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# Denver International Airport - South Terminal Redevelopment Program

## Labor and Productivity Analysis


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CVEN 5286 DESIGN OF CONSTRUCTION OPERATIONS

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## 1.0 Introduction

The South Terminal Redevelopment Program at the Denver International Airport expansion project includes the construction of a new terminal, hotel, and light rail line. The $544 million project will create a new terminal housing a transit center that serves as the final stop for the East Rail Line. The line will run from Union Station in downtown Denver to Denver International Airport with five stops in between. The rail portion of the project is a separate Public-Private Partnership (PPP) contract. The transit center will allow passengers to check into their flights, check bags, and board the inter-terminal train without going into the main terminal. A 519-room Westin hotel and conference center will be constructed above the transit center.

Denver International Airport has contracted with multiple companies to design, build, and manage the transit center and hotel. It has contracted Gensler, SA Miro, ME Engineers, and AMD for the Public Transit Center. For the hotel, the designers are Gensler, SA Miro, ME Engineers, and BCER. For the train platform, the designer is Parsons. The construction manager/general contractor is Mortenson/Hunts/Saunders. Their contract is a cost plus guaranteed price (GMP). All other subcontractors are working under lump sum contracts. There is an average of 450 craft workers on site each day. The estimated completion of the project is June 2015. The contractor employs "installed units" to track and optimize productivity. Weather has been the only unforeseen issue encountered that has affected productivity.

For this project, the formwork contractor, CFA, was observed for their labor practices and productivity. This contractor has one subcontractor, Mesa Construction, which is a disenfranchised business. The tools used to analyze the project are work sampling, five minute rating, flow diagrams, process charts, and crew balance. The details of each method, and their results are presented in this report. Finally, conclusions were derived from the data collected and analyzed of the state of the project's productivity.

## 2.0 Work Sampling

Work sampling is a method used to determine the general productivity of a construction project. It is based on the Central Limit Theorem that a sample of multiple random points will establish a profile for the whole group. Taking a random sampling of the worksite is statistically supported to represent the whole project. This is done by passing through the worksite and making instantaneous, random samplings of the construction workers' activities. An action can be placed into the predefined categories. This study uses the categories of direct work, prep work, tools/equipment, materials handling, waiting, travel, and personal. Ideally, this sample would be spread out over the workday. However, we were not able to capture the entire workday due to the active restrictions in the airport project that required the presence of a project engineer with our team at all times, among others.

Work sampling was performed during morning and afternoon hours. Observations of rebar, formwork, survey, crane, and ironworkers were made over a multiple days. The observations took place over areas of the project where work was in progress including levels 3 and 4 (Transit Center) and level 5 (Hotel). A total of 536 observations were taken. The data collected can be seen in Table 1 and Figure 1. Observations of the survey crew are presented in Table 1 and Figure 3, but were not included in analysis.

**Table 1: Work Sampling Data**

| Crew | Survey (MHS) | Rebar | Formwork (CFA) | Formwork (Mesa) | Crane | Ironwork | Total All Crews |
|---|---|---|---|---|---|---|---|
| **Direct Work** | 22 | 61 | 78 | 45 | 6 | 5 | 217 |
| **Prep Work** | 4 | 20 | 35 | 30 | 4 | 0 | 93 |
| **Tools/ Equipment** | 0 | 4 | 9 | 2 | 1 | 0 | 16 |
| **Materials Handling** | 0 | 28 | 19 | 8 | 8 | 2 | 65 |
| **Waiting** | 5 | 14 | 54 | 19 | 2 | 4 | 98 |
| **Travel** | 0 | 7 | 17 | 4 | 6 | 1 | 35 |
| **Personal** | 1 | 5 | 6 | 0 | 0 | 0 | 12 |
| | | | | | | **Total Observations:** | 536 |

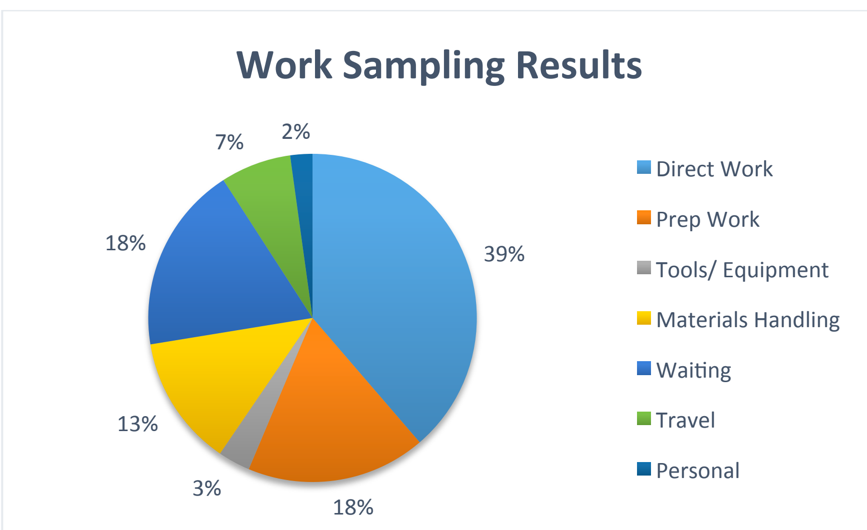



**Figure 1: Work Sampling Results**

The project overall was fairly productive, but there is room for improvement. The target direct work rate is typically 50%. While this project is strong at 39%, there are changes that should be made to achieve higher productivity. The data was collected during the periods of 8:30-9:00 and 12:00-12:30. The differences between the two time periods can be seen in Figure 2.

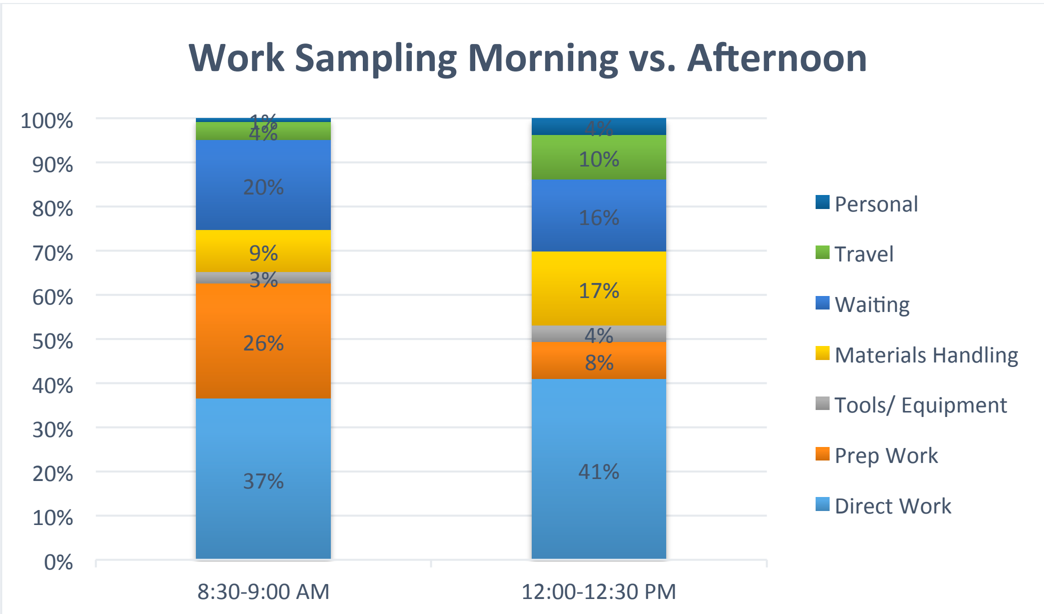



**Figure 2: Work Sampling Morning vs. Afternoon**

The largest differences between the morning and afternoon are prep work, materials handling, and travel. As expected, the amount of prep work done in the morning is 18% higher than in the afternoon while workers set up for the day. However, the direct work rate in the afternoon does not increase by 18%. The savings are split by the increase in materials handling, and travel. This can be attributed to the disruption of the worksite throughout the day. As progress is made, work moves further away from the original area were materials had been placed. Additionally, the workspace becomes more disorganized and cluttered. This leads to an increase in traveling and materials handling, among other consequences. As a result, productivity is also unbalanced between trades. Hence, workers should be reminded to keep their areas organized during the day, and to plan the location of materials more frequently. A comparison of the trades observed can be seen in Figure 3.

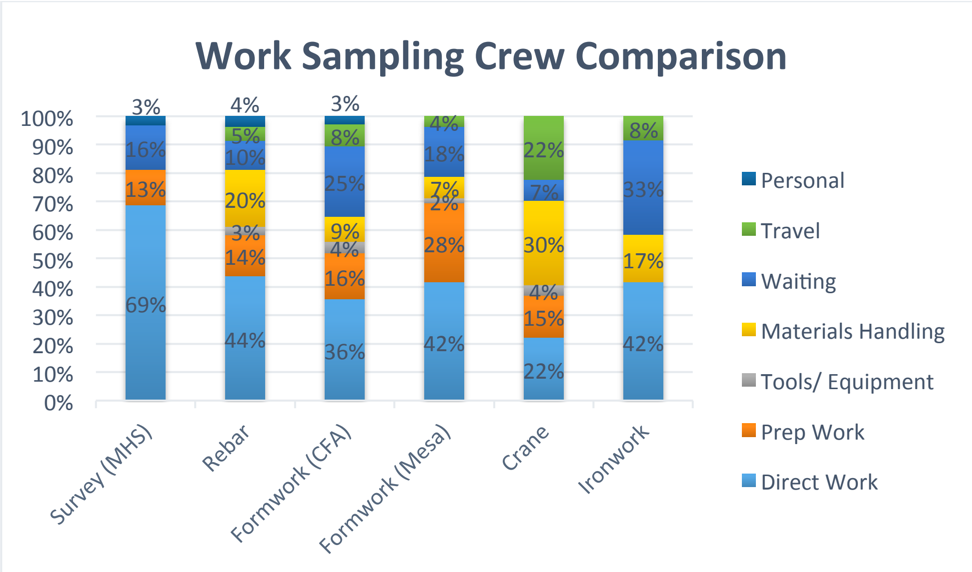



**Figure 3: Work Sampling Crew Comparison**

While some trades have inherently low direct work rates, others have room for improvement. On the high end, survey crews have very high direct work rates because total stations eliminate wasted time between taking measurements. The lowest direct work rate is that of workers guiding the crane to move materials around the site. They spend most of their time moving materials, traveling across the site, or waiting for the crane operator. While they appear unproductive, the nature of their work limits their direct work rates. Ironworkers also fall into this category waiting for cranes to pick the next steel section. Rebar and formwork crews should have higher direct work rates. Their tasks are repetitive and not a specialized skill set. This generally gives them the potential to establish a specific sequence of work and achieve high direct work rates. The following productivity analysis methods take a deeper look at the CFA and Mesa formwork crews.

## 3.0 Five Minute Rating

The observations were targeted for 15 minutes periods. Oglesby et al. (1989) indicated that the purpose of this method is:

- To make management aware that a delay has occurred and communicate its importance;
- Check the adequacy of the crew in completing goals; and
- Pinpoint where planning could produce savings.

Observations are made in blocks of time, and should not be taken for less than 5 minutes. Blocks of time are classified as delay or work. For example, if more than 50% of the time block is marked as delay, the whole block is categorized as delay.

## 3.1 Activity Description

On the first visit to the project, we were taken to an area known as "Level 3 Area F Ramp to Existing Area". The crews located in this area were working on the preparation of formwork for the sidewalls of the ramp as shown in Figure 4.

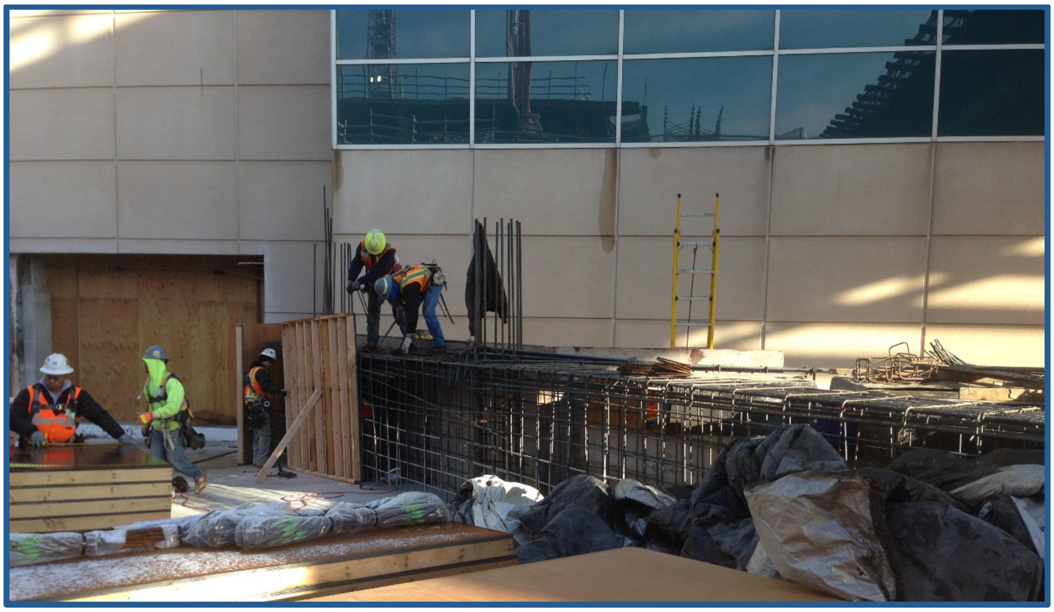


**Figure 4: Right Sidewall at Level 3 Area F**

The employees were divided in two crews. Crew 1, shown in Figure 5, was made up of five employees who executed work on the left sidewall, and performed the following tasks:

- Employees 1 and 2 fitted and installed formwork panels;
- Employee 3 and 4 locked ties to formwork panels; and
- Employee 5 installed tie rods.


**Figure 5: Members of Crew 1**

Crew 2, shown in Figure 6, was made up of four employees who executed work on the right sidewall, and performed the following tasks:

- Employees 1 and 2 measured, cut, aligned, and anchored formwork panels; and
- Employee 3 and 4 held, and anchored formwork panels in place.


**Figure 6: Members of Crew 2**

During the observation period of both crews, no supervisory figure was clearly identified until the end of the first observation period. The supervisor seemed to be responsible for crew 1 only. Crew 2 seemed to be led by one of its members. Two observers were used to conduct four five minute ratings. Each observer watched one crew over the course of two time blocks. Time block 1 began at 9:15 am and lasted eleven minutes and thirty seconds. Time block 2 began at 10:07 am and lasted fifteen minutes. A summary of the 5-minute rating set up can be seen in Table 2.

**Table 2: Five Minute Rating Time Blocks**

| Time Blocks | Time Observed | Crew | Number of Workers |
|---|---|---|---|
| **1** | 11:30 | 1 | 5 |
| | | 2 | 4 |
| **2** | 15:00 | 1 | 5 |
| | | 2 | 4 |

## 3.2 Analysis

Four observation periods are sufficient to reliably measure the effectiveness of the crews. The observation time is divided in 30 seconds to have a more accurate depiction of the movements of the workers. As shown in Table 3, the time block 1 for both crews and time block 2 for crew 2 can be classified as working blocks due to their effectiveness being above 50%. In contrast, time block 2 for crew 1 is classified as delay block due to its effectiveness being below 50%. The overall effectiveness for all both time blocks is 52%, which indicates that this area on the project can be classified as working. The results from all five minute ratings are compared in Table 3 and Figure 7. Crew 1 and 2 were close in effectiveness for time block 1. However, crew 2 surpassed crew 1 by 17% for time block 2.

**Table 3: Five Minute Rating Data**

| Time Blocks | Crew | Total Man Units | Effective | Effectiveness |
|---|---|---|---|---|
| **1** | 1 | 120 | 62 | 52% |
| | 2 | 96 | 49 | 51% |
| **2** | 1 | 155 | 67 | 43% |
| | 2 | 109 | 65 | 60% |
| | **Total:** | 480 | 243 | 51% |

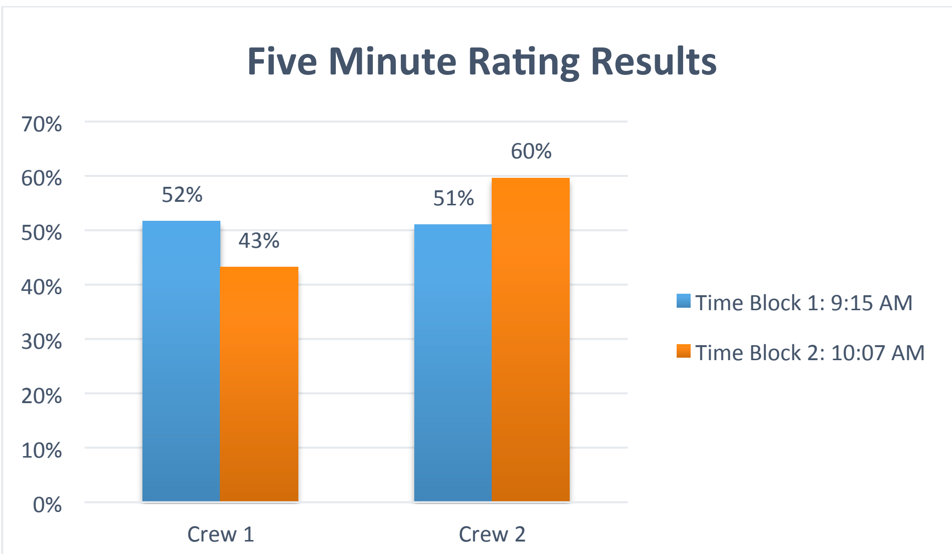



**Figure 7: Five Minute Rating Results**

The five minute rating sheets used in the field can be found in Figure 16 to Figure 19 in the appendix. Figure 16 shows the causes of variations in the effectiveness of crew 1 in time block 1, which stems from:

- 4 workers that temporarily stopped working in the middle of the observation period; and
- 3 workers that left early for break.

Figure 18 shows the causes of variations in the effectiveness of crew 1 in time block 2, which from:

- 1 worker entering the working area and quickly leaving;
- The relocation of a generator created other disruptions such as:

- 2 workers that started to work later than others.

In addition, Figure 17 shows the causes of variations in the effectiveness of crew 2 in time block 1, which stems from:

- 2 workers that started to work later than others; and
- 2 workers that left early.

Figure 19 shows the causes of variations in the effectiveness of crew 2 in time block 2, which stems from:

- 3 workers that temporarily stopped executing in the middle of the observation period.

In Figure 18, the foreman was included in the observations but was later removed from the analysis. Foremen constantly move around to supervise workers, which makes them an unreliable subject to include in the effectiveness analysis of the crew. Another consideration taken to remove the data collected from watching the foreman was due to its late entry into the observation period. The inclusion of this data would have negatively modified the results by lowering the effectiveness of the crew.

## 3.3 Recommendations

Based on the analysis performed of time block 1 of crew 1, shown in Figure 16, we recommend the relocation of employee 2 from crew 1 to another work area. Employee 5 effectively performed only nine work units. Since employee 3 has twelve ineffective units available, he can comfortably include the nine work units left by employee 4. This change to the work routine of the employees should be introduced using a job assignment sheet. Employees 1 and 2 executed work together. This can be observed in how both employees' effective units offset the ineffective units of the other worker. This reflects that their work was concurrent and complementary.

Based on the analysis performed of time block 2 of crew 1, shown in Figure 18, employee 4 should aid employee 3 in the placement of ties. This will enable the tie work to get ahead enough distance for employee 4 to lock the ties with 2x4s. This will reduce the amount non-effective units from worker 4. Thus, the overall effectiveness would increase.

Based on the analysis performed of time block 1 of crew 2, shown in Figure 17, we recommend relocating employee 4 due to his inactiveness, which lasted an approximate 2/3 of the observation period. The likelihood of his inactiveness may stem from the observation that there were three employees who seem to be assigned to prepare the formwork. These three employees produced two sidepieces of formwork wall roughly every 7 minutes. As a result, employee 4 was deemed an additional resource to the crew.

Based on the analysis performed of time block 2 of crew 2, shown in Figure 19, we recommend the relocation of one employee to another work area. As indicated above, the preparation and installation of the formwork requires only three employees. A fourth employee lowers the effectiveness of the crew by being idle. This can be seen after minute 8:00 when worker 2 leaves and joins another crew. The effectiveness before minute 8:00, with four workers, was 48%. After minute 8:00, with only 3 workers, the effectiveness increased to 63%. Even with the loss of a worker the formwork installation was still completed quickly. The data after implementing these recommendations is shown in Table 4 and Figure 8.

**Table 4: Five Minute Rating Proposed Data**

| Time Blocks | Crew | Total Man Units | Effective | Effectiveness |
|---|---|---|---|---|
| **1** | 1 | 96 | 62 | 65% |
| | 2 | 72 | 49 | 68% |
| **2** | 1 | 124 | 67 | 54% |
| | 2 | 93 | 65 | 70% |
| | **Total:** | 385 | 243 | 63% |

The differences to the five minute rating results were calculated by removing the man units from the excess workers while keeping the same number of effective units. To remove the slack from the work process, the remaining employees can absorbed the effective units from the removed crewmember. As a result, crew 1 increased its effectiveness by an average of 12%, and crew 2 benefitted by an average of 13%.

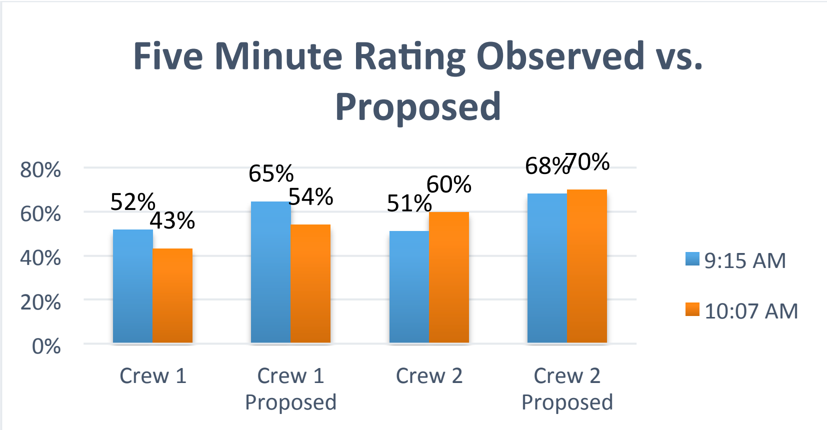



**Figure 8: Five Minute Rating Observed vs. Proposed**

Table 5 illustrates the cost savings of the proposed changes only over the time period observed. The implementation of changes would have saved $45.40 over the two time blocks. This translates into 20% in labor cost savings for crew 1, and 25% in labor cost savings for crew 2. The material costs, equipment costs, and completion time will remain equal because the same amount of work needs to be completed.

**Table 5: Five Minute Rating Cost Savings**

| Time Blocks | Crew | Observed Workers | Proposed Workers | Time Observed | Crew C-2 Hourly Costs | Observed Costs | Proposed Costs | Savings ($) | Savings (%) |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 5 | 4 | 11:30 | $51.40 | $49.26 | $39.41 | $9.85 | 20% |
| | 2 | 4 | 3 | 11:30 | | $39.41 | $29.56 | $9.85 | 25% |
| **2** | 1 | 5 | 4 | 15:00 | | $64.25 | $51.40 | $12.85 | 20% |
| | 2 | 4 | 3 | 15:00 | | $51.40 | $38.55 | $12.85 | 25% |
| | | | | | **Total:** | $204.32 | $158.91 | $45.40 | |

Some of the disadvantages of the five minute ratings are:

- The method does not have the capability to differentiate between types of delays but enables deduction of labor costs;
- The method reveals the effectiveness of employees, but not their production output. This means that employees may appear busy, but not be accomplishing their required daily output; and
- Experience is needed to determine the amount and duration extent required to effectively perform a 5-minute rating.

# 4.0 Flow Diagrams and Process Charts

## 4.1 Flow Diagram Description

A flow diagram is a two dimensional schematic that shows the movement of workers, equipment, and material. Flow diagrams are helpful to understand a construction process and to diagnose inefficiencies within a job site. In order to adequately model construction processes, the symbols listed in Table 6 are used.

**Table 6: List of Flow Diagram Operators**

| Symbol | Name | Description |
|---|---|---|
| | Operation | Something is produced or accomplished; Direct work |
| | Storage | Controlled storage where an object is kept |
| | Delay | Temporary hold-up that prevents a worker from completing a task |
| | Inspection | Worker is analyzing a completed activity or material for quality |
| | Travel | Movement of materials, equipment, or workers from one job-site location to another, excluding small movements |

## 4.2 Process Chart Description

A process chart is a chronological description of a construction task that analyzes the type and duration of each activity included. Process charts generally accompany flow diagrams to quantify results and potential solutions. The same symbols described in Table 6 are used for process charts as well.

## 4.3 Site Location

The processes for Level 4 Area A are analyzed through flow diagrams and process charts. This area is seen in Figure 9.

**Figure 9: Level 4 Area A Layout**

## 4.4 Process Descriptions

For this project, two flow diagrams were developed. The first process, seen in Figure 10, describes a worker installing the ends of metal forms. Within this process, a worker carries and installs an end form to desired location. After installation, the worker inspects the form to ensure that it has been placed correctly. The worker then returns to the storage of the forms and starts the process again. This occurs for all four end forms.

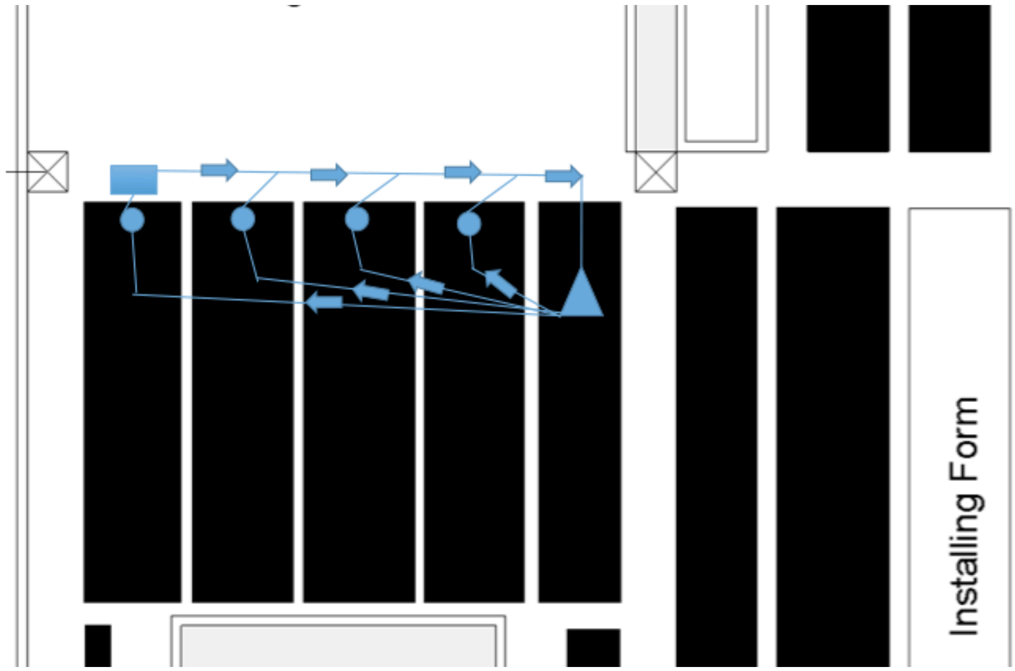



**Figure 10: Flow Diagram for Form Installation Process Observed**

In the second process, shown in Figure 11, a worker installs a guardrail around an opening to the lower level. This worker starts by measuring locations to place connection pieces. These connectors are L-shaped metal pieces that have an opening for a post to be inserted. Once the worker is finished measuring, he installs two connectors and inspects them. The worker then travels 6 feet to install two more connectors. After inspection, the worker then travels back to the original work area. Another worker inserts posts while the installation of the first two connectors occurred. The original worker then travels to a storage area 12 feet away to obtain two 2x4 boards. After travelling back, the worker hammers these boards to the posts. Next, the worker travels 60 feet to a separate storage area, obtains two more 2x4 boards, travels back, and installs the boards.

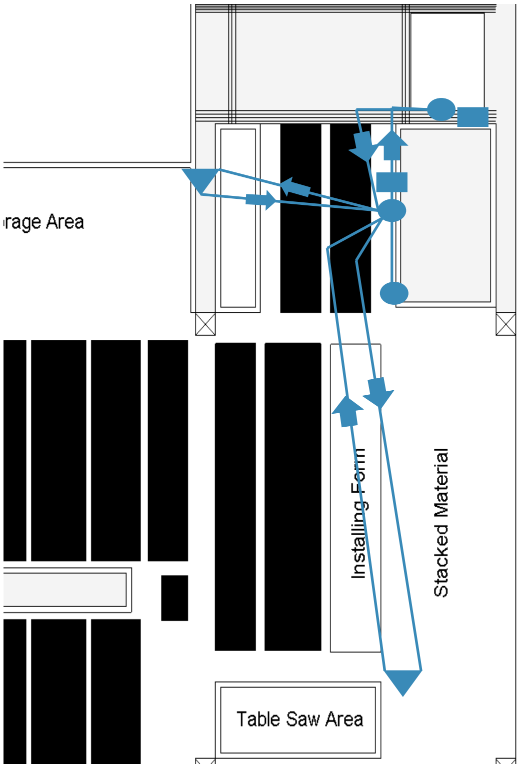



**Figure 11: Flow Diagram for Guardrail Installation Observed**

Process charts for these two cycles can be seen in the appendix in Figure 20 and Figure 22.

## 4.5 Optimization of Processes

In order to optimize both processes, all activities other than operations must be minimized. For process one there is an unnecessary amount of travel between the work area and the storage area. To minimize this, the worker could initially carry two forms and places them between the first two installation locations. The worker then installs and inspects both forms. After this, the worker travels to collect the last two forms and carries them to an area between the second two installation locations. The worker then installs and inspects these two forms. This optimized process is shown in Figure 12.

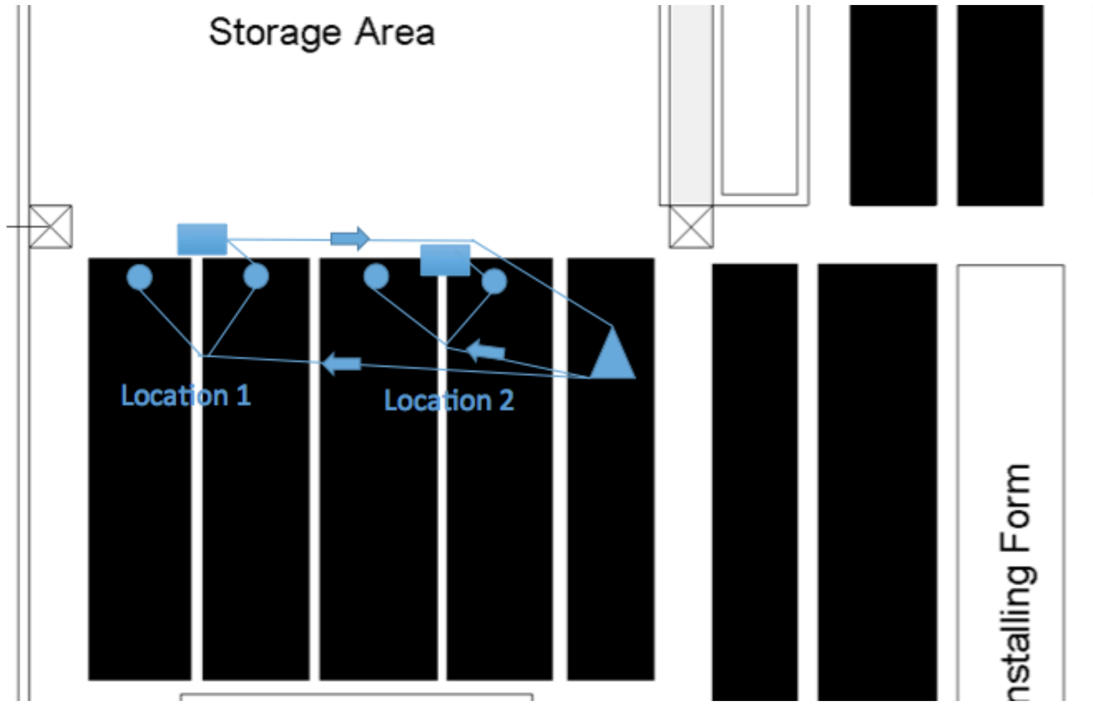



**Figure 12: Flow Diagram for Form Installation Proposed**

To optimize the second process, all boards could be located in a closer storage area. This prevents the worker from interrupting his process for two separate travel activities. The optimized process for this is shown in Figure 13.

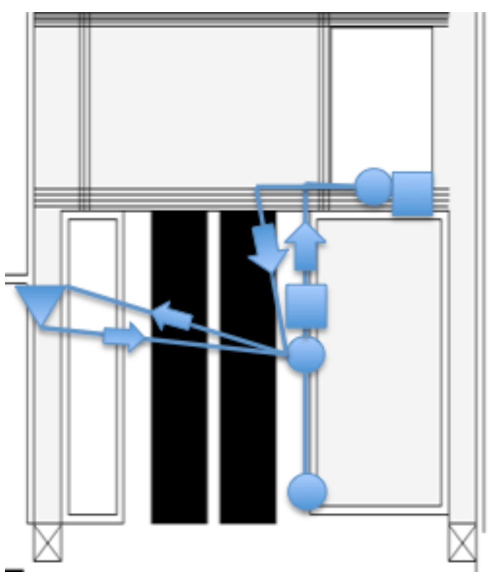


**Figure 13: Flow Diagram for Guardrail Installation Proposed**

Process charts for these optimized processes can be seen in the appendix in Figure 21 and Figure 23.

## 4.6 Results

In order to compare the results of the observed and optimized processes, it is beneficial to analyze the process charts. A summary of the results of these process charts is shown in Table 7.

**Table 7: Process Chart Proposed Savings**

| | Process 1: Form End Installation | Process 2: Guardrail Installation |
|---|---|---|
| **Distance Saved due to Travel** | 42.5 ft | 120 ft |
| **Total Time Saved** | 0.633 min | 0.383 min |
| **Time Savings Percentage** | 18% | 3.5% |

It is important to note that the applicability of the flow diagram and process charts is limited because the processes analyzed contained workers completing tasks primarily unassisted. This eliminates any delay produced by dependence on other workers.

# 5.0 Crew Balance Study

## 5.1 Crew Balance Description

A crew balance study provides a beneficial method to analyze workers' interaction within a crew. In order to complete this study, observers watch all members of a crew throughout the duration of a cycle. Observers record the specific task that each worker is completing and its duration in chronological order. The observations are then analyzed to determine inefficiencies or improvements. The main objective of a crew balance study is to observe idle time on a jobsite and minimize it

In addition to the workers described for process 1 and 2 in Chapter 4, a worker whose primary task was saw cutting is analyzed. The saw worker is observed for just under 24 minutes. The process chart for the saw worker can be seen in the appendix in Figure 24.

Within Figure 14, employee 1 is the worker that installed form ends, employee 2 is the worker that installed the guardrail, and employee 3 is the saw worker.


**Figure 14: Level 4 Area A Workers**

## 5.2 Results

The total percentage of time spent on each task category for each worker can be seen in Figure 15. Figure 15 also displays the workers from process 1 and 2 after optimization.

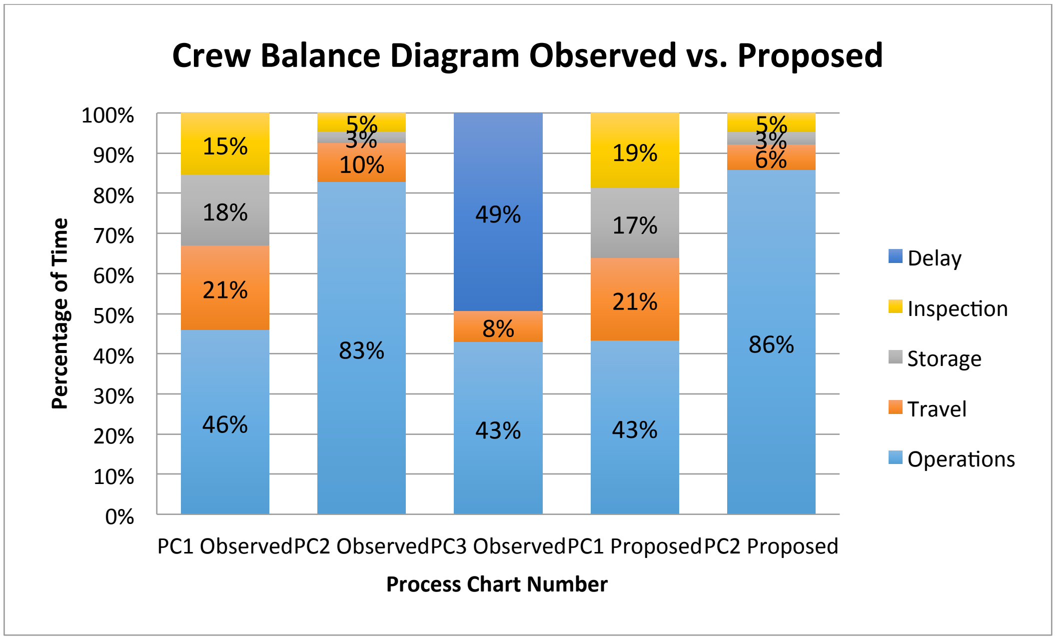



**Figure 15: Crew Balance Diagram**

In Figure 15, PC1 is the worker that is installing form ends, PC2 is the worker that is installing guardrails, and PC3 is the saw worker. It is clear that a substantial portion of the saw worker's time is spent on delays.

## 5.3 Recommendations

The crew balance study was completed using discrete event simulation models. The first model, shown in the appendix in Figure 25, is a representation of the same three processes observed in both the flow charts and process diagrams. All three workers are working alone, and worker 3 at the saw table is highly unproductive. The model was then redesigned to have all three workers cooperate, shown in the appendix in Figure 26. The main difference is that worker 3 will now be responsible for transporting all materials. He will transport four forms from the stockpile to worker 1, transport all four boards from their stockpiles to worker 2, and then complete the same amount of sawing as the previous model. This will allow workers 1 and 2 to remain working without traveling to get materials. Worker 3 creates a butterfly pattern in the new model connecting the work of all three employees. He transitions from being the least critical worker in the first model to the most critical in the proposed model.

**Table 8: Discrete Event Simulation Results**

| Metric | Observed | Proposed |
|---|---|---|
| Time for worker 1 to complete tasks (min) | 3.560 | 2.938 |
| Time for worker 2 to complete tasks (min) | 8.145 | 3.887 |
| Time for worker 3 to complete tasks (min) | 7.151 | 4.485 |
| Total time to complete all tasks (min) | 8.145 | 4.485 |
| Time spent traveling by worker 1 to get materials (min) | 0.945 | 0.000 |
| Time spent traveling by worker 2 to get materials (min) | 0.883 | 0.000 |
| Time spent traveling by worker 3 to get materials (min) | 0.000 | 2.590 |
| Total time spent traveling to get materials (min) | 1.828 | 2.590 |
| Time spent traveling by worker 1 to get materials (%) | 26.5% | 0.0% |
| Time spent traveling by worker 2 to get materials (%) | 10.8% | 0.0% |
| Time spent traveling by worker 3 to get materials (%) | 0.0% | 57.7% |
| Total time spent traveling to get materials (%) | 9.7% | 22.9% |
| Time worker 3 is idle (min) | 3.369 | 0.000 |
| Time worker 3 is idle (%) | 47.1% | 0.0% |
| Labor costs to complete all tasks ($) | $16.15 | $9.69 |

The variables recorded from the two discrete event simulation models can be found in Table 8. The work is done more efficiently in the proposed model almost reducing the time to complete all tasks in half. While the time spent traveling to get materials increases in total minutes, this is expected as one worker is now transporting all materials. The materials handling as a total percentage of the crew's time nearly doubles, but this can be explained by the total time being cut in half. Finally, the cost of both models was calculated using the same $51.40 hourly rate as the five minute ratings from the RS Means crew C-2 carpenter rate. The total costs are the hourly rate times the time each worker was active. To complete the same amount of work, the proposed model saved a total of $6.46. The savings would be much more if these adjustments were carried out throughout the entire day or an entire project.

## 6.0 Summary of Recommendations

The Denver International Airport South Terminal Redevelopment Construction project is a productive work site, but productivity could be better. Through work sampling, the direct work rate was observed to be 39%. With a target of 50% direct work, there is room for improvement on this project. The thorough analyses used identified ways to improve productivity. The five minute rating analysis brought to light the absence of coordination and supervision required for both crews to be highly effective. The use of additional human resources is deemed a detriment to effectiveness. The overall conclusion was that both crews had more human resources than required to effectively work in an area stocked with materials. The effectiveness of the crews was contingent on continuous coordination and supervision, not the addition of employees. When one worker left crew 2 and they remained productive, our proposed change was validated. Removing a worker would reduce labor costs of crew 1 and crew 2 by 20% and 25% respectively while completing the same amount of work.

The workers on Level 4 Area A could also improve their productivity. The flow diagrams, productivity charts, crew balance, and discrete event simulation models identified unproductive time spent transporting materials and idleness. The three workers were not working together. Worker 3 was designated the saw table employee, but spent much of his time idle and allowed other workers to cut their own material. By coordinating the work, worker 3 can use his idle time to supply materials to workers 1 and 2. This will allow them to focus on direct work and the whole crew will benefit. The discrete event simulation model demonstrated that the time to complete all the work could nearly be cut in half with a cost savings of $6.46 for only these tasks. Continued coordination between workers over the long term would generate even larger savings.

From the observations gathered, it can be concluded that coordination and supervision are essential to not only increase the effectiveness of certain employees, but to maintain the daily output level required for all employees. Simply placing more workers on a crew will not increase productivity. Over manning reduces a crew's efficiency and increases labor costs. Using job assignment sheets is an effective way to ensure workers know what tasks they are responsible for and how to coordinate work. Idle workers need to know how they can help other workers during their down time. Implementing these recommendations will increase crew productivity and result in cost savings.

# 7.0 Appendix

Date: 10/18/2013
Time: 9:15am
Location: Level 3 Area F
Ramp to Existing Area
Name: Valerie

| Time | White Hat Grey-Blue Sweater | Grey Hat Blue Long Shirt | Grey Hat Brown Sweater | Grey Hat Beard | White Hat Blue Sweater | | |
|---|---|---|---|---|---|---|---|
| Start | 1 | 2 | 3 | 4 | 5 | 6 | |
| 0:00 | x | x | x | x | x | | |
| 0:30 | x | x | x | x | x | | Measuring wall to exterior of form |
| 1:00 | x | x | x | x | x | | side of rebar |
| 1:30 | | | | x | | | Marking form |
| 2:00 | | | x | | | | Installing form tie rods |
| 2:30 | x | x | x | | x | | Locking form work |
| 3:00 | | | x | | | | Drilling holes in form |
| 3:30 | | | x | | x | | Lifting and placing form into rebar |
| 4:00 | | | | | | | |
| 4:30 | x | | x | | | | Installing form tie rods |
| 5:00 | x | x | x | | | | Installing form tie rods |
| 5:30 | x | | x | | | | Installing form tie rods |
| 6:00 | | | x | | x | | Installing form tie rods |
| 6:30 | x | | x | x | | | Installing form tie rods |
| 7:00 | x | x | x | x | x | | Installing form tie rods |
| 7:30 | x | x | x | x | | | Installing form tie rods |
| 8:00 | | x | | | x | | |
| 8:30 | x | | x | x | x | | Installing form tie rods |
| 9:00 | x | | x | | | | Installing form tie rods |
| 9:30 | x | x | | | | | |
| 10:00 | x | | x | | | | Left early for break: 11 total units |
| 10:30 | x | | | | | | Measuring formwork panel |
| 11:00 | x | x | | | | | Marking formwork panel |
| 11:30 | x | x | | | | | Marking formwork panel |
| 12:00 | | | | | | | |
| 12:30 | | | | | | | |
| 13:00 | | | | | | | |
| 13:30 | | | | | | | |
| 14:00 | | | | | | | |
| 14:30 | | | | | | | |
| 15:00 | | | | | | | |
| | 17 | 11 | 17 | 8 | 9 | | |

Total Man Units: 120 Effective: 62 Effectiveness: 52%

**Figure 16: Five Minute Rating Time Block 1 Crew 1**

Date: 10/18/2013
Time: 9:15am
Location: Level 3 Area F
Ramp to Existing Area
Name: Bruce

| Time | Grey Helmet Red Hoody | Grey Helmet Green Hoody | White Helmet No Hood | White Helmet Hood Up | | | |
|---|---|---|---|---|---|---|---|
| Start | 1 | 2 | 3 | 4 | 5 | 6 | |
| 0:00 | X | X | | | | | **Sequence 1:** Form Up |
| 0:30 | X | X | | | | | Doesn't Fit |
| 1:00 | | | | | | | Take Form Down |
| 1:30 | | | | | | | Planning/Measuring |
| 2:00 | X | X | | | | | Planning/Measuring |
| 2:30 | X | X | | | | | Planning/Measuring |
| 3:00 | X | X | | | | | Pulling Nails |
| 3:30 | X | | X | | | | Pulling Nails |
| 4:00 | | | X | | | | Pulling Nails |
| 4:30 | | | X | | | | Cutting Form with Saw |
| 5:00 | X | X | X | | | | Cutting Form with Saw |
| 5:30 | X | X | X | | | | Cutting Form with Saw |
| 6:00 | X | X | X | | | | Put Form Back Up |
| 6:30 | X | X | X | | | | Placing Form |
| 7:00 | X | | X | | | | Placing Form |
| 7:30 | X | X | X | | | | Placing Form |
| 8:00 | X | | X | | | | Placing Form |
| 8:30 | X | X | X | X | | | Placing Form |
| 9:00 | X | X | | X | | | **Sequence 2**: Measuring |
| 9:30 | | | X | X | | | Measuring |
| 10:00 | | | X | X | | | Measuring |
| 10:30 | | | X | | | | Measuring |
| 11:00 | | | X | X | | | Measuring |
| 11:30 | | | X | X | | | Measuring |
| 12:00 | | | | | | | |
| 12:30 | | | | | | | Left early for break: |
| 13:00 | | | | | | | 10 total man units |
| 13:30 | | | | | | | |
| 14:00 | | | | | | | |
| 14:30 | | | | | | | |
| 15:00 | | | | | | | |
| | 15 | 12 | 16 | 6 | | | |
| | | | | | | | |
| Total Man Units: | | 96 | Effective: | 49 | Effectiveness: | | 51% |

**Figure 17: Five Minute Rating Time Block 1 Crew 2**

| Time | White Hat Grey-Blue Sweater | Grey Hat Blue Long Shirt | Grey Hat Brown Sweater | Grey Hat Beard | White Hat Blue Sweater | Grey Hat Orange Sweater (Foreman) | Date: 10/18/2013<br>Time: 10:07am<br>Location: Level 3 Area F<br>Ramp to Existing Area<br>Name: Valerie |
|---|---|---|---|---|---|---|---|
| Start | 1 | 2 | 3 | 4 | 5 | 6 | |
| 0:00 | x | x | x | x | | | |
| 0:30 | x | x | x | x | | | Measuring wall from concrete to exterior of rebar |
| 1:00 | x | x | | | | | |
| 1:30 | x | x | | | | | Marking formwork panel |
| 2:00 | x | x | | | | | |
| 2:30 | x | x | x | | | | |
| 3:00 | x | x | x | | | | |
| 3:30 | | | | | | | Crane delay while |
| 4:00 | | | | | | | generator is lifted overhead |
| 4:30 | x | x | | | | | ↓ |
| 5:00 | x | | | | | | |
| 5:30 | x | x | | | | | |
| 6:00 | x | x | | | | | |
| 6:30 | x | x | | | | | |
| 7:00 | x | x | x | x | | | Helping to maneuver the landing of the Generator |
| 7:30 | x | x | | | | | Installing form tie rods |
| 8:00 | x | x | x | | | | Locking form work |
| 8:30 | x | x | x | x | | | Drilling holes in form |
| 9:00 | x | | x | | x | | Lifting and placing form into rebar |
| 9:30 | | | x | x | x | | Installing tie rods |
| 10:00 | | | x | | | | Installing tie rods |
| 10:30 | | | x | x | | | Installing tie rods |
| 11:00 | | | x | | | x | Relocating form to install location |
| 11:30 | | | x | x | | x | Installing tie rods |
| 12:00 | | | x | | | | Installing tie rods |
| 12:30 | x | x | x | | | | Marking formwork panel |
| 13:00 | | | x | x | | x | Installing tie rods |
| 13:30 | | | | | | x | |
| 14:00 | x | x | x | | | | Getting more tie rods |
| 14:30 | x | | | | | | Drillling holes in formwork |
| 15:00 | x | x | x | | | | Placing formwork panel |
| | 21 | 18 | 18 | 8 | 2 | 4 | |

Total Man Units: 155 Effective: 67 Effectiveness: 43%

*Foreman not included in effectiveness percentage

**Figure 18: Five Minute Rating Time Block 2 Crew 1**

| Time | Grey Helmet Red Hoody | Grey Helmet Green Hoody | White Helmet No Hood | White Helmet Hood Up | | | Date: 10/18/2013<br>Time: 10:09am<br>Location: Level 3 Area F<br>Ramp to Existing Area<br>Name: Bruce |
|---|---|---|---|---|---|---|---|
| Start | 1 | 2 | 3 | 4 | 5 | 6 | |
| 0:00 | | X | X | X | | | Holding Up Form |
| 0:30 | X | | X | X | | | Holding Up Form |
| 1:00 | | | | | | | Crane delay while |
| 1:30 | | | | | | | generator lifted overhead |
| 2:00 | X | X | X | X | | | Pull Nails |
| 2:30 | X | X | X | | | | Measuring |
| 3:00 | X | X | X | | | | Measuring |
| 3:30 | | X | | | | | Waiting For Saw |
| 4:00 | X | X | | | | | Waiting For Saw |
| 4:30 | X | X | | | | | Waiting For Saw |
| 5:00 | X | | | | | | Cutting Form |
| 5:30 | X | | | | | | Cutting Form |
| 6:00 | X | | | | | | Cutting Form |
| 6:30 | X | | | | | | Cutting Form |
| 7:00 | X | | | | | | Cutting Form |
| 7:30 | X | | | | | | Cutting Form |
| 8:00 | X | | X | | | | Worker 2 joined other crew |
| 8:30 | X | | X | X | | | Holding Up Form |
| 9:00 | X | | X | X | | | Holding Up Form |
| 9:30 | X | | X | X | | | Form Back Down |
| 10:00 | X | | | X | | | Cutting Form |
| 10:30 | X | | X | | | | Form Back Up |
| 11:00 | X | | X | X | | | Holding Up Form |
| 11:30 | X | | X | X | | | Holding Up Form |
| 12:00 | X | | X | | | | Measuring and Holding |
| 12:30 | X | | X | | | | Measuring and Holding |
| 13:00 | X | | X | | | | Measuring and Holding |
| 13:30 | X | | X | | | | Measuring and Holding |
| 14:00 | X | | X | X | | | Form Secured |
| 14:30 | X | | X | X | | | Form Secured |
| 15:00 | X | | X | X | | | Form Secured |
| | 27 | 7 | 19 | 12 | | | |
| Total | | | | | | | |
| Total Man Units: | | 109 | Effective: | 65 | Effectiveness: | | 60% |
| 0:00-7:30 | | | | | | | |
| Total Man Units: | | 56 | Effective: | 27 | Effectiveness: | | 48% |
| 8:00-15:00 | | | | | | | |
| Total Man Units: | | 60 | Effective: | 38 | Effectiveness: | | 63% |

**Figure 19: Five Minute Rating Time Block 2 Crew 2**

| Process Chart 1 Observed | |
|---|---|
| **Date** | 8-Nov-13 |
| **Project** | Denver International Airport |
| **Operation** | Formwork |
| **Observer** | Bruce Hall |
| **Workers** | Red hoody, grey hard hat, orange vest |
| **Notes** | Worker was finishing installing form ends |

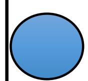
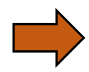
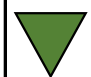
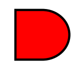
| **Description** | **Dist (ft)** | **Time (min)** | **Symbol** | | | | |
|---|---|---|---|---|---|---|---|
| | | |  |  |  |  |  |
| Carry form to installation location | 20 | 0.333 | | ■ | ■ | | |
| Install 1st form piece | - | 0.500 | ■ | | | | |
| Inspect installation | - | 0.167 | | | | ■ | |
| Travel back to material | 20 | 0.067 | | ■ | | | |
| Carry form to installation location | 15 | 0.250 | | ■ | ■ | | |
| Install 2nd form piece | - | 0.500 | ■ | | | | |
| Inspect installation | | 0.167 | | | | ■ | |
| Travel to get another form | 15 | 0.050 | | ■ | | | |
| Carry form to installation location | 10 | 0.167 | | ■ | ■ | | |
| Install 3rd form piece | - | 0.500 | ■ | | | | |
| Inspect installation | | 0.167 | | | | ■ | |
| Travel to get another form | 10 | 0.033 | | ■ | | | |
| Travel with material | 5 | 0.017 | | ■ | ■ | | |
| Install 4th form piece | - | 0.500 | ■ | | | | |
| Inspect installation | | 0.167 | | | | ■ | |
| Total | 95 | 3.583 | 4 | 7 | 4 | 4 | 0 |

**Figure 20: Process Chart for Form Installation Observed**

## Process Chart 1 Proposed

| | |
|---|---|
| **Date** | 8-Nov-13 |
| **Project** | Denver International Airport |
| **Operation** | Formwork |
| **Observer** | Bruce Hall |
| **Workers** | Red hoody, grey hard hat, orange vest |
| **Notes** | Worker was finishing installing form ends |

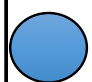
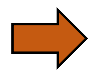
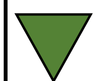
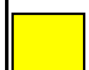
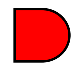
| **Description** | **Dist (ft)** | **Time (min)** | **Symbol** | | | | |
|---|---|---|---|---|---|---|---|
| | | |  |  |  |  |  |
| Carry two forms to Location 1 | 17.5 | 0.438 | | ■ | ■ | | |
| Travel Back to material | 17.5 | 0.075 | | ■ | | | |
| Carry two forms to Location 2 | 7.5 | 0.188 | | ■ | ■ | | |
| Install 1st form piece | - | 0.500 | ■ | | | | |
| Install 2nd form piece | - | 0.500 | ■ | | | | |
| Inspect Installation | - | 0.333 | | | | ■ | |
| Travel to Location 2 | 10 | 0.033 | | ■ | | | |
| Install 3rd form piece | - | 0.500 | ■ | | | | |
| Install 4th form piece | - | 0.050 | ■ | | | | |
| Inspect Installation | - | 0.333 | | | | ■ | |
| Total | 52.5 | 2.950 | 4 | 4 | 2 | 2 | 0 |

**Figure 21: Process Chart for Form Installation Proposed**

| Process Chart 2 Observed | |
|---|---|
| **Date** | 8-Nov-13 |
| **Project** | Denver International Airport |
| **Operation** | Formwork |
| **Observer** | Bruce Hall |
| **Workers** | Black Hoody, white hard hat, orange vest |
| **Notes** | Installing guardrail |

| | | | Symbol | | | | |
|---|---|---|---|---|---|---|---|
| **Description** | **Dist (ft)** | **Time (min)** | ○ | ⇨ | ▽ | □ | D |
| Measure for guardrail connection pieces | - | 0.383 | ■ | | | | |
| Hammer in 2 connection pieces | - | 2.017 | ■ | | | | |
| Inspect and discuss | - | 0.200 | | | | ■ | |
| Hammer in another metal piece | - | 0.633 | ■ | | | | |
| Get in position to install another connector (standing on rebar) | 6 | 0.250 | | ■ | | | |
| Install connection piece | - | 0.750 | ■ | | | | |
| Return to work space | 6 | 0.250 | | ■ | | | |
| Inspect | - | 0.300 | | | | ■ | |
| Travel to get boards | 12 | 0.083 | | ■ | | | |
| Pick up boards | - | 0.167 | | | ■ | | |
| Travel back to work space | 12 | 0.083 | | ■ | | | |
| Install board 1 | - | 1.333 | ■ | | | | |
| Install board 2 | - | 1.333 | ■ | | | | |
| Travel to get 2 more boards | 60 | 0.200 | | ■ | | | |
| Get boards | - | 0.150 | | | ■ | | |
| Travel with boards | 60 | 0.200 | | ■ | | | |
| Install board 3 | - | 1.333 | ■ | | | | |
| Install Board 4 | | 1.333 | ■ | | | | |
| Total | 156 | 11.000 | 8 | 6 | 2 | 2 | 0 |

**Figure 22: Process Chart for Guardrail Installation Observed**

| Process Chart 2 Proposed | |
|---|---|
| **Date** | 8-Nov-13 |
| **Project** | Denver International Airport |
| **Operation** | Formwork |
| **Observer** | Bruce Hall |
| **Workers** | Black Hoody, white hard hat, orange vest |
| **Notes** | Installing guardrail |

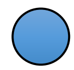
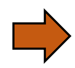
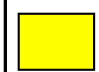
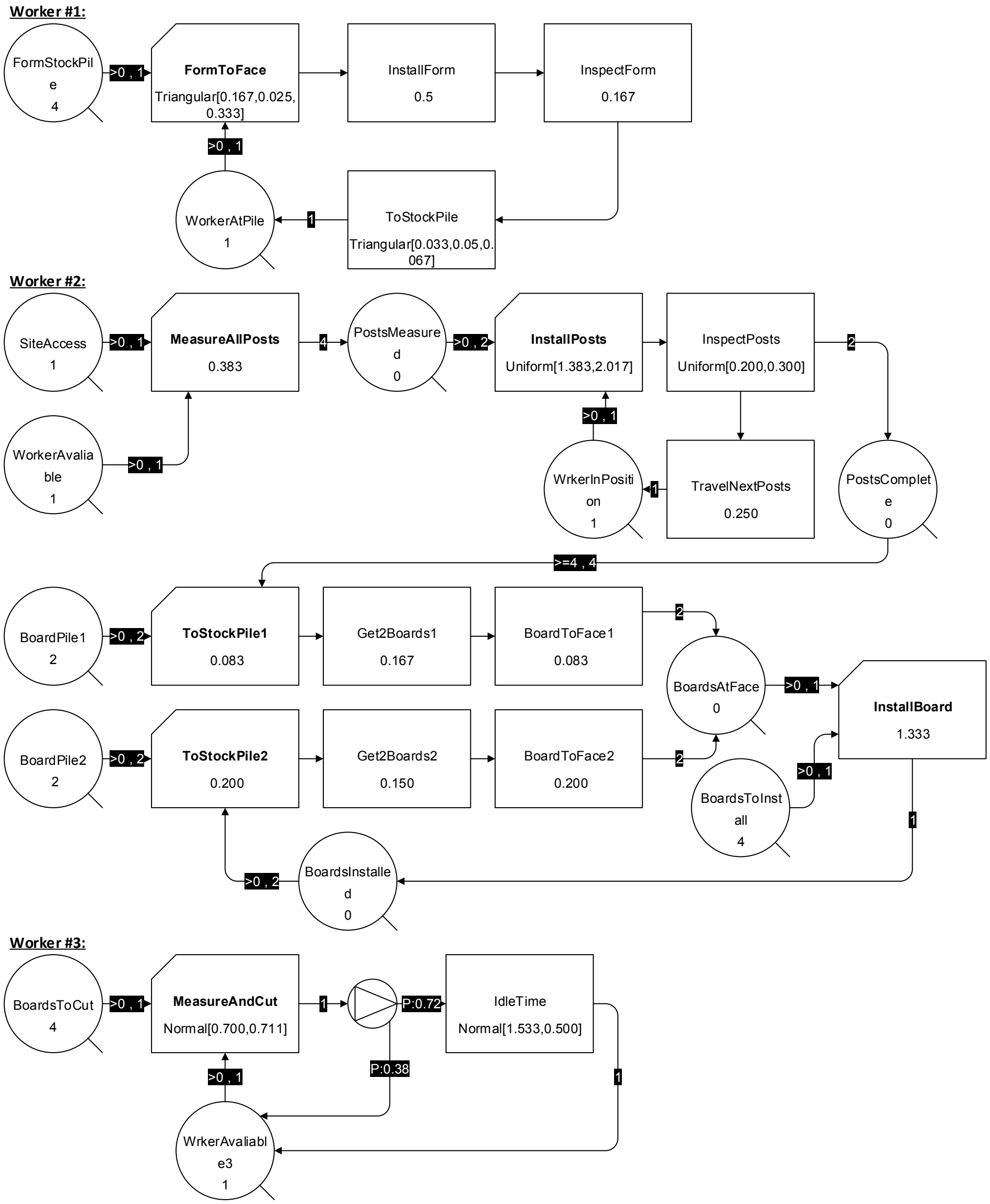
| Description | Dist. (ft) | Time (min) | Symbol | | | | |
|---|---|---|---|---|---|---|---|
| | | |  |  |  |  |  |
| Measure for guardrail connection pieces | - | 0.383 | | | | | |
| Hammer in 2 connection pieces | - | 2.017 | | | | | |
| Inspect and discuss | - | 0.200 | | | | | |
| Hammer in another metal piece | - | 0.633 | | | | | |
| Get in position to install another connector (standing on rebar) | 6 | 0.250 | | | | | |
| Install connection piece | - | 0.750 | | | | | |
| Return to work space | 6 | 0.250 | | | | | |
| Inspect | - | 0.300 | | | | | |
| Travel to get boards | 12 | 0.083 | | | | | |
| Pick up boards | - | 0.333 | | | | | |
| Travel back to work space | 12 | 0.083 | | | | | |
| Install board 1 | - | 1.333 | | | | | |
| Install board 2 | - | 1.333 | | | | | |
| Install board 3 | - | 1.333 | | | | | |
| Install Board 4 | | 1.333 | | | | | |
| Total | 36 | 10.617 | 8 | 4 | 1 | 2 | 0 |

**Figure 23: Process Chart for Guardrail Installation Proposed**

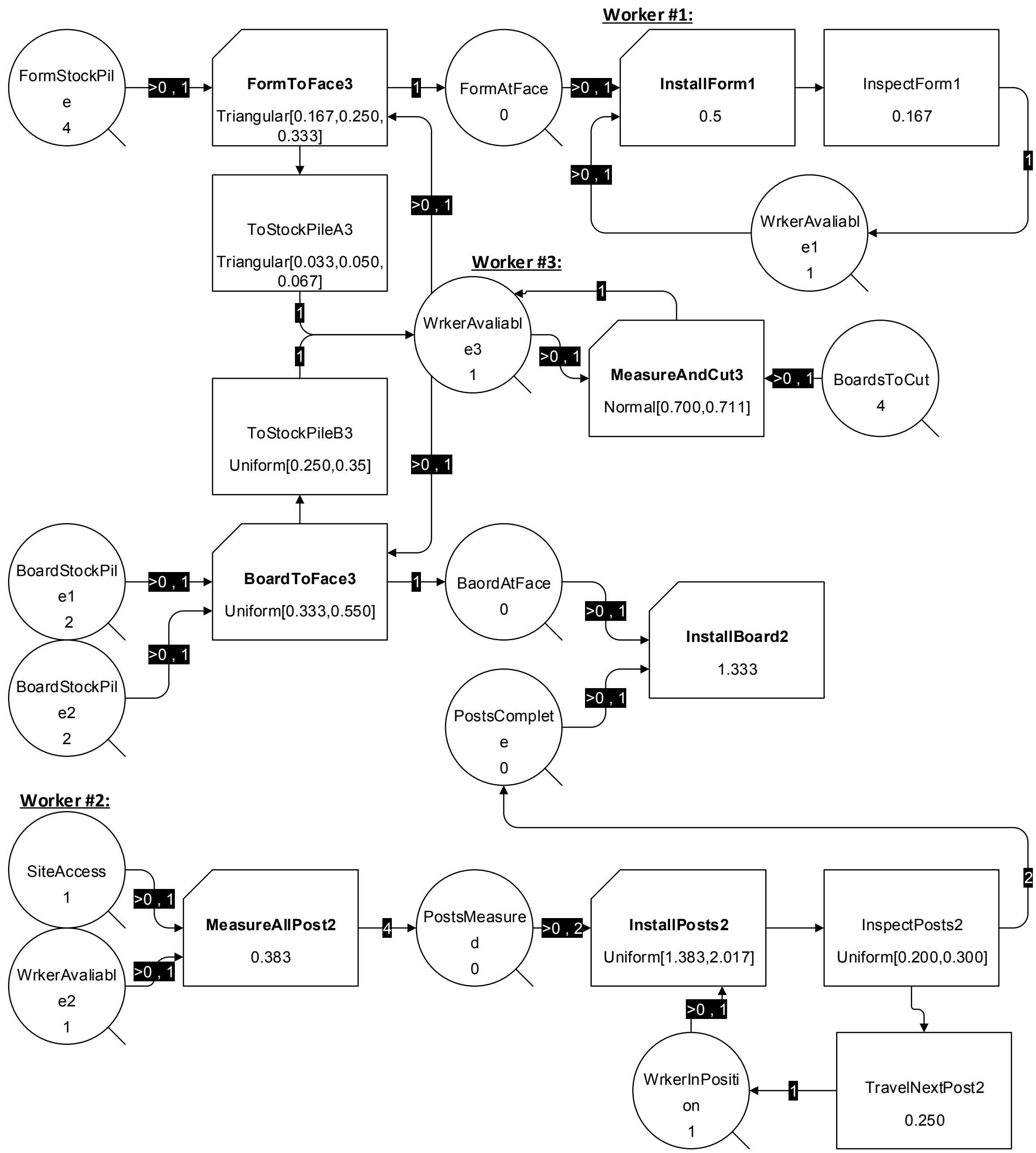
| Description | Dist. (ft) | Time (min) | Symbol | | | | |
|---|---|---|---|---|---|---|---|
| | | | ○ | ⇨ | ▽ | □ | D |
| Measure and cut | - | 0.417 | ■ | | | | |
| Idle | - | 1.717 | | | | | ■ |
| Measure and assist form worker | - | 1.917 | ■ | | | | |
| Measure and cut board | - | 0.117 | ■ | | | | |
| Idle | - | 2.033 | | | | | ■ |
| Cut plywood | - | 0.350 | ■ | | | | |
| Idle | - | 0.850 | | | | | ■ |
| Discuss, mark and cut plywood | - | 0.733 | ■ | | | | |
| Idle | - | 0.317 | | | | | ■ |
| Measure | - | 0.567 | ■ | | | | |
| Idle | - | 0.750 | | | | | ■ |
| Sharpen pencil | - | 0.300 | ■ | | | | |
| Idle | - | 0.333 | | | | | ■ |
| Measure | - | 0.233 | ■ | | | | |
| Cut board | - | 0.233 | ■ | | | | |
| Measure | - | 0.150 | ■ | | | | |
| Cut board | - | 0.083 | ■ | | | | |
| Idle | - | 1.300 | | | | | ■ |
| Move materials and cut | - | 0.733 | ■ | | | | |
| Measure | - | 0.317 | ■ | | | | |
| Idle | - | 0.150 | | | | | ■ |
| Mover materials and cut | - | 0.483 | ■ | | | | |
| Idle | - | 0.983 | | | | | ■ |
| Travel | 60 | 0.483 | | ■ | | | |
| OUT OF SCREEN | | | | | | | |
| Travel | 70 | 0.600 | | ■ | | | |
| OUT OF SCREEN | | | | | | | |
| Transport material | 15 | 0.333 | | ■ | | | |
| Idle | - | 0.433 | | | | | ■ |
| Measure, mark, and cut | - | 0.283 | ■ | | | | |
| Idle | - | 0.167 | | | | | ■ |
| Measure, mark, and cut | - | 0.550 | ■ | | | | |
| Idle | - | 1.000 | | | | | ■ |
| Cut | - | 0.133 | ■ | | | | |
| Idle | - | 0.917 | | | | | ■ |
| Measure | - | 0.233 | ■ | | | | |
| Idle | - | 0.733 | | | | | ■ |
| Travel | - | 0.400 | | ■ | | | |
| Hammer nails | - | 2.367 | ■ | | | | |
| Total | 145 | 23.700 | 19 | 4 | 0 | 0 | 14 |

**Figure 24: Process Chart for Saw Worker**




| | | |
|---|---|---|
| TimeW1 | Time for worker 1 to complete tasks (minutes) | InspectForm.LastStart+InspectForm.AveDur |
| TimeW2 | Time for worker 2 to complete tasks (minutes) | InstallBoard.LastStart+InstallBoard.AveDur |
| TimeW3 | Time for worker 3 to complete tasks (minutes) | Min[Max[MeasureAndCut.LastStart+MeasureAndCut.AveDur,IdleTime.LastStart+IdleTime.AveDur],SimTime] |
| Time | Total time to complete all task (minutes) | SimTime |
| TravelW1 | Time spent traveling by worker 1 to get materials (minutes) | FormToFace.AveDur*FormToFace.TotInst+ToStockPile.AveDur*ToStockPile.TotInst |
| TravelW2 | Time spent traveling by worker 2 to get materials (minutes) | ToStockPile1.AveDur+Get2Boards1.AveDur+BoardToFace1.AveDur+ToStockPile2.AveDur+Get2Boards2.AveDur+BoardToFace2.AveDur |
| Travel | Total time spent traveling to get materials (minutes) | TravelW1+TravelW2 |
| TravelW1Pct | Time spent traveling by worker 1 to get materials (%) | TravelW1/TimeW1*100 |
| TravelW2Pct | Time spent traveling by worker 2 to get materials (%) | TravelW2/TimeW2*100 |
| TravelPct | Total time spent traveling to get materials (%). | Travel/(TimeW1+TimeW2+TimeW3)*100 |
| IdleW3 | Time worker 3 is idle (minutes) | IdleTime.TotInst*IdleTime.AveDur |
| IdleW3Pct | Time worker 3 is idle (%) | IdleW3/TimeW3*100 |
| Costs | Labor cost to complete all tasks ($) | 51.40*(TimeW1+TimeW2+TimeW3)/60 |

**Figure 25: Discrete Event Simulation Observed**




| | | |
|---|---|---|
| TimeW1 | Time for worker 1 to complete tasks (minutes) | InspectForm1.LastStart+InspectForm1.AveDur |
| TimeW2 | Time for worker 2 to complete tasks (minutes) | InstallBoard2.LastStart+InstallBoard2.AveDur |
| TimeW3 | Time for worker 3 to complete tasks (minutes) | Min[MeasureAndCut3.LastStart+MeasureAndCut3.AveDur,SimTime] |
| Time | Total time to complete all tasks (minutes) | SimTime |
| TravelW3 | Time spent traveling by worker 3 to get materials (minutes) | FormToFace3.TotInst*FormToFace3.AveDur+ToStockPileA3.TotInst*ToStockPileA3.AveDur+ToStockPileB3.TotInst*ToStockPileB3.AveDur+BoardToFace3.TotInst*BoardToFace3.AveDur |
| Travel | Total time spent traveling to get materials (minutes) | TravelW3 |
| TravelW3Pct | Time spent by worker 3 traveling to get materials (%) | TravelW3/TimeW3*100 |
| TravelPct | Total time spent traveling to get materials (%) | Travel/(TimeW1+TimeW2+TimeW3)*100 |
| Costs | Labor costs to complete all tasks ($) | 51.40*(TimeW1+TimeW2+TimeW3)/60 |

**Figure 26: Discrete Event Simulation Proposed**