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Predictive Model for Siding Practice in Panelized Construction

Beda BARKOKEBAS[1*], Chelsea RITTER[2*], Xinming LI[3] and Mohamed AL-HUSSEIN[4]

[1,2] *PhD Student, Department of Civil and Environmental Engineering, University of Alberta*
[3] *Post-Doctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta*
[4] *Professor, Department of Civil and Environmental Engineering, University of Alberta*
[*]*Corresponding authors' e-mail: barkokebas@ualberta.ca, critter1@ualberta.ca*

ABSTRACT

Offsite construction offers an opportunity to standardize processes and better predict schedule requirements when compared with onsite construction. This predictability allows for balanced labor distribution and accurate time estimation. This research investigates the exterior wall siding practice at a panelized home manufacturing facility in order to predict future productivity of this operation based on a time study and known panel design characteristics such as wall length, wall height, and number and size of openings in the wall. The siding workstation is currently a bottleneck in the wall production line. In this area vinyl siding, window and door trim, and other exterior finishes are added to the panels. The case study plant uses a radio frequency identification (RFID) system to track panel locations and the amount of time spent at each station. This system tracks the time the panels spend in the siding area, but not the amount of time that is necessary to complete the work required. This discrepancy results in difficulties identifying the idle time and the working time within the total duration. By applying data science procedures of classification and association applied to lean manufacturing concepts, such as value-added activities and waste minimization, the research in this paper establishes a model to predict the labor requirement for each panel at early design stages. Using the developed model, the case study factory is able to quantify the idle versus working time that panels are subject to at the exterior wall siding workstation, as well as the ratio of value-added activities to non-value-added activities.

KEYWORDS

Lean manufacturing; Productivity; Panelized construction; Process improvement; Predictive scheduling.

INTRODUCTION

Offsite construction is becoming an increasingly efficient, cost-effective, and flexible approach compared to conventional construction (Rahimian et al., 2017; Zhang, 2017; Moghadam, 2014). In fact, the Australian government has identified offsite construction as a key practice to establish a sustainable construction process (Hampson and Brandon, 2004). Benefits of the offsite construction industry are due to the fact that products are manufactured in a controlled environment. These benefits are especially apparent in productivity, quality, efficiency, and safety (Zhai et al., 2014; ATCO Structures & Logistics, 2018; The Modular Building Institute, 2010). Eastman and Sacks (2008) point out that the growth of productivity for offsite construction is greater than that of onsite construction. Furthermore, monitoring offsite construction manufacturing plants is more manageable than onsite construction sites due to the controlled working environment and reduced necessary motions of workers. Several researchers conduct in-plant time studies to monitor the plant and estimate the productivity due to these advantages in order to further improve the construction processes in offsite construction plants (Ritter et al., 2016; Li et al., 2015).

To keep track of the workflow of the production lines and analyze the productivity, data collection for each workstation in terms of workstation layout, resource allocation, work schedule, and task duration is essential. Some existing manufacturing plants are equipped with radio frequency identification (RFID) systems, which provide the time data for the length of time a product remains at a certain workstation and facilitates the production analysis (Altaf et al., 2015). RFID is very useful for production tracking; however, limitations exist since the RFID cannot differentiate idle time and work time within the workstation. Additional data gaps occur when the work tasks have to be broken down into value-added and non-value-added activities for waste identification. In this case, additional time study is required to capture detailed time data for each activity.

To better manage the workflow of a panelized manufacturing production line, an accurate estimation of the overall activity duration is crucial. Accurate prediction of job task durations at each workstation can assist with resource allocation, wait time reduction, and productivity improvement. The manufacturing duration varies based on the design details, including the size, layout, material, and complexity of the product being produced. Limited research relates the work completion duration with the design complexity of the product. Thus, the research presented in this paper (1) analyzes the time taken to install vinyl siding and window trim on the wall panel manufacturing production line as an example, (2) proposes a methodology for analyzing this detailed time data, and (3) focuses on proactively predicting the task duration based on the design of the wall panel. The siding workstation in the case study includes the task of placing various sizes of siding, j-trim, smart trim, and flashing onto the wall panel. A time study is conducted to collect the time data for placing each piece onto the wall panel before further data processing. The proposed methodology integrates the process of curve fitting, statistical analysis using the coefficient of variation (CV), which measures the variability of the mean in a data set, to establish a predictive model for siding task duration estimation.

The objective of the current research is to develop a methodology to proactively predict the duration of siding operations by applying statistical analysis to data collected from previously manufactured panels. It can also be extended to estimate a customized panel. The ability to accurately estimate task durations will aid in the process improvement of the production line in addition to providing reliable input to adjust the production scheduling and aid in the management of the entire production line. Estimating the value-added time required for siding to be installed on a panel also allows for the non-value-added time in the station to be calculated based on the RFID data, indicating the actual time a panel remains at a certain workstation.

CASE STUDY

The case study occurs in an offsite housing manufacturing plant located in Edmonton, Alberta, Canada. The particular focus of this study is the application of vinyl siding to exterior wall panels. Data from 22 different panels manufactured in this facility was collected between May 26 and June 6, 2017. These 22 panels are selected from 6 different single-family projects, and are built using engineered wood with external PVC profiles (j-trim) around every opening, wood trim (smart trim) around openings on front entrance panels, and external vinyl siding. The time study is performed according to the materials and tasks required to install each piece of material or opening, which are broken down and presented in Table 1. For the scope of this paper only the trims (j-trim and smart trim) and siding are evaluated, leaving other materials such as flashing and building paper installation to be addressed in future research. The evaluated materials are responsible for approximately 70% of the time a panel spends at the siding station. Due to the relatively small amount of data collected in the time study, 25% is the assumed threshold for the coefficient of variation (CV) as per expert opinion.

Table 1. Number of observations and units of measurement (UOM) applied in time study.

Material	Task	# Observations	UOM
Smart trim	Attach	32	Per piece
	Measure/Mark	12	Per opening
	Cut	11	Per piece
	Silicon	8	Per opening
	Paint	10	Per opening
J-trim	Attach	82	Per piece
	Measure/Mark	16	Per opening
	Cut	54	Per piece
	Glue	10	Per opening
Siding	Attach	266	Per piece
	Measure/Mark	63	Per opening
	Cut	48	Per opening
	Retrieve	4	Per opening
	Glue	14	Per opening

After the time study is performed, quantity takeoffs are done based on the shop drawings of each panel evaluated in the previous stage. Table 2 demonstrates the initial takeoffs performed on a sample panel, while Figure 1 depicts the shop drawings used as the basis for the takeoff.

Table 2. Sample quantity takeoff for panel 204 10LAC-16-0015.

Panel	Front wall?	Length (mm)	Gross Area (m^2)	Net Area (m^2)	Windows	Doors
204 10LAC-16-0015	No	4,267	10.53	7.29	1	0

In addition to the information in Table 2, an additional three takeoffs are performed based on the specific features of each panel, which are outlined in the equations below. The takeoffs performed at this stage are selected based on expert experience in an attempt to determine a relationship between the physical features of the panels and the time registered during the time study.

$$J - trim = 4 \times Window + 3 \times Door \quad (1)$$

$$Smart\ trim = front \times (4 \times Window + 3 \times Door) \quad (2)$$

Where:

J-trim = number of j-trim pieces in featured panel
Window = number of windows in featured panel
Door = number of doors in featured panel
Smart trim = number of smart trim pieces in featured panel
Front = 1 if featured panel faces street (front panel), otherwise 0
Siding = number of siding pieces in featured panel

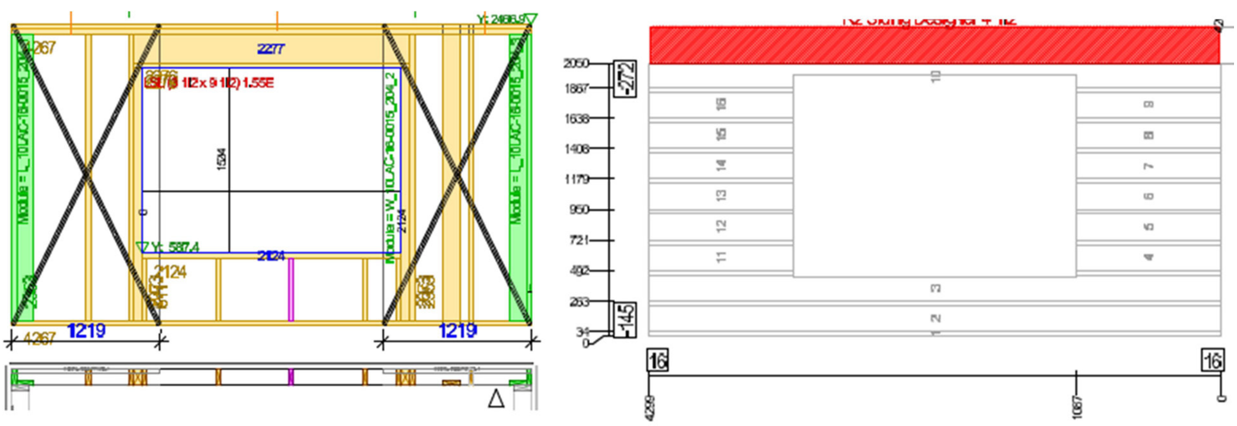

Figure 1. Sample shop drawing from panel 204 10LAC-16-0015.

METHODS

As mentioned previously, the research presented in this paper aims to develop equations that forecast the time necessary for siding operations at a panelized manufacturing facility. Figure 2 demonstrates the methods applied during this research. As previously mentioned, quantity takeoffs extracted from shop drawings are compared with their corresponding information collected during the time study in order to determine a plausible relationship that indicates the time spent to perform siding operations.

To verify the reliability of the analysis, some data cleaning is required to remove outliers identified by the time study. After selecting the material and task, the mean time (μ) per UOM is calculated for each panel and used as an input to calculate the initial mean, standard deviation, and coefficient of variation (μ_i, σ_i, and CV_i, respectively) of each set (e.g., the attachment of j-trim in the evaluated panels). In cases where CV_i is below 25%, an association analysis is performed in order to discover a stronger relationship in the data set through the categorization of an element such as opening sizes (e.g., small and large windows).

This process is based on initial assumptions and involves a significant amount of data investigation. In the case of a plausible assumption, new mean, standard deviation, and CV (μ_n, σ_n and CV_n, respectively) are calculated, and, if CV_n is less than CV_i, the assumption is validated and the equation for the task is expressed based on the new set. In cases where CV_i is greater than CV_n, the equation is expressed using the initial data set.

In cases where CV_i is above 25%, curve fitting is employed to investigate the time spent per piece or opening and, in cases where the fit is considered acceptable, the equation for the task is expressed based on the assigned distribution found in the curve fitting process. In cases where the fitting is considered unacceptable, the data is manipulated (e.g., identification and removal of newfound outliers, combination of tasks due to few data points, etc.) and tested again through the entire process. For the present research, Easyfit software is used to discover and test the fits. Easyfit software is selected because it is readily available and allows for efficient analysis.

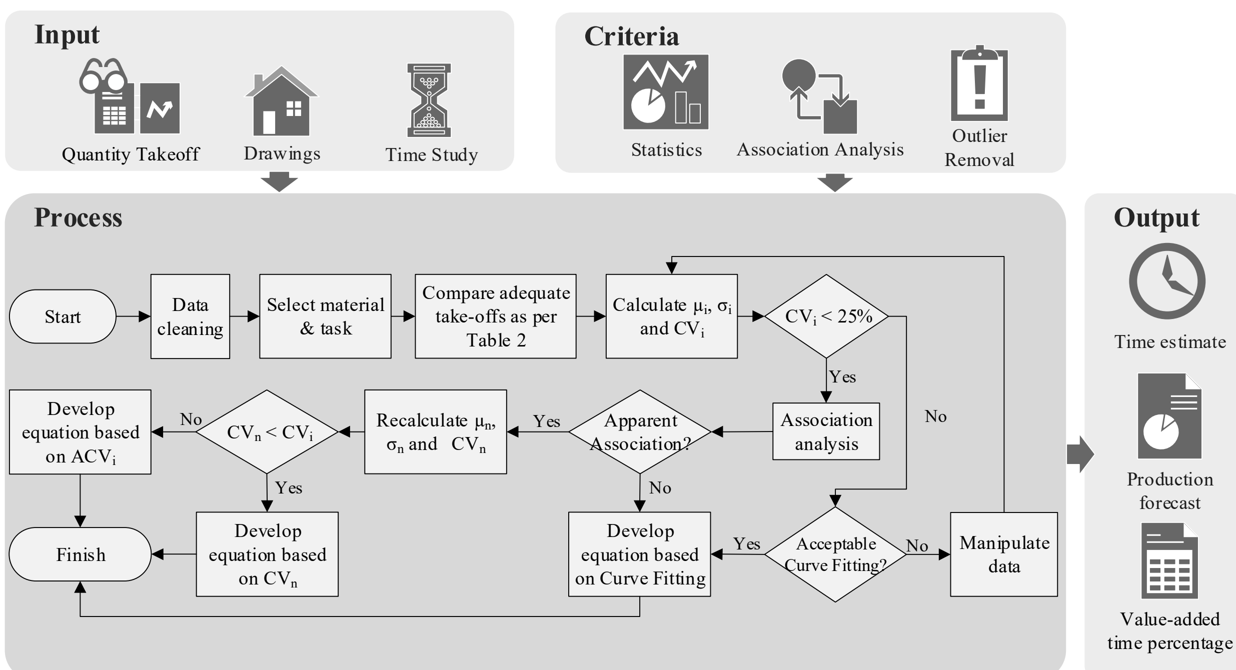

Figure 2. Applied methods.

RESULTS AND DISCUSSION

As previously mentioned, the measurements performed during the time study were done per piece or opening (as per Table 1). The results found during this research are presented in Table *3* and Table *4* below. Table *3* depicts the mean duration per assembly (e.g. window) and category (e.g. small and large). These mean durations were found using CV as validation of the relationships discovered between the time study data and panel features during the analysis process. For the evaluation of wall panel openings (i.e., windows and doors), the relationship determined is limited to only window type openings due the limited number of door components in the observed panels.

As demonstrated in Table *3*, this research managed to find acceptable mean durations for the "Attach" and "Cut" tasks for the different materials. This is expected, since these task's observations comprise a significant number of the total measurements presented in Table 1. Moreover, the acceptable CV found when window components are categorized as small or large in size (windows smaller than two feet wide are classified as small windows), demonstrates acceptable statistical reliability in the processed data. For smart trim and j-trim materials, this research found reliable statistical results by summarizing the remaining tasks (i.e., all tasks but "Attach" and "Cut") and their durations.

Table 3. Mean values found for smart and j-trim materials.

Material	Task	µ	Category	CV
Smart trim	Attach	1.44 / 2.40	Small / Large windows	20.87 / 18.62%
	Cut	3.2 / 2.72	Small / Large windows	14.46%
	Remaining	4.76	Window	21.89%
J-trim	Attach	6.84 / 6.56	Small / Large windows	20.87 / 18.62%
	Cut	2.08 / 2.92	Small / Large windows	7 / 5.43%
	Remaining	3.2	Window	22.33%

Table *4* demonstrates the distributions found through the curve fitting process for siding piece installation. The research could not identify any panel feature with a strong relationship to siding duration data gathered during the time study stage (i.e., CV >25%). The goodness of fit for these distributions is taken using Kolmogorov-Smirnov, Anderson-Darling and Chi-Squared algorithms using EasyFit software.

Table 4. Distributions found for siding material installation actions.

Attach	Cut	Remaining
$Pearson5(\alpha,\beta,\gamma)$ $= Pearson5(1.84, 0.61, 0)$	$LogPearson3(\alpha,\beta,\gamma)$ $= LogPearson3(171.03, 0.05, -8.91)$	$Burr(k,\alpha,\beta,\gamma)$ $= Burr(0.82,1.80,0.54,0)$

The proposed formulas to predict the duration of siding operations, derived from the results above, are presented in Equation 3 to Equation 6. The formulas are developed so takeoffs can be easily performed from drawings and a time estimate can be obtained quickly for siding operations at the manufacturing facility..

$$Total\ time = ST + JT + DT \tag{3}$$

$$\begin{aligned} ST &= sAttach + sCut + sRemaining = (1.44 \times sWindow + 2.40 \times lWindow) \\ &\quad + (3.2 \times sWindow + 2.72 \times lWindow) + 4.76 \times Window \end{aligned} \tag{4}$$

$$\begin{aligned} JT &= jAttach + jCut + jRemaining = (6.84 \times sWindow + 6.56 \times lWindow) \\ &\quad + (2.08 \times sWindow + 2.92 \times lWindow) + 3.20 \times Window \end{aligned} \tag{5}$$

$$\begin{aligned} DT &= Siding \times (Pearson5(1.84, 0.61, 0) + LogPearson3(171.03, 0.05, -8.91) \\ &\quad + Burr(0.82,1.80,0.54,0)) \end{aligned} \tag{6}$$

Where:

Total time = total duration of siding operation in featured panel (labor minutes)
ST = total duration for the installation of smart trims in featured panel (labor minutes)
JT = total duration for the installation of j-trims in featured panel (labor minutes)
DT = total duration for the installation of siding pieces in featured panel (labor minutes)

sAttach = total duration for the attachment of smart trim in featured panel (labor minutes)
sCut = total duration for the cut of smart trim in featured panel (labor minutes)
sRemaining = total duration for remaining tasks required to install smart trim in featured panel (labor minutes)
jAttach = total duration for the attachment of j-trim in featured panel (labor minutes)
jCut = total duration for the cut of j-trim in featured panel (labor minutes)
jRemaining = total duration for remaining task to install j-trim in featured panel (labor minutes)
sWindow = quantity of small windows (<2 ft length) in featured panel
lWindow = quantity of large windows (>2 ft length) in featured panel
Window = total quantity of windows in featured panel
Siding = quantity of siding pieces in featured panel

Despite the acceptable statistical results, more data is needed for the development of improved estimates and further identification of relationships between each panel's features and the time required to perform the siding operations. There is also a need to validate the results with the manufacturing facility

Finally, future work is recommended to utilize building information modelling (BIM) to automate the quantity takeoffs, allowing for efficient time estimation and additional information for better decision-making during the design process. Moreover, the percentage of value-added time in the siding area, which can be calculated when the results are combined with the RFID data collected at the facility, can be monitored. The following equation can be used to find the value-added time percentage.

$$VA\% = \frac{Total\ time}{RFID\ duration} \quad (7)$$

Where:
VA% = percentage of time spent adding value to the panel out of the total time spent in the station
Total time = total duration of siding operation in featured panel (labor minutes)
RFID duration = total time the panel is in the siding station, based off of RFID data

CONCLUSION

This research presents a detailed solution for improving production forecast based on job time estimates and the its respective panel's features through the application of data and statistical analysis concepts. Detailed time study data is used to determine relationships between the wall panel characteristics and task duration for siding installation activities. Mean task durations are used where the coefficient of variation is less than a specified benchmark. If a reasonable coefficient of variation for the mean task duration cannot be reached through the removal of outliers, the duration, curve fitting is done. With the collected data, the total time required to complete the siding operations is calculated.

The determination of total time based on wall panel characteristics enables benchmarking of production time, as well as a way to approximate the percentage of value-added time per panel in the siding area when combined with RFID data from the facility. These time approximations are useful for the company to forecast production and to identify possible areas for process improvement.

Future time study should be done in the same area to verify the time estimates produced through this study (data validation) and to collect additional data to enable an even further understanding of how panel characteristics and siding installation time are related.

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