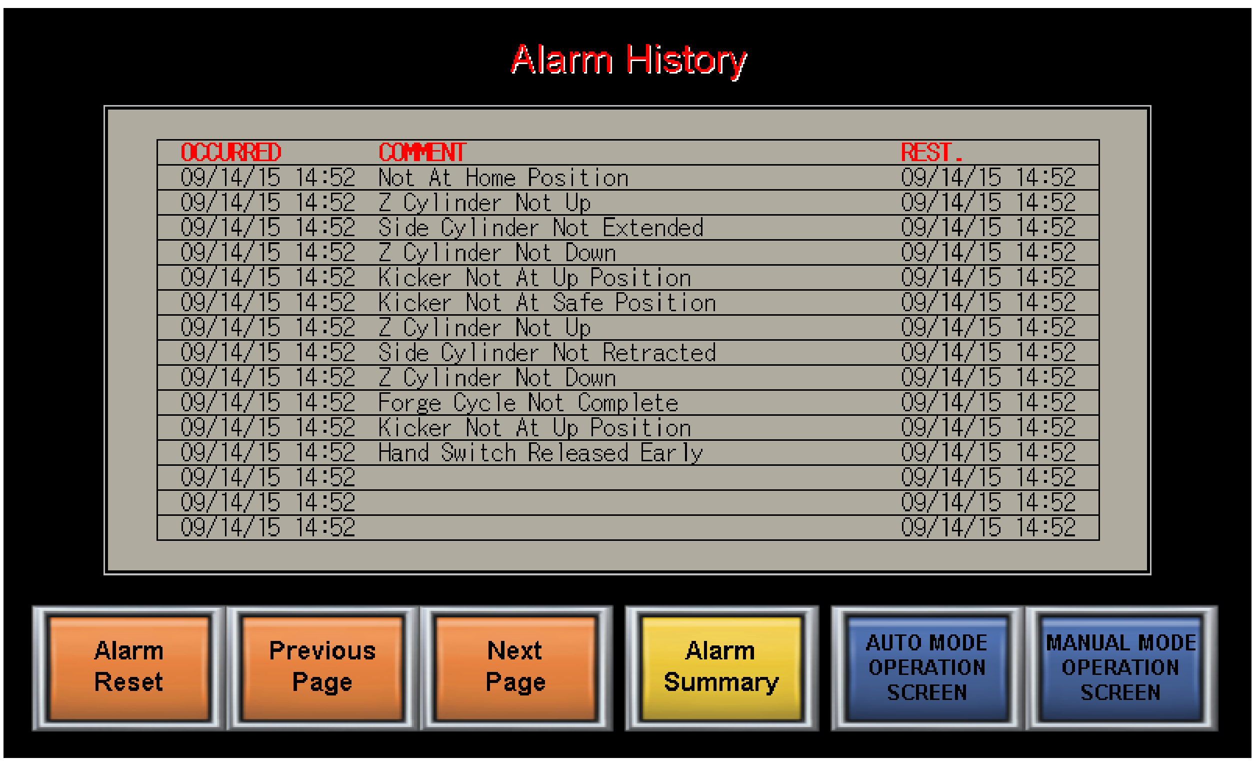
Auto Mode Set Up/Control: This page is used by the user to establish the vertical position of the slug in the die when it is being heated and its position when the punch strikes the heated slug. It also provides an input field to set the length of heat time that was established during the set up process. The page also has lamps that indicate to the user of the current machine mode and position of the part.



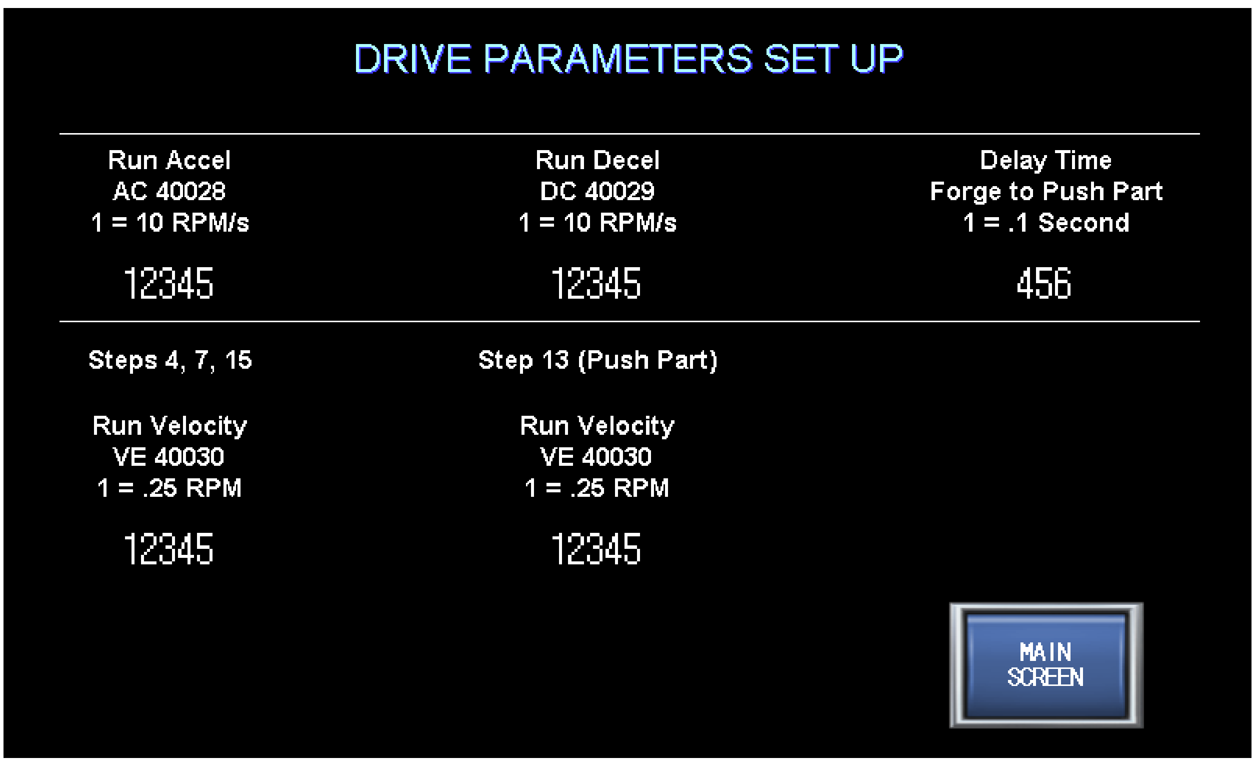
Alarm Summary: This page show any current alarms or faults that would stop the machine from functioning due to an error code created by safety issue, machine was not operated correctly or machine did not function properly. The HSAM is directly tied into the existing press safety circuit but does allow for it to be taken offline so the press can function in its original state when desired while maintaining the full functionality of its existing safety system. The page provides the type of fault along with time and date. At the bottom of the page button are provided to allow the user to reset the alarm function and go to other pages when desired.



Alarm History: This page is similar to the Alarm Summary Page in function but also keeps a running log of all alarms but also records the time and date of when the alarm was reset.



Drive Parameter Set Up Page: This page is a hidden control page and can only be accessed from the Main Menu Page using a code to open. These settings are not to be modified regularly and are used in the tuning of the motorized actuator that moves the slug vertically in the die.



2015 Innovation in Advanced Manufacturing Challenge Grant Reporting Form

Agreement #	IAMG-15-02	Report (circle one)	Progress Report / Final Report
Company Name	Interlink Engineering	Reporting Period Dates	04/08/2016

Part 1: Funding Summary

Please update the following funding summary table to reflect the grant project's current progress.

Project Funding Sources	Budget Amount *from Grant Agreement*	Actual Amount *at time of Progress Report*	Actual Amount *at time of Final Report*
Innovation in Advanced Manufacturing Challenge Grant funds	$72,390	$	$57,912
Grantee cash and in-kind match	$0	$	$
Partner cash match	$0	$	$
Partner in-kind match	$28,390	$	$30482.38
Total Project	$100,780	$	$88,394.38

Part 2: Milestone Checklist

Please update the following milestone checklist to reflect the grant project's current progress.

Report	Milestones to be met	Status	Supporting Documentation	Attached?
Progress Report			Invoice	
			Signed Statement/Invoices	
			Progress report containing detailed diagrams and descriptions	
			Progress report containing detailed measures for the selected machine tools	
Final Report	Provide award payment #4 invoice.	Complete	Invoice	Yes
	Provide copies of all invoices associated with project.	Complete	Signed Statement/Invoices	Yes

	Conduct verification testing: Prepare and test induction heating coils for the original (existing) and modified designs. Document the results for time, temperature and power. Iterate as necessary to reduce energy requirements, and maintain productivity. Conduct validation testing: use the modified design(s) at the manufacturing partner's facility. Micro-section parts and document results.	Complete	Progress report containing detailed measures for the selected machine tools (in comparison with the baseline measurements)	Yes

Part 3: Narrative

Summary	Briefly describe the progress made since the award of the grant
Verification and Validation testing complete.	
Outcomes	List any quantifiable outcomes that have resulted since the award of the grant
Optimized energy savings based on new coil configuration. See attached final report for details.	
Issues	Identify any current or anticipated issues with the planned performance of the grant
None at this time.	

Part 4: Signature and Submission

Please complete and sign this form. Attach all required supporting documentation and submit to: bennettc@azcommerce.com

Progress Reports Due on or before: **TBD**

Final Report Due on or before: **TBD**

I affirm that the information contained in this report is true, correct, and complete to the best of my knowledge and belief.			
Signature		**Date**	04/08/16
Name	Richard Kost	**Phone number**	480.699.0263
Title	Operations Manager	**Email address**	richk@interlinkengineering.net

BLACKERBY ASSOCIATES
Transforming Organizations

March 6, 2015

Arizona Commerce Authority
Attn: Bennett Curry
333 N. Central Ave., Ste. 1900
Phoenix, AZ 85004

Re: Final Report - Energy Reduction Challenge Grant Award AZERCG-2014-01

Dear Mr. Curry:

Please accept this documentation in support of Grant Award Payment #3 and Payment #4 regarding the referenced Energy Reduction Challenge Grant Award AZERCG-2014-01.

At this time, tasks 1 through 10 have been completed. The following tables show the project milestones to be met and the supporting documentation.

Grant Award Payment #3

Milestones to be met	*Supporting documentation to be submitted with Progress Report*
Up to 176 hours of consultant services performed since execution of grant award	See attached invoice 15-004-Detail documenting 102 hours through February 28, 2015. Previous invoice (14-005, 3/10/2014) had documented 66 hours, for a total of 168 cumulative hours. Implementation of some kaizen events did not require intensive consultation because they were outsourced to plumber, compressor manufacturer, etc.
Implementation of any remaining *kaizen* events not implemented in earlier quarter	Consultant and Partner completed implementation of six *kaizen* events as of February 28, 2015. See listing below.
End of project metric data collected	End of project metric data has been collected, including electricity usage (KWH) and monthly cost and volume of bottled methane and acetylene shipped into Partner during calendar 2014.
Up to $12,636 of Partner match used since execution of grant award	Partner match of $36,134.22 has been used since execution of grant award, including $11,613.86 in payroll, $8,174.14 in fringe and allocated overhead, $16,259.50 in equipment, and $86.70 in other direct expenses. See attached Match Analysis.

16858 Avenue of the Fountains
Fountain Hills, Arizona 85268
602-908-1082 Tel
480-837-6608 Fax
info@BlackerbyAssoc.com
www.BlackerbyAssoc.com

Grant Award Payment #4

Milestones to be met	*Supporting documentation to be submitted with Final Report*
Up to 200 hours of consultant services performed since execution of grant award	See attached invoice 15-004-Detail documenting 102 hours through February 28, 2015. Previous invoice (14-005, 3/10/2014) had documented 66 hours, for a total of 168 cumulative hours. Implementation of some kaizen events did not require intensive consultation because they were outsourced to plumber, compressor manufacturer, etc.
Metric data collected 6 months after implementation	Project was completed February 28, 2015. Metric data will be collected starting August 1, 2015.
Metric data collected 12 months after implementation	Project was completed February 28, 2015. Metric data will be collected starting March 1, 2016.
Up to $13,134 of Partner match used since execution of grant award	Partner match of $36,134.22 has been used since execution of grant award, including $11,613.86 in payroll, $8,174.14 in fringe and allocated overhead, $16,259.50 in equipment, and $86.70 in other direct expenses. See attached Match Analysis.

Kaizen Events Implemented

Project	*Reason*	*Description*	*Status Feb. 28 2015*
1. Work instructions not clear	Operators frequently have to waste time calling customers to clarify which standards to meet, scope of work, etc.	Revise work instructions template to clarify and put in checklist form; get written clarifications from customers; review engineering before sending project to manufacturing.	***Project implemented.*** Standard work instructions have been clarified; template for future work instructions has been completed.
2. Combine logons for multiple steps	Current computer system allows only one status update per logon. Operators must logon, update one work instruction step status, then logoff, then logon again, update the next work instruction step status, then logoff again. New system protocol will (a) consolidate work instruction steps requiring fewer updates, and (b) allow operators to update multiple work instructions during the same logon.	Update and consolidate about 100 work instructions into about 20 consolidated work instructions to allow for a single project tracking system logon to update all tasks for a project. Typical project will require 12 steps instead of 20.	***Project implemented.*** Work instruction documents have been consolidated, operators have been trained, and combined logon/logoff procedures have been implemented.

Project	Reason	Description	Status Feb. 28 2015
3. Deposition efficiency	Currently, overspray (spray metal powder that does not land on the part, or that does not stick to the part) is wasted material that is swept up and recycled. In order to minimize this waste, it must be measured. Current procedures do not provide for measuring the actual deposition rate, the inverse of overspray.	Create procedure to weigh raw materials and parts before and after metal spraying to measure deposition rate; analyze variances compared to manufacturer standards, changes over time, changes in equipment settings and operators to identify best practices and reduce waste materials.	***Project implemented.*** New procedures for weighing materials and products before and after processing are written and implemented. Data collection is in progress. After sufficient data are collected, analysis will identify any deposition improvement opportunities.
4. Point-of-use methane	Currently, methane and acetylene are delivered in pressurized steel cylinders ("bottles") by truck as needed. Methane (55.7 kJ/g) contains more energy per unit of mass than acetylene (11.8 kJ/g). Acetylene is explosively volatile under high heat or shock. Bottles contain agamassan, and acetylene is dissolved in acetone for stability. Acetylene is a more significant greenhouse gas than methane.	Eliminate use of bottled methane and acetylene by getting natural gas service to the building, compressing the gas, and piping it to each spray booth.	***Project implemented.*** Installed piping from front of building to each spray booth Oct. 27; existing natural gas compressor with retrofit modifications and a new compressor chiller received Nov. 13; piping welded and inspected Jan. 5, 2015; Gilbert permit issued Jan. 10; Gilbert approval Jan 26; installed natural gas service and meter Jan. 29.
5. Set-up kits for high-volume products	Currently, operators must waste time walking to the tool crib to look for nozzles and other needed supplies before starting any project. No procedures exist to identify restocking needs, so supplies may not be available when needed.	Each booth will be stocked with standard set-up kits depending on the booth's functional capabilities; kits will be placed in pre-cut foam forms to identify restocking needs; procedures will ensure regular restocking.	***Project completed.*** Kits were designed and procedures were documented; personnel were trained and set-up kits were implemented Nov. 25.

Project	*Reason*	*Description*	*Status Feb. 28 2015*
6. Quality assurance requirements for updated operations	Company depends on its certification as an FAA Repair Station, as its primary work is repairing aircraft engine parts. Any significant process change requires re-testing of samples ("coupons") affected by the change.	Updated data regarding new compressed natural gas-produced process samples will be submitted to FAA for approval under 14 CFR 145.105.	***Project completed.*** New process samples (14) were manufactured Feb. 9, 2015 to Feb. 20, and lab results were completed Feb. 28 and submitted to FAA.

If you have any questions regarding this invoice or documentation, please call me, at 602-908-1082, or write back at phillip@blackerbyassoc.com.

I hereby swear that the foregoing is true to the best of my knowledge and belief,

Phillip Blackerby

2015 Innovation in Advanced Manufacturing Challenge Grant Reporting Form

Agreement #	IAMG-15-04	**Report (circle one)**	Final Report
Company Name	Rugo Machine Shop Services	**Reporting Period Dates**	

Part 1: Funding Summary

Please update the following funding summary table to reflect the grant project's current progress.

Project Funding Sources	**Budget Amount** *from Grant Agreement*	**Actual Amount** *at time of Final Report*
Innovation in Advanced Manufacturing Mini-Challenge Grant funds	$10,000	$
Grantee cash cost share	$7,407	$
Total Project	$17,407	$

Part 2: Milestone Checklist

Please update the following milestone checklist to reflect the grant project's current progress.

Report	**Milestones to be met**	**Status**	**Supporting Documentation**	**Attached?**
Final Report			Rugo invoice to the ACA	
			This completed final report	
			Copies of all paid invoices for labor and materials	

Part 3: Narrative

Summary	Briefly describe the progress made since the award of the grant

Outcomes	List any quantifiable outcomes that have resulted since the award of the grant
Issues	Identify any current or anticipated issues with the planned performance of the grant

Part 4: Signature and Submission

Please complete and sign this form. Attach all required supporting documentation and submit to: bennettc@azcommerce.com

Final Report Due on or before: **May 31, 2016**

I affirm that the information contained in this report is true, correct, and complete to the best of my knowledge and belief.			
Signature		**Date**	
Name		**Phone number**	
Title		**Email address**	

THE UNIVERSITY OF ARIZONA.

Integrated Energy Reduction and Productivity Enhancement of Machine Shop Operations

Sponsor: Arizona Commerce Authority and US DOE

Project Participants: The University of Arizona
Sargent Aerospace & Defense

Principal Investigator: Dr. Young-Jun Son

Students: Chao Meng, Sojung Kim, Sungjoong Kim

THE UNIVERSITY OF ARIZONA TUCSON ARIZONA

JUNE 4th 2014
WASHIONGTON, D.C.

THE UNIVERSITY OF ARIZONA.

Project Overview

- Goals
  - Develop smart sensing and control, and software-enabled technologies for making energy-intensive machines smart
  - Establish optimum starting, stopping, and idle times of machines to reduce electricity cost

2

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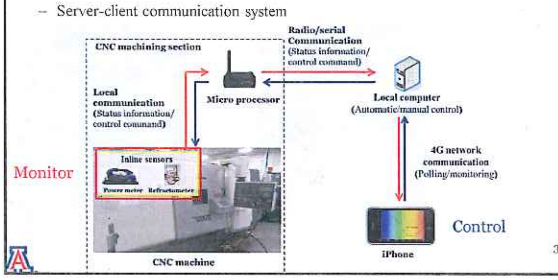
Proposed Approach and Solutions

- Remote monitoring and control
  - Inline sensors (power meter and refractometer)
  - Server-client communication system



3

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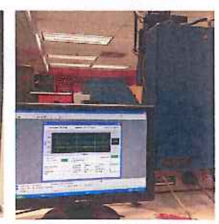
Electricity Consumption Data Collection (1)

- Electricity consumption monitoring
  - Smart Power Meter: collect electricity consumption data of an individual mac hine or entire facility in real time
    - Sampling frequency option: 200 samples/sec. or 240 samples/sec.



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Electricity Consumption Data Collection (2)

- Electricity consumption database
  - Record all status data given by the smart power meter
    - Available data: min. KW, avg. KW, and max. KW

Status of electricity consumption (CIMS lab)

RecNo.	CurrTime	EquipID	EquipType	EquipStatus	MaxKW	MaxKW Time	MinKW	MinKW Time	AvgKW	AvgKW Time
1	2014-05-13 13:09:00	1	Sensor	test	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.532	2014-05-13 13:09:00
2	2014-05-13 13:09:15	1	Sensor	test	1.963	2014-05-13 13:07:15	1.021	2014-05-13 12:06:00	1.542	2014-05-13 13:09:15
3	2014-05-13 13:09:30	1	Sensor	test	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.541	2014-05-13 13:09:30
4	2014-05-13 13:09:45	1	Sensor	test	1.894	2014-05-13 13:08:30	1.082	2014-05-13 12:06:15	1.548	2014-05-13 13:09:45

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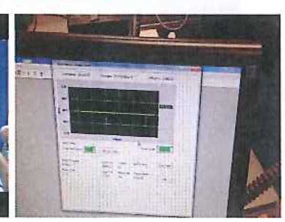
Electricity Consumption Data Collection (3)

- Electricity consumption monitoring demo
  - Electricity consumption status while a milling machine running
  - Instant load for machine start-up is **more than 2.4 times** of regular machining

Machining video

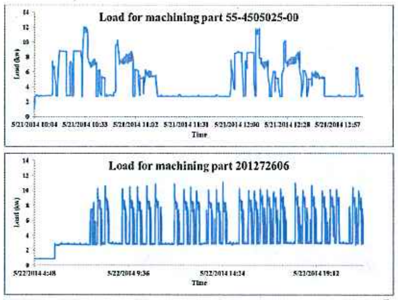


Real-time monitoring

6

Electricity Consumption Data Collection (4)

Power meter installed on LC07 at Sargent Aerospace & Defense Inc.



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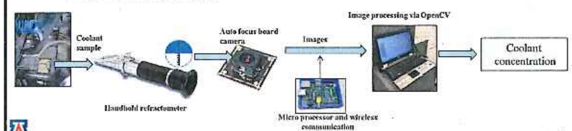
Coolant Concentration Monitoring (1)

- Inline process refractometer
  - Low maintenance requirement
  - High cost (more than $5000/unit)

[1]

- Proposed refractometer
  - No additional refractometer purchase
  - Low cost (less than $500) with good resolution
  - Less installation efforts



[1] http://www.sartorius.com/en/products/bioprocess/process-analysers/online-process-refractometers/

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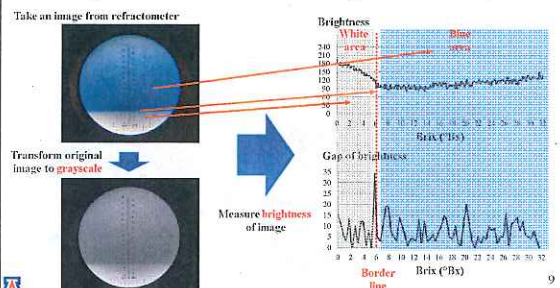
Coolant Concentration Monitoring (2)

- Example of concentration monitoring



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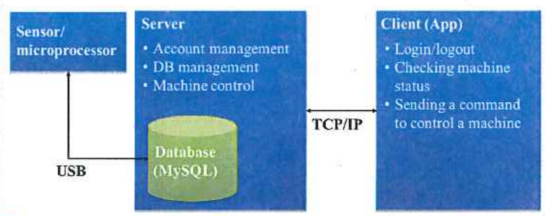
Structure Model for Communication System

- System components
  - Server (MySQL)
  - Client (Android and IOS apps)



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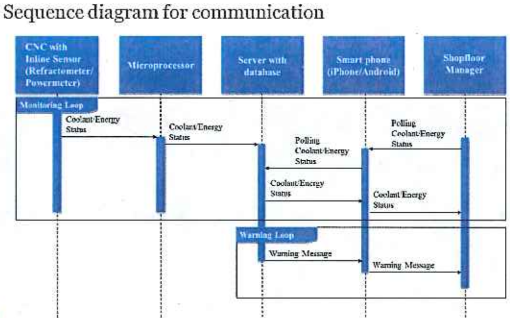
Communication System

- Sequence diagram for communication



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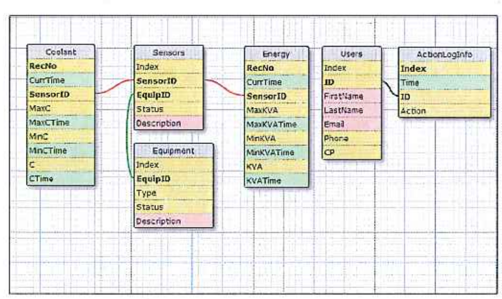
Database Schema



Mobile Application (1)

- Monitoring & warning service

- Predict future status of energy consumption & coolant concentration
- Schedule a production plan to reduce energy consumption or to maintain productivity of the facility
- Dynamic control (Automatic or Manual) machines

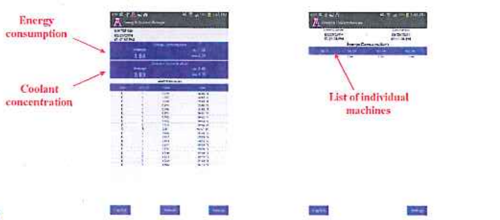
Mobile Application (2)

- Login and settings
  - Login with username and password
  - Set parameters of notification and data retrieval frequency

Login window | Login options window | Settings window

Mobile Application (3)

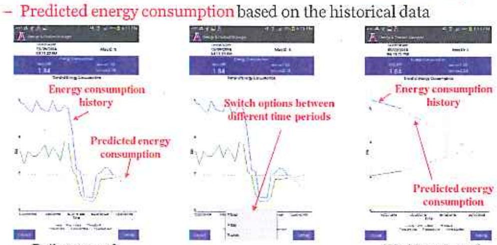
- Status monitoring
  - Check status of energy consumption and coolant concentration
  - Monitor two level status information: facility level and individual machine level



Main window | Detail info. window

Mobile Application (4)

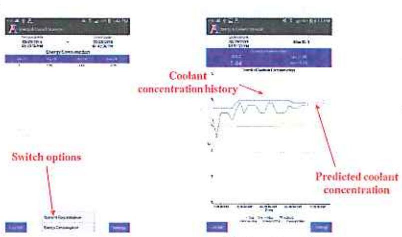
- Status monitoring (cont'd)
  - Historical status with three different values (i.e., min., max., avg.)
  - Predicted energy consumption based on the historical data



Daily status of energy consumption | Switch menu | Weekly status of Energy consumption

Mobile Application (5)

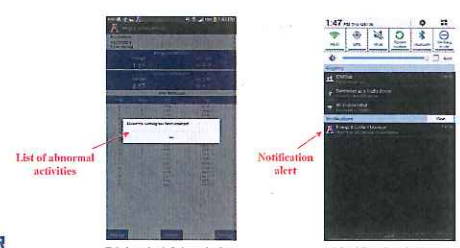
- Status monitoring (cont'd)
  - Switch from energy consumption window to coolant concentration window



Switch menu | Daily status of coolant concentration

Mobile Application (6)

- Notification
  - Get a notification message when abnormal activity is detected



Dialog in Main window | Notification in status

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Project Overview

- Goals
  - Develop smart sensing and control, and software-enabled technolog ies for making energy-intensive machines smart
  - Establish optimum starting, stopping, and idle times of machines to reduce electricity cost

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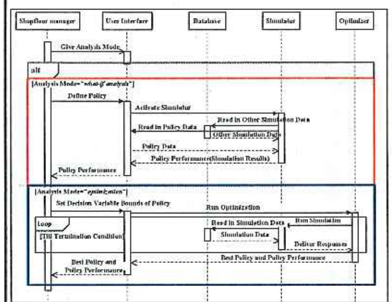
Proposed Approach and Solutions



What-if analysis mode

Optimization mode

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Shop Operation Simulation

- Main features
  - Incorporated major equipment at Sargent (e.g. CNC machines)
  - Data-driven for energy consumption rate, production planning and sh op operation scheduling
  - Instant simulation output for energy consumption of individual equip ment
  - Optimization for production planning and shop operation scheduling
- Applications
  - Production plan optimization considering market demand
  - Workforce scheduling for cell level operation

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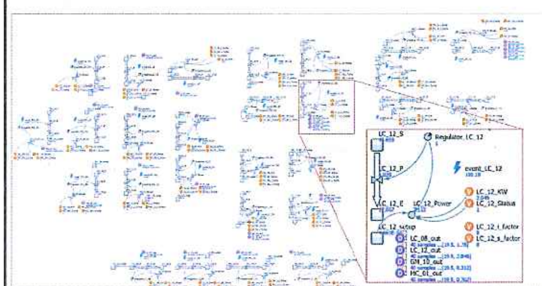
Simulation Logic for Sargent South Facility



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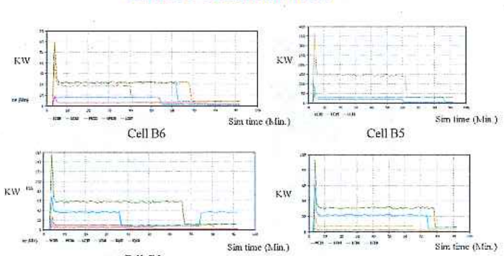
Instant Load Outputs for Individual Machines

- Animation for instant loads of individual equipment



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Demand Response Program

- Time-of-Use (TOU)[1]

Electricity price

	Summer May-Sep	Winter Oct-Apr
On-peak kWh	14.94 cents/kWh	11.39 cents/kWh
Off-peak kWh	11.12 cents/kWh	9.16 cents/kWh

Time periods for summer

Time Periods	Summer		
All weekends are off-peak	Off-peak	On-peak	Off-peak
	midnight-2pm	2pm-8pm	8pm-midnight

Time Periods	Winter				
All weekends are off-peak	Off-peak	On-peak	Off-peak	On-peak	Off-peak
	midnight-6am	6am-10am	10am-5pm	5pm-9pm	9pm-midnight

- Real time pricing (RTP)[2]

$$p(l(t)) = p_{base} + \alpha(l(t) - l_{base})^k$$

$l(t)$: load at time t (kW)

$p(l(t))$: real time price ($/kWh)

p_{base}: base price ($/kWh)

l_{base}: the base load for price calculation (kW)

α and k: control parameters for shaping the price curve

[1] https://www.tep.com/efficiency/business/timeofuse/
[2] Zhao, J., S. Kucuksari, E. Mazhari, and Y-J. Son, 2013. "Integrated analysis of high-penetration PV and PHEV with energy storage and demand response." Applied Energy, 112: 35-51.

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Experiment Inputs

Equipment power data

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Volts	208	208	208	208	208	480	480	208	208
Amps	25	20	30	42	42	200	40	60	60

Workforce schedule for shop operations

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Day (# of operators)	3	3	3	3	3	1	1	1	2
Night (# of operators)	2	2	2	2	2	1	1	1	0

Product machining times

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10	LC15	LC16	LC08
Rate (min/part)	74.88	75.54	32.84	76.11	39.86	62.30	86.88	59.37	39.39
Setup (min/part)	7.49	7.55	3.28	7.61	3.99	6.23	8.69	5.94	3.94
Total rate (min/part)	149.76	151.09	65.67	152.23	79.71	124.60	173.75	118.75	78.79

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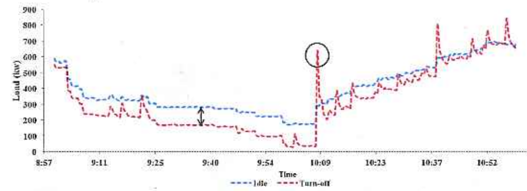
Simulated Instant Load of South Facility

- Instant load for machine start-up could be **2.4 times more** than that of regular machining



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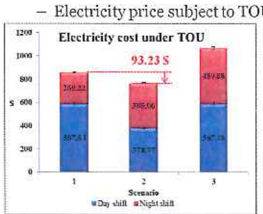
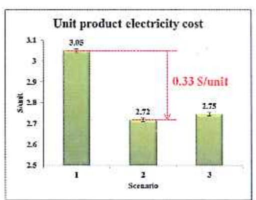
What-if Analysis for Workforce Schedule

- Experiment settings
  - Simulation duration: 24 hours
  - Number of replications: 10
  - Electricity price subject to TOU





Scenario 1: 2/3 production scheduled for day shift (current schedule in the facility)
Scenario 2: 2/3 production scheduled for night shift
Scenario 3: production increased by 1/3, evenly scheduled for in two shifts

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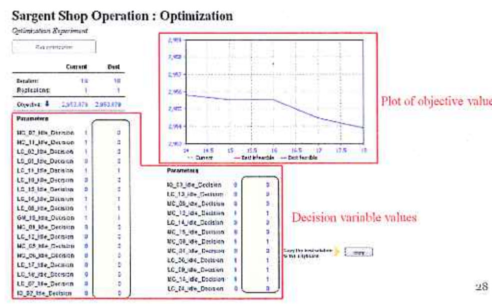
Optimization for Machine Status

- Optimization interface



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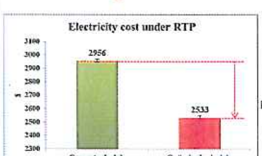
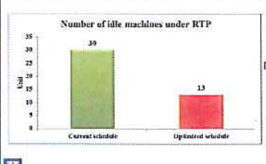
Optimization for Machine Status





- Minimizing electricity cost under RTP
- Simulation duration: 48 hours
- Stopping condition: 500 iterations
- Replications: 10/iteration
  - 423 $ saving for two days
  - 14.3% saving

Optimized machine status for periods between jobs

Equip ID	MC02	MC11	LC02	LC01	LC11	LC10
Idle/off	off	off	idle	off	idle	idle
Equip ID	LC15	LC16	LC08	GM10	MC01	LC12
Idle/off	off	off	idle	off	idle	off
Equip ID	MC05	MC06	LC17	LC18	LC07	IQ02
Idle/off	off	off	idle	off	idle	idle
Equip ID	IQ03	LC13	MC09	MC12	LC14	MC15
Idle/off	off	off	idle	idle	off	off
Equip ID	MC08	MC04	LC06	LC09	MC14	LC04
Idle/off	off	off	idle	off	idle	idle

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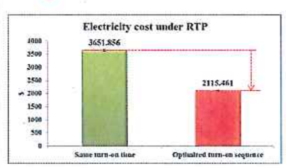
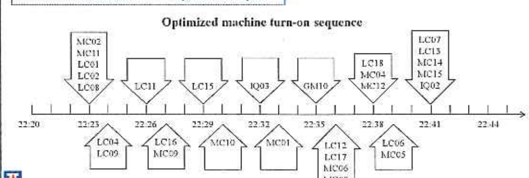
Optimization for Machine Turn-on Sequence



- 1536.395 $ saving for two days
- 42.1% saving

Optimized machine turn-on sequence



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Ongoing Work

- Data collection of machining energy consumption for different jobs
- Implementation & test of the energy consumption monitor system at Sargent
- Refractometer testing and implementation

Test-bed machine

Working area at Sargent

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Questions & Comments