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PRODUCTIVITY IMPROVEMENT FOR POSITIONING INDUSTRIAL MODULES USING GPS TECHNOLOGY AND SCHEDULING DATA

Amin AminiKhafri[1,5], Hosein Taghaddos[2], Ulrich Hermann,[3] and Simaan AbouRizk[4]
[1,4] University of Alberta, Canada
[2] University of Tehran, Iran
[3] PCL Industrial Management Inc., Canada
[5] amin.amini@ualberta.ca

Abstract: Heavy industrial construction is primarily involved with construction of petrochemical or oil-and-gas related facilities. Due to cost and schedule savings, many industrial construction projects in Alberta, Canada are delivered using a modular construction approach. Modules are traditionally positioned using measuring tape, and coordinates are determined using construction site drawings. The practice of locating and positioning modules, however, is time consuming. Industrial construction projects are carried out in open fields, which is conducive to the use of GPS-based surveying equipment. Locating and positioning modules using a GPS-based approach, particularly one that incorporates automation, could result in considerable improvements to activity-level productivity. In this research study, an automation system, comprised of a GPS handheld device and an automated tool that calculates a module's coordinates from available scheduling data and yard layout, is proposed. This system allows module positions to be automatically determined and precisely located. Implementation of the proposed automation system was estimated to improve productivity by over 500% and to reduce activity duration by two-thirds.

1 INTRODUCTION

Heavy industrial construction refers to non-residential construction and is primarily concerned with construction of oil-and-gas or petrochemical facilities. Heavy industrial construction is complex, requiring the precise assembly of a large variety of components, including pipes and mechanical equipment. Modular construction methods are often more productive than traditional stick-built approaches (Eastman and Sacks 2008). Accordingly, industrial facilities are commonly built using a prefabrication or modular construction approach. During modular construction, industrial facilities are built using smaller components known as modules. Industrial modules are constructed and assembled in open fields known as module assembly yards or module yards. To maximize the use of limited module yard space, modules are built in predefined rows or bays. Each bay has a different width, length, and orientation and can occupy up to five modules depending on bay and module size. In turn, each module may be comprised of up to 14 columns depending on module design and size. As modules are temporarily built in yards and shipped to construction sites for final installation, module construction takes place on temporary steel or lumber foundations known as "blocks." A completed module that is positioned on blocks (indicated by circle) is pictured in Figure 1. The activity of positioning and placing blocks on the ground in a module assembly yard is referred to as "blocking." To ensure blocks are correctly positioned, the location of each block must be determined by a surveying crew.

Figure 1: A module sitting on blocks ready to be shipped for site installation (reprinted with permission from PCL Construction Inc., 2016)

To locate block positions, project coordinators and field engineers manually draw the module's envelope (i.e., a rectangular box representing the perimeter of the module)—based on the module yard schedule (e.g., start date, bay, and location in the bay) and module dimensions (e.g., overhangs, number of bays of the module, and width)—in the AutoCAD drawing of the module yard. The AutoCAD coordinates are then transformed into Cartesian coordinates, which are used for blocking. The survey crew, which consists of three technicians and one foreman, locate a column's position in the module yard and perform the necessary blocking activities using measuring tape. This occurs in two steps: the module envelope is first laid using nails/color flagging or spray paint; on a subsequent day, blocks are positioned according to column location.

The current practice for blocking is time-consuming. Data needed to calculate coordinates are distributed throughout various databases, which may not be updated with current project information. Furthermore, locating columns is tedious and exposes workers to increased accident risk, particularly on congested module assembly yards. In a typical industrial construction project, the survey crew may position up to 2000 blocks. Given the large volume of items requiring blocking, improvements to the current methodology could have a considerable impact on overall project productivity.

Here, the conventional blocking method was improved by implementing global positioning system (GPS) technology to perform blocking activities in a more cost- and time-effective manner. GPS surveying equipment is comprised of two main components: a GPS antenna and a GPS handheld device. First, the GPS antenna is paired with the handheld GPS device and is calibrated to allow the device to precisely locate coordinates based on the antenna's location. Note that measurements obtained using a GPS device with predefined antenna coordinates are accurate within one centimeter (Ogaja 2011), which is sufficient for module blocking. In addition to GPS-based surveying, an automated system is developed to calculate the column's coordinates using data available in the company's database (i.e., module yard layout, construction schedule, and module dimensions). Block placement coordinates are uploaded to handheld GPS devices and blocks are subsequently laid in the module yard. This method is expected to improve productivity by lowering time-associated labor costs and decreasing blocking errors.

In the following sections, a literature review is provided to summarize previous applications of GPS in construction and research related to modular industrial construction. Then, an automated system that uses GPS technology and available scheduling data to calculate block coordinates for blocking activities is proposed. Finally, potential improvements of the proposed system to blocking-activity productivity are assessed.

2 LITERATURE REVIEW

Previous research findings relevant to the research presented here are grouped into the two main categories of (1) application of GPS in construction and (2) research related to modular industrial construction, as follows:

2.1 Application of GPS in construction

The ability of GPS technology to improve productivity has been appreciated for several decades. Accordingly, there are numerous examples of GPS applications throughout construction research literature and within the construction industry. Previous studies examining the use of GPS technology in construction can be grouped into two main categories, namely its application in surveying and its use as a real-time monitoring tool. Since the primary objective of this study is to investigate improvements resulting from the application of GPS technology, only findings related to GPS application in the context of productivity will be discussed. Garu et al. (2009) investigated the impact of tracking construction materials using GPS technology on labor productivity. Lu et al. (2007) combined a car navigation system with GPS signals to improve the accuracy of tracking concrete mixer trucks in dense urban areas. Ergen et al. (2007) integrated radio frequency identification (RFID) with GPS to automatically locate and identify precast concrete elements in laydown areas. Li et al. (2005) developed a GPS-and-GIS-integrated system to provide real-time data for material and equipment tracking. Real-time data improve productivity by reducing waste in construction sites. Using simulation as a robust experimental tool, Han et al. (2006) investigated the effects of implementing GPS technology in earthmoving operations on productivity using simulation. In this earthmoving case, the authors explored how both enhanced accuracy and direct time-savings could result in improved productivity. While previous studies have demonstrated that GPS technology can be combined with other systems (i.e., RFID, simulation, GIS) to improve construction productivity, direct improvements resulting from the implementation of GPS-based surveying techniques to activity-level productivity in industrial construction have yet to be explored.

2.2 Modular industrial construction

Many researchers have attempted to improve upon the practice of modular construction using a variety of approaches. Murtaza et al. (1993) created a decision-making tool for practitioners to investigate the impact of implementing modular construction methods on industrial construction project costs. Mohamed et al. (2007) developed a discrete event simulation model to schedule resource-constrained module assembly processes. Taghaddos et al. (2009) tackled the scheduling complexity issue of a module assembly yard using the high level architecture technique. In addition, Taghaddos et al. (2014) attempted to schedule a module assembly yard using a simulation-based auction protocol to optimize module yard layout. Improving scheduling and layout planning during industrial modular construction was primarily focused on improving productivity at a project level. Notably, efforts to enhance productivity by improving performance at an activity level have yet to be described. Controlled working environment and repetitive activities associated with modular construction provide an opportunity to implement automated systems. Developed automated systems can be used in multiple projects regardless of the future projects' characteristics. While these automated systems have the potential to improve construction project performance (Zhai et al. 2009), studies examining effect of automated systems on industrial construction project productivity have yet to be conducted.

3 PROBLEM STATEMENT

Despite the use of modern surveying technologies, such as GPS-based surveying equipment, conventional surveying methods (e.g., use of total station and measuring tape) remain commonly used within the construction industry. Industrial construction is conducive to the application of GPS surveying technology, which in turn, is conducive to automation. With respect to modular construction, column coordinates can be automatically calculated from available data, such as module yard schedule, module dimensions, and module yard coordinates, that are stored within existing company databases. The impact of implementing GPS-based surveying techniques in combination with automated systems in industrial construction, however, has yet to be studied. Here, direct improvements to activity-level productivity, which result from the implementation of GPS-based surveying equipment in combination with an automated system capable of calculating coordinates based on stored module data, was investigated.

4 METHODOLOGY

In the present study, an automated, GPS-based surveying approach designed to locate module's block positions using coordinates calculated from data within company databases was developed. For an automated system to calculate a column's coordinates, data describing module yard layout, module yard schedule, and module dimensions must be available and retrievable from a company's database. While the required data exists in the database of the studied company, required pieces (e.g., module yard schedule and bay dimensions) are stored in three separate sources, as shown in Figure 2. Consequently, raw data must be combined and/or processed to obtain the information required for GPS- based surveying.

As discussed in Section 1, modules are built in bays, and each module is comprised of several columns. To locate a column, module dimensions (e.g., length, width, etc.), location of the module inside the bay, and bay dimensions (e.g., length, width, etc.) must be known. Calculations are implemented in the sequential manner outlined in the coordinate calculation section of Figure 2. First, the southwest corner of a bay, which is considered the bay's datum point, is calculated based on the bay's dimensions, angle (Figure 4), and centroid coordinates. As denoted in the bay dimensions table, "tblBays" in Figure 3, bay information exists in the module yard's database, which is controlled by module yard managers. Bay southwest corner definition also varies based on the angle of the bay, as shown in Figure 4. In turn, column (block) coordinates are calculated with respect to the bay's datum point. Datum point of modules is also assumed to be the southwest corner of each module (e.g., column 1 in Figure 4). Consequently, column coordinates are calculated based on a module dimensions (e.g., module width and module overhang) and its location within the bay, which is measured with respect to the bay's southwest corner. A module's dimensions are extracted from drawings, are stored in the module dimension database, and are also populated into the module yard scheduling database, "tblMain" in Figure 3. The calculated coordinates of each module block are uploaded to a GPS handheld device to locate a block's position in the module yard. The GPS handheld device is then paired with an antenna and is used to locate blocks coordinates in the module yard.

As described above, to calculate a column's coordinates, practitioners must retrieve information from two to three databases, which is a time-consuming and error-prone task. Hand calculated coordinates are then provided to the surveying crew, who locate block positions. The proposed method is expected to improve productivity of the blocking activity by automating coordinate calculation and incorporating the use of GPS technology. To demonstrate detailed implementation of the proposed approach, an example case study and detailed explanations of the implemented process are presented in the following section.

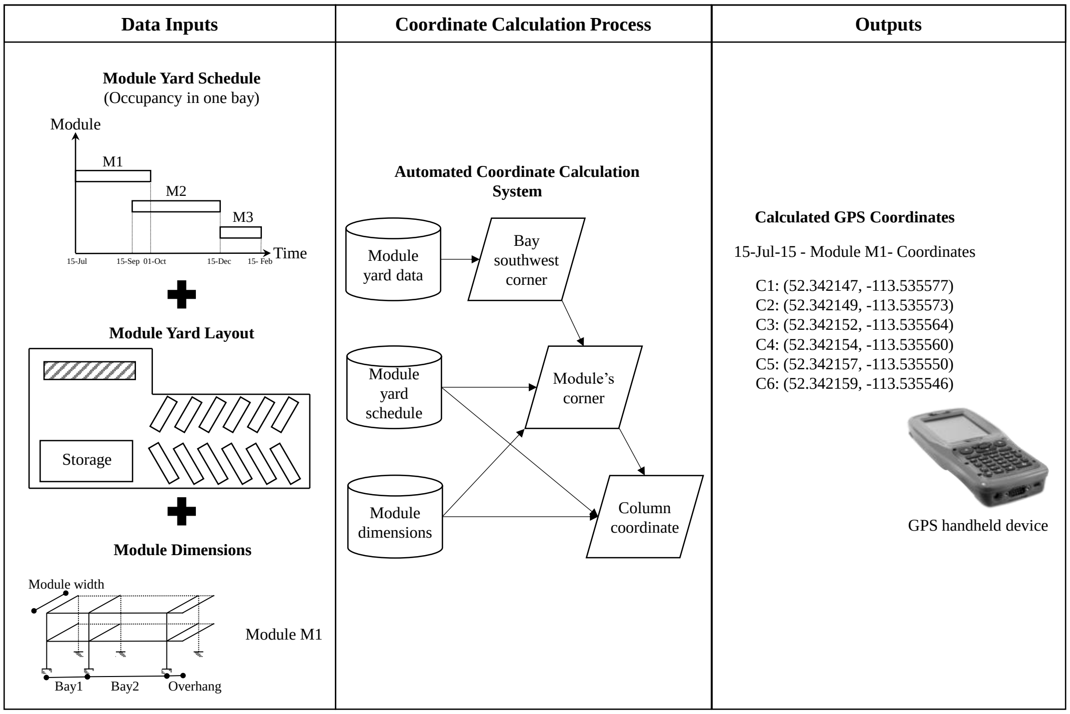

Figure 2: Flow chart of the proposed methodology

5 CASE STUDY

In this section, a detailed explanation of the implemented system and example calculations are presented. Currently, at the studied company, module dimensions with construction site schedules are used to sequence, as well as allocate bay resources for, module fabrication and assembly.

Figure 3 illustrates the overall database structure of the automated system. The module yard schedule contains information regarding construction start and finish dates, as well as module location within the construction site. In the database, “tblMain” contains module yard schedule and module dimension information. “Module,” “yard,” “bay,” and “angle” refer to the module identifier, yard to be constructed, bay in the module yard, and angle of the bay, respectively. Notably, “module,” “yard,” “bay,” and “angle” are with respect to the east-west axis. The “construction begin” and “construction end” data denote the start and finish time, respectively, of module assembly and fabrication. Module location within the bay is expressed as “distance from the back of the bay.” “Module width,” “module length,” and “overhang begin” denote module dimensions. “Bay 1” to “bay 7” denote distances between module columns. “tblBays” or “module yard bays” database expresses bay information-related data. “Yard” and “bay” express the yard and bay identifier, respectively. “Length,” “width,” and “angle” represent bay length, bay width of the module dimension that is imported from design drawings, and bay angle with respect to the east-west axis. “X center” and “Y center” express the centroid coordinates of the bay.

To calculate the coordinates of module columns, module dimensions (e.g., number of bays in the module, bay size) must first be retrieved. At the case company, module dimensions are stored in the company’s database for scheduling purposes and are retrieved form this source. Then, the location of each bay must be calculated. This calculation is based on an assumed datum point in the module yard; here, the southwest corner of each bay is selected to represent the bay’s location. The definition of the southwest corner is dependent on the orientation of the bay. In Figure 4, a satellite photo, extracted from Google Maps, depicts the module yard; bays are highlighted using rectangles and southwest corners are indicated by stars.

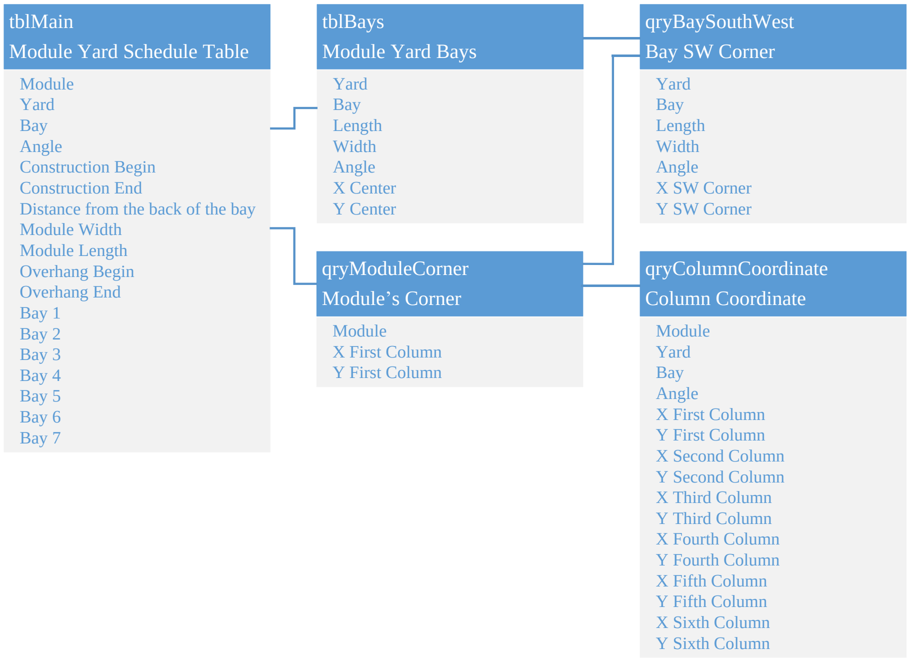

Figure 3: Database structure of the automation system.

Figure 4: Southwest corner of various bays.

Given the datum point of each bay, module location within the bay is extracted from the module yard schedule and is measured from the end of its associated bay. The first column's coordinates are calculated using the coordinates of the bay's datum point, bay's orientation, module's width, and the distance of the module measured from the end of the bay. The module's dimensions, bay's orientation, and coordinates of the other columns can then be calculated in relation to the first column. Figure 5 demonstrates the sample numbering of a module. To calculate the coordinates of the remaining columns, ΔX and ΔY must be determined. Equations [1] and [2] show the SQL calculation of ΔY and ΔX for the first bay (Bay1). ΔY and ΔX are calculated using the bay's distance [tblMain.Bay1] and the orientation of the module inside the bay [tblMain.AngleEW] in radian.

[1] ΔY.Bay1=Nz([tblMain.Bay1]*Sin([tblMain.AngleEW]*π/180))

[2] ΔX.Bay1=Nz([tblMain.Bay1]*Sin([tblMain.AngleEW]*π/180))

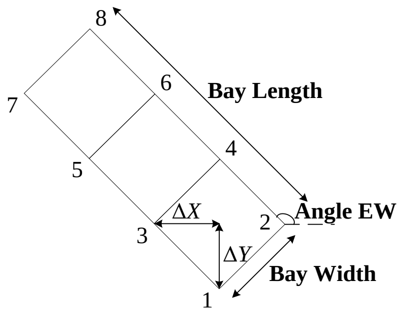

Figure 5: Definitions of ΔX and ΔY for determining the relative position of the column.

When the coordinates of all columns are calculated with respect to Column 1, final coordinates of other columns can be established by determining the coordinates of Column 1. The coordinates of Column 1 are calculated based on the bay's southwest corner, distance of the module from the end of the end of the bay, module width, and possible overhang, as shown in Equation [3] for the X coordinate. The Microsoft Access Nz function returns a zero value when the input is null; otherwise, it will return the input value.

[3] X1=[BaySWQuery]![E]+Nz([tblMain.OverhangBegin]+Nz([tblMain.Distance from the back of the bay]))* Abs(Cos([tblMain.AngleEW]*(π/180)))+([Width]-[ModuleWidth(ft)]+Nz([WidthOffset]))*Abs(Sin([tblMain.AngleEW]*(π/180)))

The calculated coordinates are based on data obtained from the AutoCAD drawing. Accordingly, coordinates must be transformed to real-world Cartesian coordinates using a linear transformation function. Transformed coordinates are uploaded to handheld GPS devices, which are used to locate module block positions within the module yard.

The generated coordinates are also plotted in AutoCAD for visual verification of the results. Table 1 summarizes the data of to-be-built modules located in bay A10. A screenshot of the calculated coordinates in bay A10 over the period of the construction, along with the calculated AutoCAD coordinates, is shown in Figure 6. Note that plotted modules may share the same space at different times during a project.

Table 1: Sample module data for bay A10.

Items	M1	M2	M3
Yard	MainYard	MainYard	MainYard
ModuleWidth (ft)	21.00	21.00	19.68
ModuleLength (ft)	66	65	52
ModuleHeight (ft)	19.68	23.62	21.98
Bay	A10	A10	A10
Distance from the back of the bay (ft)	20	21	34
AssemblyStart	1-Jun-15	15-Sep-15	5-Jan-16
Shipping	10-Sep-15	20-Dec-15	23-Mar-16
OverhangBegin (ft)	0	0	0
Bay1 (ft)	21	22	19

Bay2 (ft)	-	-	19
Bay3 (ft)	-	-	-
Bay4 (ft)	-	-	-
Bay5 (ft)	-	-	-
Bay6 (ft)	-	-	-
Bay7 (ft)	-	-	-
OverhangEnd (ft)	-	-	-
AngleEW	120	120	120

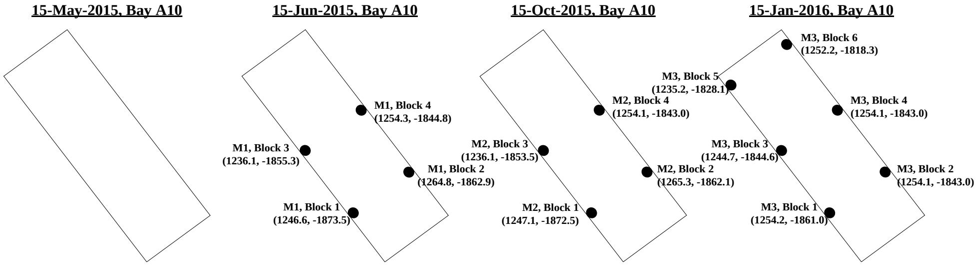

Figure 6: Demonstration of different modules in Bay A10 throughout different time spans.

6 PRODUCTIVITY IMPROVEMENT

Interviews were conducted with practitioners to assess the impact of implementing the proposed approach on blocking productivity at an activity level. The conventional method of locating module columns is performed in three steps: calculation of the module envelope, laying down the module envelope, and locating columns within the module envelope.

Table 2 details the man-hours required to locate block positions of an eight-column module using conventional surveying methods. Total man-hours required to perform blocking for an 8-column module using conventional techniques is 17, with a total duration of five hours.

Table 2: Man-hours required to locate block positions of an 8-column module using the conventional surveying method.

Blocking tasks	Crew	Time (hours)	Man-hours
Calculate module envelope	1 Engineer	1	1
Lay down module envelope	3 Workers	2	6
	1 Foreman	2	2
Locate the column	3 Workers	2	6
	1 Foreman	2	2
Total		5	17

In contrast, only two steps are required to locate the same eight blocks in the module yard using the GPS and automated coordinate technique. First, the column's coordinates are calculated using the developed system. Here, the model is only required to run and use the populated data once. Then, the calculated coordinates are uploaded to the handheld GPS device and block positions are located. Note that additional time is required to calibrate the GPS device and antenna.

Man-hours required to conduct blocking of this module was estimated from interviews with experts. Total man-hours and duration required were estimated to be 3.25 and 1.75, respectively. From these results, the proposed automation system is estimated to be 500% more productive and approximately 3 times faster than the conventional positioning method. It is important to note that improvements following the implementation of the proposed approach are expected to increase during winter. With conventional positioning methods, snow or ice may be removed twice: once to locate the module envelope and once to position blocks within the nailed envelope. In contrast, snow or ice may only be cleared once using the proposed automated system. In addition to improvements to productivity, the proposed positioning system is expected to reduce errors and improve accuracy. Furthermore, as actual, real-time data is used by the proposed positioning system, changes to schedules or module size are easily adjusted by running the automation system program again.

Table 3: Man-hours required to locate block positions of an 8-column module using the proposed automation approach.

Blocking tasks	Crew	Time (hours)	Man-hour
Upload the columns' coordinate to the handheld device	1 Surveyor	0.25	0.25
Calibrate the GPS device	2 Surveyors	0.5	1
Locate the column	2 Surveyors	1	2
Total		1.75	3.25

7 CONCLUSION

In this article, potential productivity improvements resulting from application of GPS technology coupled with scheduling data is identified in an industrial modular construction project. An automated, coordinate calculation system is also developed to improve the accuracy and speed of data collection. Based on the proposed approach, the coordinates of the module blocks are calculated using available module yard schedule, module yard layout, and module dimension data. Calculated coordinates are then uploaded to handheld GPS devices to locate module block positions within a module yard. Interviews with field experts were conducted to quantify improvements to productivity, where the combination of an automated coordinate calculation system with GPS-based surveying was estimated to improve activity-level productivity by 500% and to reduce total duration by two-thirds. In addition to improved productivity, the developed automated system allows for flexibility and expandability based on input data. Construction projects are subject to change throughout project delivery. As the proposed system is integrated with company databases, implementation of this system may relieve practitioners from constantly checking for project updates and changes. Practitioners simply refresh block coordinates with information obtained from databases updated with current construction data.

Contributions of this study are summarized as follows: (i) potential productivity improvement is identified as resulting from more effective use of existing data, (ii) calculations and procedures implemented by practitioners using available data and queries of the databases are presented; (iii) an automation system that combines GPS technology with available data for productivity improvement is introduced.

Although the proposed methodology holds considerable promise, limitations of this methodology should be noted. Output accuracy of the proposed method is dependent on accuracy and completeness of input data. The proposed system is not capable of addressing incomplete or wrongly-formatted data. To overcome this limitation, data adaptors should be devised to refine incomplete input data before analysis. Also, productivity improvement was estimated based on values obtain from a typical 8-column module. Productivity measures should be obtained from modules of varying sizes to ensure results are consistent across different module dimensions.

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