FINAL REPORT

Lean-Six Sigma Laboratory
University of Idaho, Boise

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2005 Sigma Cell
A Senior Design Project

http://seniordesign.engr.uidaho.edu/2004_2005/sigmacell/
ABSTRACT

In January 2005, the Sigma Cell project was created as a University of Idaho electrical engineering senior design project. The project was created to provide Dr. Larry Stauffer of UI Boise with a machine capable of demonstrating lean manufacturing principles. Most of the parts to construct the machine were donated from Hewlett Packard of Boise. Specifically, the goals of Sigma Cell were to: (1) install a donated Bosch conveyor, (2) design and install two workcells that integrate onto the conveyor, and (3) demonstrate SMED principles with the workcells. All three goals were met under budget.

Each workcell is a pick-and-place device that moves product off of a palette and into a bin. Two products—either plastic couplings or wooden blocks—can be handled by a workcell. Therefore, the workcells provide a means to perform a changeover. The workcells can be outfitted with standard or lean components that contrast the changeover time.

With standard components, a changeover to transform handling of plastic couplings to wooden blocks took 21 minutes. The workcell was then retrofitted with lean components. The same changeover was repeated, and the changeover time reduced to 9 minutes—over 50% less time.

The entire system will be used by UI graduate students as a learning tool in laboratory experiments.
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In the spring of 2004, Hewlett Packard Boise agreed to donate a Bosch conveyor and various assembly-line components to the University of Idaho. The equipment had been used as part of an automated process that produced ink-jet cartridges. Due to changes in business infrastructure at HP, the entire assembly line was shut down, and many components were scrapped or used elsewhere. The remaining components were sent to the University of Idaho for use in research and education.

Dr. Larry Stauffer, professor of mechanical engineering, decided to utilize the equipment in the new Lean/Six-Sigma laboratory. He recruited UI Boise graduate student Charles Ford to design a laboratory experiment that demonstrates the SMED (Single Minute Exchange of Die) technique. Before an experiment could be designed, the assembly line would need to be reassembled, modified, and made operational. To complete this task, the Sigma Cell project was created as a University of Idaho senior design project.
PROBLEM DEFINITION

The Need

The University of Idaho at Boise has a comprehensive manufacturing engineering curriculum, and there are several courses that specialize in lean manufacturing concepts. To make the concepts more concrete, there is a need to apply them to real-world applications through classroom experiments. The goal of the Sigma Cell project is to transform a used assembly line into a valuable teaching tool.

Requirements

The Sigma Cell project must fulfill the following requirements:

• Install a donated Bosch manufacturing line.
• Develop two manufacturing work cells that will integrate into the manufacturing line.
• Provide a means to demonstrate SMED (Single Minute Exchange of Die) with the workcells.

Note: The workcells will be utilized in a laboratory experiment as a SMED teaching tool. The experiment will be designed by a UI graduate student and is outside the scope of the Sigma Cell project.

Constraints

To save cost, donated equipment must be modified to fit the above requirements. The following is a list of constraints:

• HP Donated actuators must be used in the workcell.
• The entire system must be controlled by an HP donated PLC (programmable logic controller).
• An HP donated parallel gripper must be used as one of the end effectors (The other end effector shall be purchased).
• The end user should not be required to access PLC code for changing workcell behavior. A simple, intuitive user interface must be provided instead.
CONCEPT DEVELOPMENT

The first phase in the project involved interviewing the customer, Dr. Larry Stauffer. Originally, Dr. Stauffer intended to use the equipment as a Six-Sigma teaching tool. This explains why the senior design project is titled “Sigma Cell”. But after further discussion, the equipment was deemed more suitable for lean manufacturing experiments; and in particular, SMED was chosen due to its high applicability to the donated equipment.

This prompted research into the lean concept of SMED. The research process took about one month before SMED was sufficiently understood. A large amount of information was compiled from the internet, but several books on the topic were also reviewed. A brief summary of the research can be found in the following section.

SMED Overview

To remain competitive in today’s business environment, manufacturers must realize the necessity to reduce lot sizes and minimize inventory. Stocked goods can quickly become obsolete, and a large inventory creates significant overhead expenses. Furthermore, cycle-time must also be minimized so that new products fulfill customer demand as quickly as possible. In order to resolve these challenges, many companies have employed manufacturing techniques that promote fast product changeover. One such proven technique is the SMED (Single Minute Exchange of Die) technique.

SMED was originally conceived in the 1950’s by Shigeo Shingo of Japan. He applied SMED primarily in the automotive industry; and companies such as Mazda, Mitsubishi, and Toyota realized substantial increases in production efficiency through SMED. Later, non-automotive companies such as GE, Honeywell, Motorola (and the list goes on...) adopted SMED with great success. The payoff included reduced manufacturing costs, high-quality products, satisfied customers, and increased profits.

The goal of SMED is to convert a tool from handling an existing product to a new product in less than ten minutes (“single minute” means that setup time is counted on a single-digit).
SMED is defined in four concepts:

1. Suppress useless operations,
2. Work together,
3. Simplify fittings and fasteners, and
4. Suppress adjustments and trials.

Concepts 1 and 2 relate to tool organization, changeover procedures, and allocation of resources. The lab experiment to be developed by Charles Ford will focus on these concepts. However, concepts 3 and 4 relate more to the equipment itself. Consequently, the Sigma Cell project focuses on the latter.

**Implementing SMED**

SMED heavily promotes the simplification of fittings on equipment. Items such as blocks, jigs, and templates can reduce the need for equipment adjustments, and custom tools can allow for quick changeover of components. Furthermore, parts standardization can increase changeover efficiency and reduce the quantity of required hand tools. These concepts formed the basis for the Sigma Cell conceptual design.

The conceptual design phase proved to be the most difficult challenge of the Sigma Cell project. Indeed, the task of transforming a pile of parts into a useful teaching tool was daunting and required good imagination. After several brainstorming sessions, design concepts were compiled and presented to Dr. Stauffer and Charles Ford. Four concepts were explored:

1. Converting internal to external tasks,
2. Utilizing quick-change components,
3. Utilizing quick adjust components, and
4. Promoting commonality of components.
**Internal to External**

Some changeover tasks can be re-allocated from internal time to external time. Internal time is the time during which the production line is stopped. External time, on the other hand, is defined as the time prior to the production line ceasing to produce. The idea is to move as many tasks as possible from internal time to external time because fewer tasks within internal time will reduce the setup time (downtime). For example, a 15mm socket may be required to secure a new die in place during the setup phase. A particular task may be to retrieve the socket from the tool crib. This task, which may take a few minutes, can be performed in internal or external time. It would make sense perform this task in external time before the line is stopped. If the task is performed during changeover time, it only adds a few minutes to the changeover time—which equates to lost production. By dissecting the changeover process, many tasks within a manufacturing process can be moved into external time, and the benefits can be quite noticeable.

Of the four concepts, internal-to-external was the least considered for the Sigma Cell project. From an equipment design standpoint, the concept proved extremely difficult to implement because internal-to-external conversion is an organizational concept. It was decided that it could be more easily realized in the laboratory experiment through procedural techniques. Needless to say, internal to external conversion is probably the most important concept to SMED.

**Quick-Change Components**

SMED heavily promotes the simplification of fittings on equipment. Or, if at all possible, fittings should be removed altogether. Consider a screw which holds a bracket on a piece of equipment. Only the last few screw threads actually secure the bracket, so there is no sense in having a screw with 20 threads. The added screw length only translates to an increased time to add or remove the bracket—especially if the bracket is held in place by ten screws. An even better alternative is to use clamps to hold the bracket in lieu of screws. As shown in Figure 1, clamps can be added or removed in one swift movement. The clamps and associated brackets may cost more than a handful of screws, but they will quickly pay for themselves in time savings. Plus, no tools are required for a clamp.
Electrical and/or pneumatic connections for a changeover component can also be optimized. For electrical terminations, terminal blocks should be avoided. Instead, quick connectors can be employed to reduce changeover time.

Many assembly line components function pneumatically and thus require pneumatic connections. Like the electrical connectors, certain pneumatic connectors can be used to reduce changeover time. One such example is the use of quick connectors in lieu of hose barbs.
Quick-Adjust Components

After equipment components have been replaced or modified to accept a new product, they often have to be adjusted/aligned to properly handle the new product. If quick-adjust components are used, alignments will become more efficient, and equipment downtime is reduced. Quick-adjust components include components like camlocks, stop blocks, and adjustment jigs. Camlocks eliminate the need for tools whereas stop blocks and alignment jigs eliminate the need for measurement during equipment downtime. Instead, measurements are performed before downtime, and the jigs and blocks are configured in advance. During a changeover, the components are aligned quickly because the jigs are stops are pre-configured.

Common Components

As mentioned in the “Quick Change Components” section, quick connectors can be employed to speed up the changeover process. However, without commonality of connectors on changeover components, the connectors serve no purpose because the entire connector has to be removed from the system. If a common mating connector is used for each changeover component, then connectors don’t need to be swapped out during a changeover.

Component commonality also drives a reduction in required tooling. With reduced tooling comes reduced costs associated with tool maintenance and tool retrieval time. For example, a system could be modified such that all ½” fasteners are replaced with 12mm fasteners. Now, only metric tooling must be stocked. Furthermore, similar sized fasteners with alan, hex, and screwdriver heads could be replaced with all hex heads. The necessity for three tools has been reduced to one.
Final Concept

The final concept was a conveyor with two pick-and-place workcells. Each workcell operates independently of the other, and two are required simply to maximize experimental flexibility. A workcell is designed to remove a product from a palette and drop it into a bin. It will continue this action so long as product is available on the conveyor belt. The workcell can handle two product types: Product A and Product B. The workcell is designed such that it cannot handle a changeover from A to B (or vice-versa) without modification. Specifically, a different end-effector (gripper) must be installed, and the workcell must be re-aligned to accommodate the alternative product.

Two component sets are provided for changeover. The first set is non-optimized, and the second set is optimized via SMED. The non-optimized set requires many hand tools, is slow to tighten or loosen, and provides no means for alignment. In contrast, the optimized set requires few hand tools, is fast to tighten or loosen, and provides an efficient means of alignment.
**SYSTEM DESIGN**

**Conveyor**

The conveyor is a Bosch Model TS-2 that is approximately 12 feet in length. It houses two main belts running parallel to each other but opposite in direction. Each end of the conveyor has a half-circle “turn-around” that connects the two main belts. The end result is a continuous recalculating transport that moves product in a clockwise direction. Figure 4 shows the conveyor shortly after reconstruction.

![Figure 4. Bosch TS-2 Conveyor](image)

The entire unit is powered by four 480V 3-phase motors. All motors are mechanically independent of each other but powered by a common 480VAC starter panel.
**Starter Panel**

The starter panel is an off-the-shelf unit manufactured by Cutler Hammer. The design requirements were researched and sent to an outside contractor for construction. (Because the panel must be NEC 2004 compliant and UL listed, it was assembled and inspected by certified technicians.)

The panel consists of a fused disconnect switch, an electrical contactor, a 480V-to-120V (4:1) transformer, and some 120V control circuitry. An additional overload relay panel is connected to the Starter Panel. It contains four overload relays to protect each motor. Together, the panels function as a single starting system.

![Figure 5. Starter and Overload Panels](image)

The size of the disconnect was determined by two requirements:

- The disconnect must be sized to handle at least 115% of the sum of all full-load amps (FLA’s) of all motors. The FLA sum is determined by converting each horsepower rating to FLA’s using Table 430-150 of the NEC, and then sum all the FLA’s.
• The disconnect must be sized to handle the sum of all locked rotor currents for all motors. The locked rotor total amps are determined by converting each horsepower rating to amps using Table 430-151(B) of the NEC, and then sum the amps.

The total full load amps (FLA) of all four motors was added and multiplied by 125%. Based on a total FLA of 5.9A, the NEC required a 5HP disconnect. Next, total locked rotor amps was found to be 47.5 amps from conversion tables in the NEC. This increased the disconnect size requirement from 5 HP to 7.5 HP.

After the disconnect was sized, the fuses themselves had to be specified. Per NEC Article 430-52 and Table 430-52, a time delay type fuse can be rated at no more than 175% of the total FLA of the system. Per Article 430-53(a), all motors can be connected to a single branch circuit because each motor FLA does not exceed 6A and overcurrent protection does not exceed 15A. For a total FLA of 3.98A, the 175% value mandated the use of (3) 7A Class J dual-element time-delay fuses.

Because all motors are rated 600V or less, and all motors drive several parts of a single machine, only one contactor is needed. (Ref Article 430.87(a)). The size of the contactor is determined by two requirements:

• The contactor must be sized to handle at least 115% of the sum of all FLA’s of all motors. The FLA sum is determined by converting each horsepower rating to FLA’s using Table 430-150 of the NEC, and then sum all the FLA’s.

• The contactor must be sized to handle the sum of all locked rotor currents for all motors. The locked rotor total amps are determined by converting each horsepower rating to amps using Table 430-151(B) of the NEC, and then sum the amps.

Again, total locked rotor amps superceded the FLA requirements, and a single 7.5 HP starter was specified.

Because each motor is automatically started (via the contactor), overload protection was be included. Per NEC Article 430-32(c)(1), the overload relays should be set to trip at no more than 125% of the motors’ nameplate FLA’s.
Motor 1: 1.4A * 125% = 1.75A  
Motor 2: 1.7A * 125% = 2.125A  
Motor 3: 0.44A * 125% = 0.55A  
Motor 4: 0.44A * 125% = 0.55A

The system design includes four overload relays for individual protection of the four electric motors. All overload relays include a set of normally closed auxiliary contacts wired in series with the starter control circuit. Upon tripping of any relay, the main contactor will open.

**Product**

The product is either a 2” PVC coupling or a 2” cubic wooden block. A product rests on a 6” square palette, and each palette can handle only one product piece. Because the conveyor is capable of handling two products, a palette must be modified to switch between products. They are modified by switching out a wooden template designed for either the coupling or the block.

![Figure 6. Palettes and Products](image)

**Workcells**

The conveyor assembly holds two identical workcells. Each workcell is constructed with 80-20 inc. modular construction tubing, which they refer to as an “industrial erector set”. The tubing lengths were determined from hand drawings, and they were cut at the factory. All the components were assembled in the Lean/Six Sigma laboratory and then installed onto the conveyor assembly. Because the
Bosch tubing and 80-20 tubing are very similar in design, the mounting of the workcells onto the conveyor was surprisingly easy.

![Figure 7. Workcell](image)

At the heart of each workcell are two PHD Inc. pneumatic slides. The slides are connected as to form a twin-axis cartesian-style actuator. The large (primary) slide is used to position the gripper in a horizontal direction perpendicular to the conveyor belt. The small (secondary) slide is used to position the gripper vertically above the belt. The gripper (end effector) is physically attached to the small slide, the small slide is physically attached to the large slide, and the large slide is physically attached to a gantry-style mounting assembly.

Each slide is driven by a pneumatic cylinder with pneumatic ports for retract and extend. Each cylinder’s ports are connected to A and B ports on a 24VDC 4-way electro-pneumatic control valve mounted in the PLC enclosure.

Each workcell utilizes one of two grippers. Thus, a total of four grippers will be available for use. Two of the grippers use parallel movement, and they will handle the wooden block. The other two grippers use angular movement, and they will handle the PVC coupling. Each gripper has two pneumatic ports—one for clamp, and one for unclamp. The ports are connected via hoses back to a control valve in the DC Enclosure. Each gripper has 1 proximity switch that must be connected to the PLC. The electrical connection consists of 3 wires.
An adapter plates was fabricated to mount both grippers to the small slide, because direct mounting is not possible with the available bolt-hole configuration. Each workcell has its own adapter plate.

**Stop Gates**

Each workcell has a stop gate. The stop gate has a plastic plunger which is pneumatically actuated to an up or down position. Without air applied to the stop gate, its spring return keeps the plunger in the “up” position. When up, the plunger will contact a traveling palette, and the palette will not be permitted to travel further down the line until the plunger goes down.

Each stop gate also houses a Turck inductive proximity switch. The switch detects when a palette is overhead.

![Stop Gate](image)

**Figure 8. Stop Gate**

**PLC Enclosure**

The PLC enclosure mounts under the conveyor belt drive and houses the following components:

- the programmable logic controller (PLC)
- eight pneumatic control valves,
- a 120VAC breaker and two 24VDC breakers,
- a 24VDC power supply,
- an interlock relay, and
- terminal blocks for most device interconnections.
The following components are mounted to the PLC enclosure and are accessible outside of the enclosure:

- a power switch,
- an air pressure regulator,
- a pneumatic supply valve,
- four pneumatic ports for hose connections to the grippers on either workcell,
- a terminal strip for electrical connections to the grippers on either workcell.

The Allen Bradley SCL series PLC is the brain of the workcells. The PLC has a 13-slot chassis that excepts a CPU module, four 16-point NPN input modules, four 16-point PNP output modules, and a power supply module. The CPU module can hold 4K of programming instructions and control up to 4096 input/output points. It has a DH-485 port for communications. A DH485-to-USB converter is used to interface with a laptop for programming and diagnostic purposes.

All slides and grippers are connected to a bank of 24VDC control valves located in the PLC Enclosure. All of the valves are bolted together into a valve assembly (valve manifold) with a common supply and exhaust port. All valves are controlled by the PLC. If a control valve is powered, port A becomes supply, and port B becomes exhaust. If the valve is not powered, port B becomes supply, and port A becomes exhaust. Thus, a slide or gripper is only controlled as either fully
extended or fully retracted—depending on the state of the control valve. Unless the pneumatics are depressurized, all actuators will be exerting force.

A conveyor interlock relay is controlled by the PLC, and it gives the PLC the capability to shut OFF the conveyor if required. The relay is wired in series with the two emergency stop switches. With this configuration, the conveyor motors will not run unless the PLC program is active and both emergency stop switches are pulled outwards.

The pneumatic supply valve is also controlled by the interlock relay. The supply valve is a 3-way valve. When energized, air is supplied to the 8 pneumatic control valves; when de-energized, supply air is blocked, and trapped air within the workcells is vented to atmosphere. When an emergency stop switch is pressed, the actuating force from all pneumatic devices is removed.

**Operator Panel**

The Operator Panel is the control point for the conveyor and workcells. It allows either manual or automatic control of each workcell. (Both workcells cannot be simultaneously controlled.) The Operator Panel houses a Program Switch, Mode Switch, Run Button, Pause Button, Primary Slide Switch, Secondary Slide Switch, Gripper Switch, Gate Switch, and Emergency Stop Switches.

![Figure 10. Operator Panel](image-url)
Program Switch

The Program switch is a 3-position switch that selects which software program the PLC will run. At the time this document was published, the Program switch serves no purpose, and all three positions run the same program. However, it adds flexibility to the conveyor for future additions or modifications.

Mode Switch

The Mode switch is a 3-position switch that selects which workcell will operate. (Only one workcell can operate at a time.) When “A” is selected, Workcell A will operate; when “B” is selected, Workcell B will operate. If the switch is set to HOME, both workcells will sit idle in their home position. The home position occurs when all electro-pneumatic solenoids are OFF. In this state, all slides are fully retracted, all grippers are open, and all stop gates are in the upward position.

Run Button

The Run button is a green illuminated pushbutton. When pressed, the selected workcell will enter into run mode, and the Run button will illuminate green. The workcell will perform its pick-and-place operation as long as a palette is present at the workcell.

If no palette is present after the Run button is pressed, the workcell will return to home position and remain idle until the next palette arrives. During the idle time, the Run button will flash indicating that the workcell is waiting for a palette.

Pause Button

The Pause button is a yellow pushbutton which pauses the running workcell in its current position. When pressed, the Run button will de-illuminate.

Primary Slide Switch

The Primary Slide switch is a 3-position rotary switch which allows manual operation of the primary slide of the selected workcell. If set to AUTO, the PLC will
control the slide. If set to RETRACT, the slide is forced to fully retract; if set to EXTEND, the slide is forced to fully extend.

Secondary Slide Switch

The Secondary Slide switch is a 3-position rotary switch which allows manual operation of the secondary slide of the selected workcell. If set to AUTO, the PLC will control the slide. If set to RETRACT, the slide is forced to fully retract; if set to EXTEND, the slide is forced to fully extend.

Gripper Switch

The Gripper switch is a 3-position rotary switch which allows manual operation of the gripper of the selected workcell. If set to AUTO, the PLC will control the gripper. If set to OPEN, the gripper is forced to open (unclamp); if set to CLOSE, the gripper is forced to close (clamp).

Gate Switch

The Gate switch is a 3-position rotary switch which allows manual operation of the stop gate of the selected workcell. If set to AUTO, the PLC will control the gate. If set to UP, the gate is forced to extend (upward position); if set to DOWN, the gate is forced to retract (downward position).

Emergency Stop Switches

The conveyor has two Emergency Stop switches. When pressed, the conveyor belt will stop, and the pneumatics will be de-pressurized via a supply-line solenoid valve. Upon resetting the Emergency Stop switch(s), the pneumatic supply line will re-pressurize, and the workcell will resume its previous state of operation. To start the conveyor, the black “Run” button must be pressed on the Starter Enclosure.
Software

The software program resides in the SLC 5/02 CPU module of the Allen Bradley PLC. The PLC can be put in one of four modes via a connected laptop: (1) Run Mode, (2) Stop Mode, (3) Program Mode, and (4) Remote Mode. The default mode is Run Mode, and Run Mode activates whenever the PLC is powered up. In Stop Mode, the execution of the program is halted. In Program Mode, the software from a laptop can be uploaded or downloaded to the PLC. In Remote Mode, the PLC is executing code, and the state of the code can be monitored by the laptop.

The software is programmed in “ladder logic”. Because PLC’s are commonly programmed by electricians, ladder logic is a good choice for a PLC programming language. Ladder logic is a graphical interface (GUI) that represents an electrical ladder diagram if the PLC were to be replaced by physical relays, timers, counters, etc. With ladder logic, programming the PLC is intuitive and time efficient.

The execution of software is done in four steps: (1) Input scan, (2) Program scan, (3) Output scan, and (4) Housekeeping. The CPU completes each step sequentially and repeats the process indefinitely. In the input scan, the on/off status of all digital inputs are loaded into a register. In the program scan, the input registers are computed, instructions are executed, and output registers are modified. In the output scan, the on/off status of digital outputs is updated. In the housekeeping scan, tasks for communications, timer updates, and counter updates are computed. The loop time for the entire process is typically less than 10ms.

Due to the sequential and repetitive nature of the workcell’s pick-and-place movement, the software for the Sigma Cell project is written as a state machine. The value of the state is kept in an integer register. Upon startup, the software starts at state zero. During any state, a combination of outputs unique to that state are activated. Consequently, certain valves are energized, and the workcell will position itself accordingly. Meanwhile, input conditions are sent via the 6 inductive proximity switches mounted on a workcell. Once a proper combination of input conditions are met because of the workcell’s position, the software will enter the next state in its sequence. In the next state, a different combination of valves are actuated, and the workcell will move to a different position. Again, once certain input conditions are met, the state is advanced. Once the eighth state is completed,
the integer register returns to state 1, and the entire process repeats itself. Figure 11 below summarizes the state sequence. See the Appendix for a software printout.

Figure 11. State Diagram
**NON-OPTIMIZED CONFIGURATION**

In the non-optimized configuration, the conveyor is configured with “standard components” which create a baseline for changeover time. Table A. summarizes all the components affected by a changeover.

<table>
<thead>
<tr>
<th>Changeover Component</th>
<th>Qty</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator assembly fastener (for vertical adjust)</td>
<td>2</td>
<td>Screw = M8 w/ 5mm alan head Nut = M8 T-nut (80-20, Inc)</td>
</tr>
<tr>
<td>Actuator assembly fastener (for vertical adjust)</td>
<td>2</td>
<td>Screw = M8 T-stud (80-20, Inc) Nut = M8 w/ 13mm hex head</td>
</tr>
<tr>
<td>Actuator assembly fastener (for horizontal adjust)</td>
<td>4</td>
<td>Screw = M6 w/ 5mm alan head Nut = M6 T-nut (80-20, Inc)</td>
</tr>
<tr>
<td>Angular gripper fastener</td>
<td>2</td>
<td>M4 w/ phillips head</td>
</tr>
<tr>
<td>Parallel gripper fastener</td>
<td>2</td>
<td>#6-32 w/ 5/64” alan head</td>
</tr>
<tr>
<td>Pneumatic fitting</td>
<td>2</td>
<td>1/4” barb style w/ #10-32 threads</td>
</tr>
<tr>
<td>Electrical connection</td>
<td>3</td>
<td>stripped wire to terminal block on PLC enclosure</td>
</tr>
<tr>
<td>Palette fasteners for plastic cylinder configuration</td>
<td>1</td>
<td>Screw = 1/4” w/ 7/16” hex head Nut = 1/4” w/ 7/16” hex head</td>
</tr>
<tr>
<td>Palette fasteners for wood block configuration</td>
<td>2</td>
<td>Screw = 1/4” w/ 7/16” hex head Nut = 1/4” w/ 7/16” hex head</td>
</tr>
<tr>
<td>Stop gate fastener</td>
<td>2</td>
<td>Screw = M8 T-stud (Bosch) Nut = M8 w/ 13mm hex head</td>
</tr>
<tr>
<td>Vertical adjust stop blocks</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Stop gate stop blocks</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Horizontal adjust jig</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Wire/Hose tie-down</td>
<td>As Req’d</td>
<td>Plastic zip-ties</td>
</tr>
</tbody>
</table>
The entire actuator assembly is held to the gantry via two sets of M8 fasteners. The top set requires a 5mm alan wrench, and the bottom set requires a 13 mm hex wrench. By loosening these fasteners, the gripper can be vertically adjusted during a changeover. The requirement for two types of wrenches illustrates the need for commonality. The result is increased tool retrieval time.

Also note that no stop blocks are installed on the gantry. Thus, alignment time significantly increases during the changeover process. See Figure 12 below.

The primary slide is held into place via (4) M6 (5mm alan head) screws. By loosening these fasteners, the gripper can be horizontally aligned during a changeover. During the non-optimized changeover, an alignment jig is not used, and changeover time is increased. See Figure 13.
The angular gripper is held into place with (2) M4 Phillips head screws. Unlike thumbscrews, the Phillips screws will require tool retrieval.

The (2) hoses that supply air to the gripper are connected to hose barbs. To ensure the hoses do not blow off during operation, zip ties are secured to the hose. To remove or install hoses, cutters are required for the zip ties. The use of tools during the changeover will increase changeover time.

See Figure 14 below.

![Angular Gripper](image)

Note: (2) ¼” to ¼” quick unions are used when hose barbs are connected to gripper.

M4 screw w/ Philips head (2) plc’s

¼” hose barb w/ #10-32 thread (2) plc’s. Zip ties attached.

Figure 14. Angular Gripper
The parallel gripper is held into place with (2) #6-32 screws (5/64” alan head). Unlike thumbscrews, the alan screws will require tool retrieval.

The (2) hoses that supply air to the gripper are connected to hose barbs. To ensure the hoses do not blow off during operation, zip ties are secured to the hose. See Figure 15 below.

![Figure 15, Parallel Gripper](image)

Note: ¼” to ¼” quick union used when hose barbs are connected to gripper.

#6-32 w/ 5/64” alan head (2) plc’s

¼” hose barb w/ #10-32 thread (2) plc’s. Zip tie attached.
Both angular and parallel grippers have an electrical cable connection. The cable contains (3) wires that connect to terminal blocks on the PLC Enclosure. A screwdriver must be used to connect the wires to the terminals. Thus, changeover time is increased because of the retrieval and use of tools. See Figure 16.

Figure 16, Electrical Connection

The terminal block consists of four wiring points:
1. Terminal 1 → +24VDC
2. Terminal 2 → Gnd
3. Terminal 3 → Signal for gripper connected to Workcell A.
4. Terminal 4 → Signal for gripper connected to Workcell B.

Important Note: Connect the black wire of the electrical cable to terminal 3 if the gripper is installed on Workcell A. Connect the black wire of the electrical cable to terminal 4 if the gripper is installed on Workcell B.
The template (for plastic cylinders) is held into place with a ¼” hex screw and nut. (2) 7/16” wrenches (or crescent wrenches) must be used to loosen and secure the template. Thus, changeover time is increased because of retrieval and use of tools. See Figure 17.

Figure 17, Template for Plastic Cylinder

The template (for wood blocks) is held into place with (2) ¼” hex screws and nuts. (2) 7/16” wrenches (or crescent wrenches) must be used to loosen and secure the template. Thus, changeover time is increased because of retrieval and use of tools. See Figure 18.

Figure 18. Template for Wood Block
The stop gate is held to the conveyor chassis via two M8 fasteners. A 13mm wrench is required to tighten or loosen the fasteners. Thus, changeover time is increased because of retrieval and use of tools.

Also note that no stop blocks are installed on conveyor chassis. Thus, alignment time increases during the changeover process. See Figure 19 below.

To remove or install the electrical cable for the gripper, cutters are required for the zip ties. The use of tools during will increase changeover time. See Figure 20.

Note: zip ties are used to bundle and secure hoses and cables.
OPTIMIZED CONFIGURATION

In the optimized configuration, the conveyor is configured with “lean components” which create a reduced changeover time. Table B. summarizes all the components affected by a changeover.

<table>
<thead>
<tr>
<th>Changeover Component</th>
<th>Qty</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator assembly fastener (for vertical adjust)</td>
<td>4</td>
<td>Screw = M6 quick release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut = M6 self-holding T-nut</td>
</tr>
<tr>
<td>Actuator assembly fastener (for horizontal adjust)</td>
<td>4</td>
<td>Screw = M6 w/ 5mm alan head</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut = M6 T-nut (80-20, Inc)</td>
</tr>
<tr>
<td>Angular gripper fastener</td>
<td>2</td>
<td>M4 thumbscrew</td>
</tr>
<tr>
<td>Parallel gripper fastener</td>
<td>2</td>
<td>#6-32 thumbscrew</td>
</tr>
<tr>
<td>Pneumatic fitting</td>
<td>2</td>
<td>1/8” quick connect w/ #10-32 threads</td>
</tr>
<tr>
<td>Electrical connection</td>
<td>1</td>
<td>Electrical quick connector near PLC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enclosure.</td>
</tr>
<tr>
<td>Palette fasteners for plastic cylinder configuration</td>
<td>1</td>
<td>Screw = 1/4” w/ 7/16” hex head</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut = 1/4” w/ 7/16” hex head</td>
</tr>
<tr>
<td>Palette fasteners for wood block configuration</td>
<td>2</td>
<td>Screw = 1/4” w/ 7/16” hex head</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut = 1/4” wing nut</td>
</tr>
<tr>
<td>Stop gate fastener</td>
<td>2</td>
<td>Screw = M8 T-stud (Bosch)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nut = M8 wing nut</td>
</tr>
<tr>
<td>Vertical adjust stop blocks</td>
<td>1</td>
<td>1.5 x 3” plate w/ 2 drilled holes</td>
</tr>
<tr>
<td>Stop gate stop blocks</td>
<td>1</td>
<td>1.5 x 3” plate w/ 2 drilled holes</td>
</tr>
<tr>
<td>Horizontal adjust jig</td>
<td>1</td>
<td>1 custom jig, plastic</td>
</tr>
<tr>
<td>Wire/Hose tie-down</td>
<td>As Req’d</td>
<td>Re-usable cable clamps</td>
</tr>
</tbody>
</table>
The entire actuator assembly is held to the gantry via (4) M6 quick release fasteners. Unlike the non-optimized configuration, all four fasteners are common. Additionally, they quick release fasteners require no tools. The result is decreased changeover time.

Also, stop blocks are installed on the gantry to allow fast positioning during a changeover. See Figure 21 below.

Figure 21, Gantry Fasteners

The primary slide is held into place via (4) M6 (5mm alan head) screws. By loosening these fasteners, the gripper can be horizontally aligned during a changeover. During the non-optimized changeover, an alignment jig is used to reduce changeover time.

Figure 22. Horizontal Adjustment
The angular gripper is held into place with (2) M4 thumbscrews. Thus, no tool retrieval is required.

The (2) hoses that supply air to the gripper are connected to pneumatic quick connects. Again, no tools are required, and changeover time is reduced.

See Figure 23 below.

Figure 23, Angular Gripper
The parallel gripper is held into place with (2) #6-32 thumbscrews. Thus, no tool retrieval is required.

The (2) hoses that supply air to the gripper are connected to pneumatic quick connects. Again, no tools are required, and changeover time is greatly reduced.

See Figure 24 below.

Figure 24, Parallel Grippers

Note: 1/8” to ¼” quick union used when quick connects are connected to gripper. (2) plc’s.

#6-32 thumbscrew (2) plc’s

1/8” quick connect w/ #10-32 threads (2) plc’s.
Both angular and parallel grippers have an electrical cable that needs to be connected to the PLC Enclosure. The angular and parallel grippers each utilize a 3-conductor male connector. The female end is electrically connected to the terminal blocks. During a changeover, the angular-gripper male connector is removed and replaced with the parallel-gripper male connector. In this case, the point of connection/disconnection occurs at the quick connector; not the terminal block. This action requires no tools, and changeover time is reduced. See Figure 25.

![Figure 25, Electrical Connection](image)

The terminal block consists of four wiring points:

5. Terminal 1 → +24VDC
6. Terminal 2 → Gnd
7. Terminal 3 → Signal for gripper connected to Workcell A.
8. Terminal 4 → Signal for gripper connected to Workcell B.

Important Note: Ensure the black wire of the electrical cable is electrically connected to terminal 3 if the gripper is installed on Workcell A. Ensure the black wire of the electrical cable is electrically connected to terminal 4 if the gripper is installed on Workcell B.
The template (for plastic cylinders) is held into place with a ¼” hex screw and wing nut. No tools are required to secure the template to the palette. Thus, changeover time is reduced. See Figure 26.

Figure 26, Template for Plastic Cylinder

The template (for wood blocks) is held into place with (2) ¼” hex screws and wing nuts. No tools are required to secure the template to the palette. Thus, changeover time is increased because of retrieval and use of tools. See Figure 27.

Figure 27, Template for Wood Block
The stop gate is held to the conveyor chassis via two M8 wing nuts. No tools are required, and changeover time is reduced.

Also note that stop blocks are installed on conveyor chassis. Thus, alignment time is decreased during the changeover process. See Figure 28 below.

Figure 28, Stop Gate

Screw = M8 T-stud (Bosch)
Nut = M8 wing nut
(2) plc’s.

Stop blocks installed (2) plc’s.
1.5 x 3” plate w/ 2 drilled holes.
Horizontal alignment is achieved quickly by the use of an alignment jig. The jig consists of a main body and two attached "fingers". The jig is positioned by placing the main body against the gantry.

If the workcell is configured for the plastic cylinders, then the primary slide must touch the small finger, as illustrated in Figure 30.

Figure 29, Jig Position

Figure 30, Horizontal Alignment for Cylinder
If the workcell is configured for the wood blocks, then the primary slide must touch the large finger, as illustrated in Figure 31.

Figure 31, Horizontal Alignment for Block

To remove or install the electrical cable for the gripper, cable clamps are used in lieu of zip ties. No cutters are required, and changeover time is reduced. See Figure 32.

Figure 32. Cable Clamps
RESULTS AND DISCUSSION

After the workcells were constructed and tested, two changeovers were performed. Both changeovers involved converting the machine from handling plastic couplings to handling wooden blocks. In the first changeover, only standard components were used, and this changeover was referred to as “non-optimized”. Refer to Table A for a list of standard components. Each major phase of the changeover was timed and recorded in Table C.

After the first changeover, the workcell was modified with lean components, and the workcell was said to be optimized. Refer to Table B for a list of lean components. Again, a changeover from handling plastic couplings to wooden blocks was performed on the workcell. Each major phase of the changeover was timed and recorded in Table C.

<table>
<thead>
<tr>
<th>Table C. Changeover Time in Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
</tr>
<tr>
<td>Remove the angular gripper</td>
</tr>
<tr>
<td>Install the parallel gripper</td>
</tr>
<tr>
<td>Adjust the palettes to handle the wooden block</td>
</tr>
<tr>
<td>Vertically align the gripper</td>
</tr>
<tr>
<td>Horizontally align the gripper</td>
</tr>
<tr>
<td>Adjust the stop gate</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

Because power down, power up, test, and cleanup phases of both changeovers took the same amount of time, they were not accounted for in the table. Only the tasks that were affected by standard vs. lean components are shown. The data shows that a changeover with lean components takes about 40% of the time it takes to do a changeover with standard components. The best time savings of 3.5 minutes occurred during the installation of the parallel gripper. The electrical and pneumatic quick connects were big contributors to time reduction in
this task. Interestingly, a time savings of only 2 minutes occurred during the removal of the angular gripper. This is attributed to the fact that it is always easier and faster to remove components than it is to install components. Therefore, the lean components do not contribute as much time savings to removal of components.

The least amount of time savings occurred with the horizontal alignment of the gripper. Although a plastic jig was used to speed up the alignment process, an M5 allen wrench was still required to loosen four screws. Only 0.5 minutes was saved during the lean changeover. In contrast, the vertical alignment had a time savings of 2.5 minutes. This difference is attributed to the use of camlock fasteners. Adjustment of the camlocks was swift, and no tools were required.

**PROJECT COST**

The total parts expense for the Sigma Cell project totaled $3301.64. Table D summarizes the purchases.

<table>
<thead>
<tr>
<th>Date</th>
<th>Purchase Description</th>
<th>Supplier</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/13/05</td>
<td>PLC programmer, RSLogix Software</td>
<td>Columbia Electric</td>
<td>350.00</td>
</tr>
<tr>
<td>4/13/05</td>
<td>PLC enclosure parts</td>
<td>Columbia Electric</td>
<td>724.81</td>
</tr>
<tr>
<td>4/21/05</td>
<td>Numatics, Inc valves</td>
<td>Disco Associates</td>
<td>129.17</td>
</tr>
<tr>
<td>4/22/05</td>
<td>Gantry parts for workcell</td>
<td>Warden Fluid Dynamics</td>
<td>403.80</td>
</tr>
<tr>
<td>5/6/05</td>
<td>Misc. parts, fasteners, hoses</td>
<td>Home Depot</td>
<td>33.56</td>
</tr>
<tr>
<td>5/11/05</td>
<td>Robohand angular grippers</td>
<td>Robohand</td>
<td>1311.97</td>
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<tr>
<td>8/1/05</td>
<td>Electrical connectors</td>
<td>Mouser</td>
<td>17.46</td>
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<tr>
<td>8/1/05</td>
<td>Quick releases</td>
<td>Nashbar</td>
<td>37.25</td>
</tr>
<tr>
<td>8/1/05</td>
<td>Pneumatic fittings</td>
<td>Clippard</td>
<td>77.49</td>
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<tr>
<td>8/1/05</td>
<td>80-20 Inc misc fittings</td>
<td>Warden Fluid Dynamics</td>
<td>36.76</td>
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<tr>
<td>unknown</td>
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<td>Home Depot</td>
<td>54.15</td>
</tr>
<tr>
<td>9/1/05</td>
<td>80-20 Inc misc fittings</td>
<td>Warden Fluid Dynamics</td>
<td>94.81</td>
</tr>
<tr>
<td>10/2/05</td>
<td>Quick releases</td>
<td>Nashbar</td>
<td>30.41</td>
</tr>
</tbody>
</table>

**TOTAL** $3301.64

Note that the Starter Panel is not listed in Table D. It was purchased through UI Engineering as part of contracting bid to renovate several labs in the facility. Estimated cost for the panel and installation is around $2500.00. The Sigma Cell project logged 423 hours of design, construction, testing, and paperwork.
CONCLUSIONS AND RECOMMENDATIONS

All three goals of the Sigma Cell project were accomplished. In May 2005, the machine was made operational with one functioning workcell. By August 2005, both workcells were operational, and lean components were ordered. By September 2005, all lean components were installed and tested. In October 2005, changeovers were conducted and refined on the equipment, and SMED concepts were realized. In November 2005, the equipment was turned over to Charlie Ford for development and testing of a SMED laboratory experiment.

The allowable budget for this project was $7000. With a total expenditure of approximately $3300 on parts and $2500 for the Starter Panel, the total project cost totaled approximately $5800 and was under budget approximately $1200.

The Sigma Cell project was slated for a completion date of May 2005. With an actual completion date of November 2005, the project was six months late. Several factors attribute to late delivery:

1. The project started in January 2005, as opposed to August 2004. This allowed for only one semester to complete, and the project scope required more time.
2. No outside help. The project was primarily completed by one member.
3. “Snowball effect”. Bryan Pepper started work at Micron Technology in January 2005. Micron allowed for a six month period of part-time work to assist Bryan with completing school. Because the project was not completed by June, he was then committed to full time work at Micron. This further limited the amount of time he could spend on the Sigma Cell project.

Because the biggest challenge of this project was making the workcells operational in the first place, many opportunities still exist for design improvement. Listed below are some recommendations:

1. Develop a camlock for the horizontal adjust. This design would be similar to that of the vertical adjust. Portions of the camlock would need to be custom machined, as there is no combination of off-the-shelf components that will accomplish this task. With this completed, virtually no tools would be required for a lean changeover.
2. Make the workcells truly pick-and-place. Currently, the workcells only pick the product from the palettes. Instead of placing them on another palette, the product is simply dropped into a bin. Many more alignment challenges exist if a product must be placed onto another palette, because the need for precision is far more demanding in placement. One possible way to accomplish pick-and-place functionality would be to pick up a product on one side of the conveyor and place it on the other. The donated slides from HP were not long enough to accomplish this task, dropping the product into a bin was the only suitable option. Therefore, a longer horizontal slide would need to be ordered from PHD, Inc.

3. Add additional workcells to the conveyor. Even with the two existing workcells in place, the conveyor still has plenty of available space for future workcells. Furthermore, the PLC has an abundance of spare inputs/outputs and CPU clock cycles to support additional workcells. The new workcells need not be pick-and-place, and there functionality is only limited by the imagination of the designer.

**ACKNOWLEDGEMENTS**

Thanks to Hewlett Packard Boise for donating thousands of dollars of equipment. The equipment will provide a great teaching tool for lean manufacturing techniques.

Special thanks to Michael Keyes of HP. Michael was always willing to answer questions, locate parts, and provide outstanding technical advice for this project. Without his professional expertise, this project would not have been possible.
REFERENCES


APPENDIX A: CAD Drawings
APPENDIX B: Software Printout
APPENDIX C: Operator Manual
APPENDIX D: Starter Panel (AC Panel) Design