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A RAPID LIFT STUDY GENERATION SYSTEM FOR HEAVY INDUSTRIAL PROJECTS

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Abstract: The process of creating mobile crane lift studies for heavy industrial projects can be time-consuming and tedious. A large portion of the lift studies required for such projects involve modules that are prefabricated and transported to the site. Composing these lift studies currently requires a considerable amount of time and manual work. Due to the complex nature of these projects the lift studies also often require significant revisions to accommodate changes to the initial plans. This paper introduces a rapid lift study generation program to assist in the planning stage by expediting the drafting process. The program utilizes Autodesk's AutoCAD, which is one of the most widely used drafting software applications in North America. A custom plug-in to AutoCAD written in the Visual Basic programming language is used to create the graphic portion of the lift study. A separate Windows Form application is used to produce a table of the crane and lift information, such as lifting capacity, ground bearing pressure calculations, and mat design. This application is supported by a database of specifications for various crawler cranes and configurations as well as capacity information. The application allows the user to input information such as the module's weight, rigging weight, and lift radius in order to obtain a table of relevant information for each lift. This rapid lift study generation program has been tested for validation on a heavy industrial project for which the lift studies had already been prepared by NCSG Crane & Heavy Haul Services using the traditional method.

1 INTRODUCTION

In Alberta, Canada, mobile cranes are frequently used in heavy industrial projects to erect modules that are prefabricated in a controlled environment and then shipped to site. (This offsite construction process is efficient and consumes less waste in general.) In order to achieve a successful lifting process, extensive planning is needed and lift studies are required for each individual lift. Lift studies contain detailed drawings of the crane picking the modules off of the delivery trucks, as well as drawings of the crane placing each module at its final destination. These drawings need to be dimensioned to ensure that the crane and module are placed in their intended locations. Supportive engineering information and calculations are also necessary, such as: (i) the crane configuration; (ii) the length of the boom; (iii) the percent of the crane's capacity used for the lift, and (iv) the ground bearing pressure (GBP) and mat pressure. However, due to the complicated planning process, lift study requires much preparation time and is error-prone. In addition, any change to the site or project will lead to re-planning and re-design. The objective of the system described in this paper is to accelerate the process of creating these lift studies by programming the designing algorithms into computer applications. The system involves two main components, one that handles the graphics and one that handles the calculations and table of information. The graphical component is achieved using a plug-in to AutoCAD, which aids with the insertion of transport trucks, modules, rigging, mats, and cranes as well as with dimensioning. The calculations and tables are made by means of a Windows Form application called Smart Lift Planner. This two-program system improves upon the traditional methods of drafting by making it faster and more user-friendly. In previous crane-related research, automation has been the focus in engineering planning and design; this scholarship has included (i) automatic crane selection and positioning (Hanna and Lotfallah 1999; Huang et al. 2011; Safouhi et al. 2011; Wu et al. 2011; Lien et al. 2014); utilizing 3D visualization to simulate crane operations (Al-Hussein et al. 2006; Tantisevi et al. 2009; Lin et al. 2012; Hasan et al. 2013); and lift path planning with the assistance of computer technology (Chang et al. 2012; Zhang and Hammad 2012; Juang et al. 2013; Lei et al. 2013a and 2013b; Olearczyk et al. 2014). However, there are few software applications/systems in the market that can be directly used for heavy lift planning. In Alberta, most large-scale construction companies currently employ drafting personnel that create the graphical portion of lift studies using drafting software such as AutoCAD. Once the site layout has been prepared and the locations of modules, cranes, and transport trucks have been determined, the graphic portion of the lift study must be prepared. To do so the draftsperson must manually insert the transport truck into the drawing, orient it correctly, place the module in the correct position on top of the truck, manually insert the rigging on top of the module, place the crane in its predetermined location, orient the tracks in the right direction, rotate the crane body such that it is facing the module, raise or lower the boom so that the hook block is on top of the pick point, draw a lift line, insert a layout tab, generate the correct view ports, and dimension both the plan and elevation views. Then when it comes time for the set-point drawing to be created, the draftsperson is required to move the module to its set position, rotate it to the correct angle, reposition the rigging in a similar fashion, rotate the crane body, raise or lower the boom, delete the old lift line and draw a new one, delete the old dimensions, and create new dimensions. It is easy to see that this process is tedious and time-consuming. Therefore a level of automation to make the process faster and more efficient would prove to be extremely valuable.

2 AUTOMATED LIFT STUDY GENERATION

The graphical component of the system is handled by an AutoCAD (AutoDesk 2015) plug-in developed in the Visual Basic programming language (Microsoft 2015) at the University of Alberta. The primary use of this plug-in is to aid in the insertion of blocks—objects created from AutoCAD drawings that can be inserted into other drawings. The blocks used by the program have been previously created specifically for the project used to test the program. (These blocks must be saved as individual *.dwg* files in a specific location so that the program can properly insert them.) Various measurements of the block must be carried out and entered into the spreadsheets from which the program retrieves data. The plug-in is designed to be used after the user has created and inserted the site layout into AutoCAD’s model space.

2.1 Step 1: Crane Matting insertion

The user selects the insert button from a custom toolbar developed for the program. They then specify where they would like to place the mat—either on screen or by entering coordinates into the command line. Options are then given for the insertion angle. For the purpose of selecting the insertion point and angle by moving the cursor and clicking in the 3D environment, the program supports what is known as jigging. In this process, the object being inserted will follow the user’s cursor around the 3D environment and its position will become fixed when the user clicks the mouse. Jigging provides the user with a visualization of the block before its insertion point has been fixed in order to more closely represent how the block will appear in the drawing. This provides an efficient method for determining where to place blocks in relation to existing objects in the drawing. Once a mat has been inserted, if the user requires additional matting they can simply specify a location in relation to the previously placed mat (front, back, left or right). A mat will be automatically inserted in the specified direction and at the same angle as the previous mat.

2.2 Step 2: Transport Truck/Module Insertion

In this step the user first selects the insertion button from the custom toolbar. A prompt will then appear which will allow the user to directly insert a module or to first insert a transport truck into the drawing. Next the option is presented for the user to specify an insertion point either by clicking a point in the model space (jigging supported) or by entering coordinates into the command line. For inserting a module, the insertion point is at ground level directly below the southwest rigging attachment point. For inserting a transport truck the insertion point is located at ground level directly below the trailer hitch. Similar options are then given for the insertion angle. The required module is then selected from a project specific list. This list contains relevant information such as module dimensions and weight, number of cranes necessary for lifting, number of rigging attachment points, rigging height, and locations of pick points in relation to the insertion point. Finally either the user selects where the module is to be placed or it is automatically placed on a previously inserted truck trailer.

2.3 Step 3: Rigging Insertion

After the module has been inserted the user selects the "insert rigging" option, and the rigging (previously designed and saved as a block) necessary to lift the module will be automatically placed on top of it. The automatic rigging placement is performed by inserting the rigging at the same (*x*,*y*) coordinates as the module insertion point but at the elevation of the rigging attachment point, which has been measured and entered into a spreadsheet. This displacement is shown in Equation [1] as position vector $\vec{R}_{RIG}$ relative to the origin, where M_X, M_Y, and M_Z are the insertion points of the module and H_M is the height of the module. The block is then rotated about the *z*-axis to match the angle of the rigging.

[1] $$\vec{\mathbf{R}}_{\mathbf{RIG}} = \left\langle \mathbf{M}_{X}, \mathbf{M}_{Y}, \mathbf{M}_{Z} + \mathbf{H}_{\mathbf{M}} \right\rangle$$

2.4 Step 4: Crane Insertion

Now that the module and rigging are in place the user selects a crane to insert. (Cranes available in the current program are the Demag CC2800 and the Manitowoc18000; however, the program could easily be expanded to accommodate other similar cranes.) The user is then prompted to select the desired boom length from a list of crane configurations. Next, the maximum radius must be specified. The program calculates the maximum radius for which the top of the boom will be above the top of the rigging. This value is used as the default maximum radius but can be easily overridden. It is recommended that the second component of the program (Smart Lift Planner) be used when determining this value, as it references the tables supplied by the crane manufacturer in order to determine the maximum radius for a given load. The next prompt provides the user with various options for inserting the crane. These options include:

- Side1/Side: Places the crane perpendicular to the module at a user-defined radius and elevation.
- Specify: Allows the user to either click a point on the screen on which to place the crane or specify the location by entering coordinates. Similar options are given for the crane's track angle. This method supports jigging.
- Distance Direction: The user enters the location in polar coordinates (radius and angle) relative to the module's center. Options for track angle are also given.
- Previous Location: This option is available if a crane has previously been inserted and will place the crane in the same location as the previous crane.

While these options are given temporary indicators appearing in the model space that show the locations of sides 1 and 2, as well as circles that show the minimum and maximum allowable radii, these indicators automatically disappear once the crane has been inserted. For all of the options the crane body and boom are automatically configured such that the crane hook will be on the rigging pick point (hook point). The hook point is described using 3D coordinates in Equation [2] by the module's insertion point (M_X,M_Y,M_Z), the distance in the *x*-*y* plane from the module's insertion point to the hook point (MH_D), the module's insertion angle (θ_M), the angle in the *x*-*y* plane from the module's side to the hook point with the vertex being the module's insertion point (θ_{MH}), the height of the module (H_M), and the height of the rigging (H_{RIG}). Figure 1 provides a labelled plan and dimension views of the module and rigging. The equations the program uses to automate the crane orientation process are outlined below. In all cases the insertion point for a crane is located at ground level directly below the crane's pivot point (Piv_X,Piv_Y,Gnd), shown in the position vector relative to the origin in Equation [8]. This is the position at which the crane track is to be inserted. The crane body is then inserted directly over the track at the position described by the position vector in Equation [9], where $Elev_{BODY}$ is the elevation of the insertion point of the crane body relative to the ground. Next the crane body is rotated in the *x-y* plane by the angle θ_{BODY} (Equation [5]) relative to the positive *x*-axis. The boom is then inserted at the position described by the position vector in Equation [10], rotated in the *x-y* plane by the same angle as the crane body (θ_{BODY}), and finally rotated in the *z* dimension relative to the *x-y* plane by an angle of θ_{BOOM} (Equation [7]). In Equation [7] the variable, r, represents the distance from the pivot point to the hook point in the *x-y* plane (i.e., the lifting radius), L_{BOOM} is the length of the boom, and O_{BOOM} is the boom's offset from the pivot point in the *x-y* plane. With everything in position the program also automatically draws a vertical line from the crane's boom head to the hook block, representing the load line.

[2] $\mathrm{Hp} = \left(\mathrm{M_X} + \mathrm{MH_D} \bullet \cos(\theta_\mathrm{M} + \theta_\mathrm{MH}), \mathrm{M_Y} + \mathrm{MH_D} \bullet \sin(\theta_\mathrm{M} + \theta_\mathrm{MH}), \mathrm{M_Z} + \mathrm{H_M} + \mathrm{H_{RIG}}\right)$

[3] $\Delta\mathrm{X} = \mathrm{Hp_X} - \mathrm{Piv_X}$

[4] $\Delta\mathrm{Y} = \mathrm{Hp_Y} - \mathrm{Piv_Y}$

[5] $\theta_\mathrm{BODY} = \arctan(\Delta\mathrm{Y}/\Delta\mathrm{X})$ (Angle in *x-y* plane relative to positive *x*-axis)

[6] $\mathrm{r} = \sqrt{\Delta\mathrm{X}^2 + \Delta\mathrm{Y}^2}$

[7] $\theta_\mathrm{BOOM} = \arccos((\mathrm{r} - \mathrm{O_{BOOM}})/\mathrm{L_{BOOM}})$ (Angle in *z* dimension relative to *x-y* plane)

[8] $\vec{\mathrm{R}}_\mathrm{TRACK} = \left\langle \mathrm{Piv_X}, \mathrm{Piv_Y}, \mathrm{Gnd} \right\rangle$

[9] $\vec{\mathrm{R}}_\mathrm{BODY} = \left\langle \mathrm{Piv_X}, \mathrm{Piv_Y}, \mathrm{Gnd} + \mathrm{Elev_{BODY}} \right\rangle$

[10] $\vec{\mathrm{R}}_\mathrm{BOOM} = \left\langle \mathrm{Piv_X} + \mathrm{O_{BOOM}} \bullet \cos(\theta_\mathrm{BODY}), \mathrm{Piv_Y} + \mathrm{O_{BOOM}} \bullet \sin(\theta_\mathrm{BODY}), \mathrm{Gnd} + \mathrm{Elev_{BOOM}} \right\rangle$

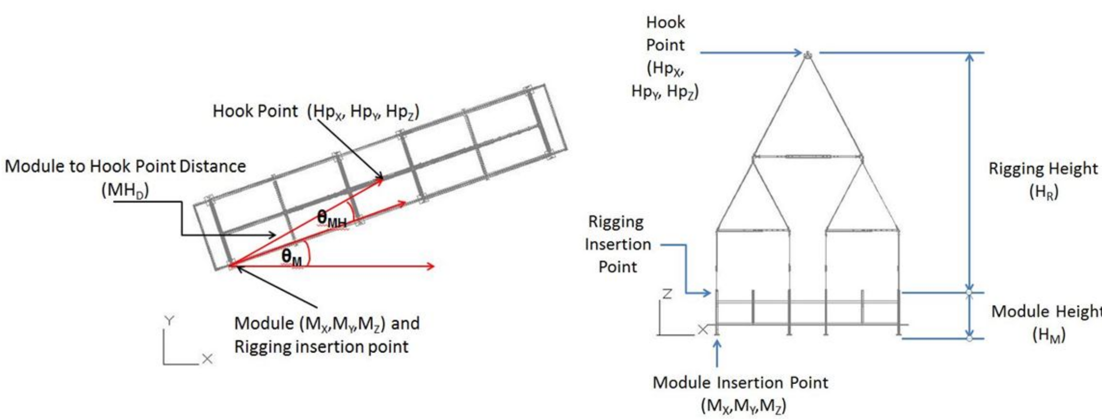

Figure 1: Labelled plan and elevation views of the module and rigging

2.5 Dimensioning and Lift Study Layout

An available feature of the program can automatically create a plan view dimension for the lift study. The program generates radial dimensions for the lift radius, tail-swing radius, and super-lift radius. It also creates both horizontal and vertical dimensions from the crane to the pick point. The user can use the dimension grips to arrange the dimensions as they see fit. The dimensions are placed on a layer, called PlanDimension, that the program creates. Once the user is satisfied with the drawing, another function from the custom toolbar can automatically insert a lift study layout into paper space. When this option is selected a command line prompt appears asking the user if the layout is for the final or initial position (pick point or set point). These layouts contain viewports for a plan view, an elevation view, and an additional custom view. The user then creates the elevation dimensions on the layout with a pre-made dimension style on a layer, called ElevationDimension, created by the program. Finally, the user turns off the PlanDimension layer in both the elevation and the custom viewports in order to find a custom view they are satisfied with. The graphical component of the pick point lift study is now complete. An example is shown in Figure 2.

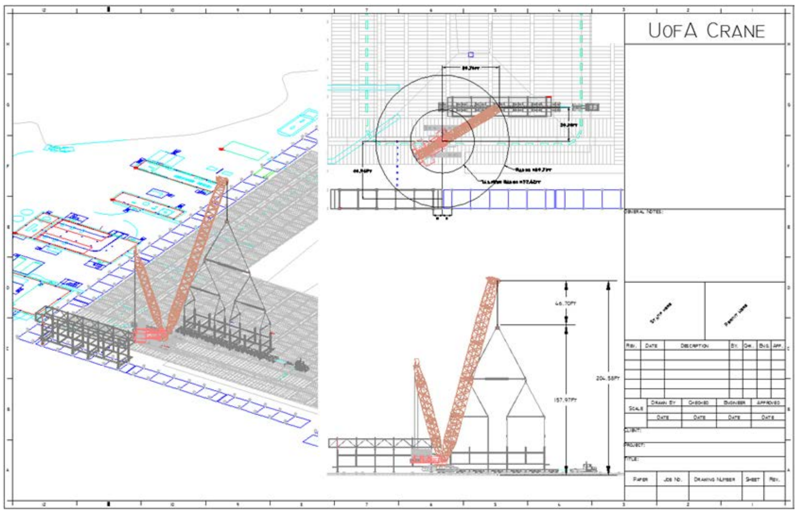

Figure 2: Completed lift study graphics

2.6 Module Movement Options

Now that the pick point lift study is complete, the crane and module can be manipulated. These options, available on the custom toolbar, include lifting, straightening, swinging, and rotating the module, as well as raising or lowering the boom to move the module backwards or forwards (see Figure 3). The crane will automatically respond to these operations by orienting itself in the correct fashion. Another available option is to simply choose the set point, which will remove the module from its pick position and allow the user to manually select the module's set point and set angle. Again the crane will automatically change orientations to accommodate this (see Figure 4). The user can then create a set point lift study layout in much the same way as with the pick point.

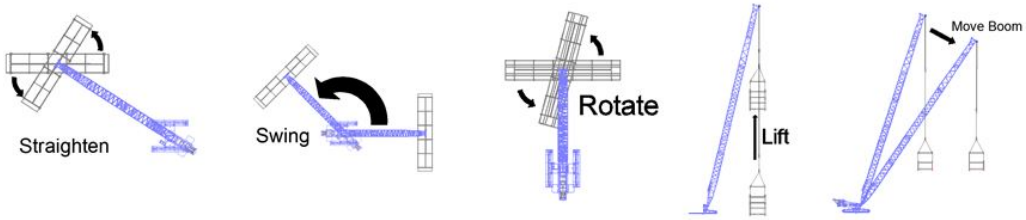

Figure 3: Module and boom manipulations

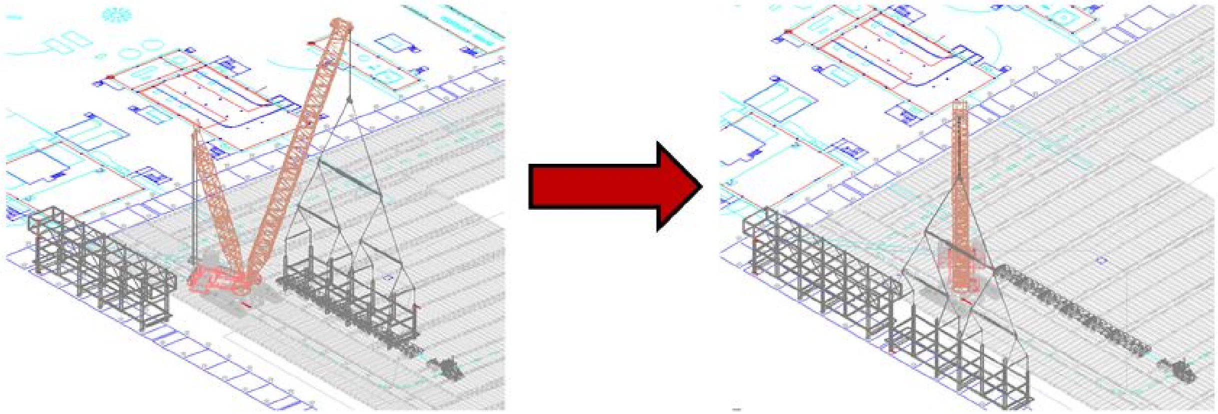

Figure 4: Set point option

3 SMART LIFT PLANNER

The Smart Lift Planner (SLP) is a Windows Form application designed to aid in planning and calculations necessary for lift studies. It accomplishes this through use the combined use of databases and user inputs such as module weight, lifting radius, and matting type. Several databases of technical data are constructed in order to minimize the need to sift through data tables to obtain information. These include a crawler crane database, a capacity database, and a rigging database. The crawler crane database contains hundreds of unique crane configurations, each with 45 parameters including weights, dimensions, and lift form. The capacity database contains the capacities at different radii for many of the configurations. The rigging database contains the specifications for hundreds of shackles, slings, spreader bars, and turnbuckles. The SLP can be used to determine maximum lift radius, percent capacity, total weight, ground bearing pressure, mat pressure, and matting necessary, among other things. Further details pertaining to the SLP are provided below.

3.1 Crane Info Page and Lift Design Page

Dropdown menus allow the user to select the crane manufacturer and the crane model they require. Once these selections have been made a data grid view appears, where the user can scroll through and select the configuration that will meet the specific needs of the project. Crane Info Page 1 then automatically displays information such as weights, lift form, and boom length. It also brings up the capacity table for the chosen crane, which shows how the lifting capacity varies with radius. A hook block table is also available for the user to select a hook block. The dimensions of the chosen crane are automatically displayed on Crane Info Page 2 (see Figure 5). Now moving to the lift design page the user inputs the weights of the module, rigging, and other relevant components. The program then calculates the total weight and checks the capacity chart to provide the user with a range of radii acceptable for lifting modules with the selected crane. The user then inputs the radius for the current lift, and the program outputs the maximum capacity at that radius and the percentage of the maximum capacity that the lift requires.

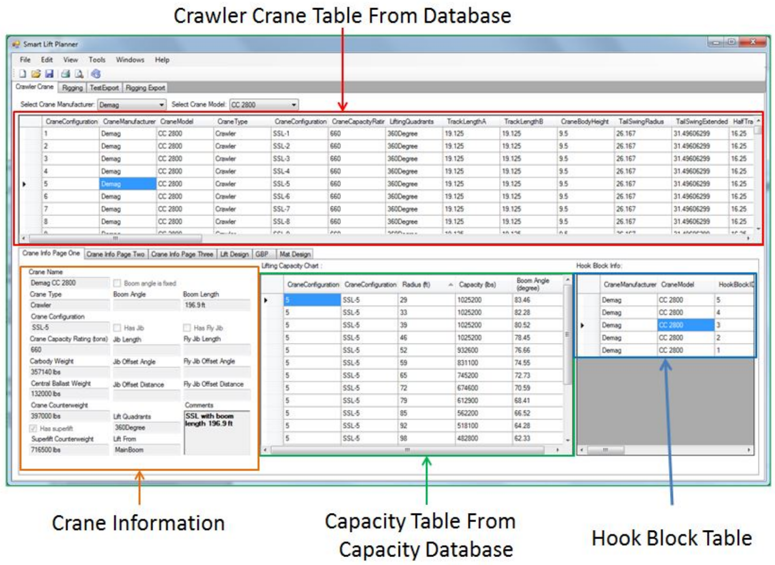

Figure 5: Labelled screen capture of crane info page 1

3.2 Ground Bearing Pressure Page

After the capacity has been determined the ground bearing pressure must be calculated. All of the information needed for this calculation is already available, so the user simply needs to click "calculate GBP". The required information is retrieved from the database entries for the selected crane, as well as from the lift design page where information has been inputted by the user. By default these values are used in GBP calculations; however, they can be manually overridden if need be. The program also generates a chart that displays the GBP on each side of the crawler as a function of the boom angle. The values given are the maximum pressures on the front boom side, rear boom side, front counter weight side, rear counterweight side, and the crane body angle that gives these maximum pressures. If the GBP at a specific crane body angle is required, then that angle can be specified and the program will give the corresponding pressure values. A screen capture of the ground bearing pressure page can be seen in Figure 6.

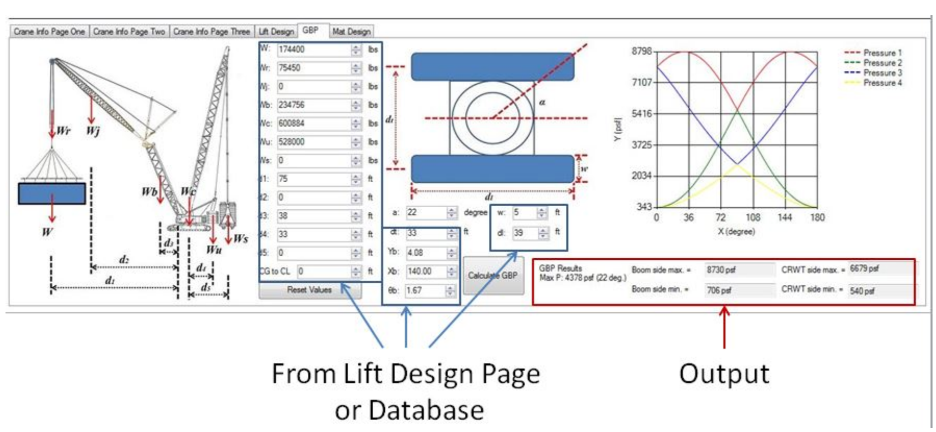

Figure 6: Labelled screen capture of ground bearing pressure page

3.3 Mat Design Page

GBP information is automatically passed to the Mat Design page. The user is prompted to input the allowable soil bearing capacity for the project site, the number of timbers forming the mat, number of layers of mats, and sectional dimensions of the mat, and to choose the type of wood for the mats. The program then verifies if the stresses induced by the lift are within the allowable limit. If the allowable limit is exceeded then an error message is displayed along with a message containing suggestions such as “Bending Fail! Please increase the depth of mat or number of layers”. If the pressures are within the allowable limit then the necessary mat length, p value, load on mat, and minimum mat cantilever distance are generated. A screen capture of the mat design page can be seen in Figure 7.

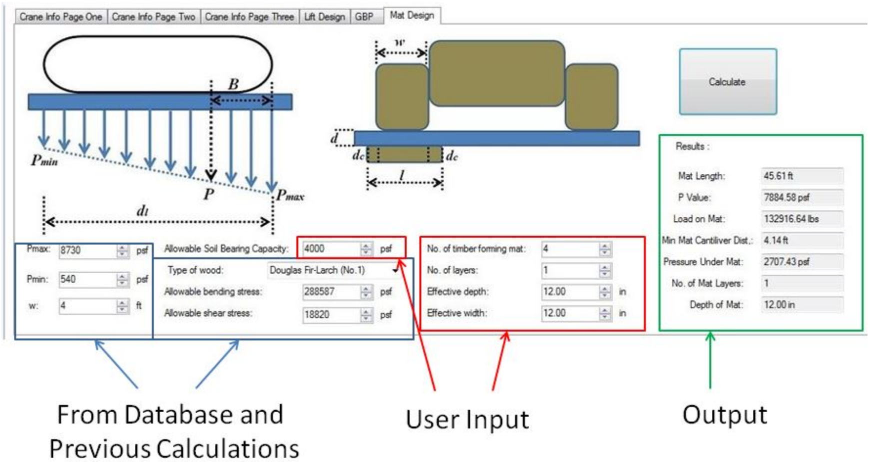

Figure 7: Labelled screen capture of mat design page

3.4 Generating and Exporting Lift Study Table

With all information required for a lift study table now available, the user returns to the Lift Design Page and clicks “Generate Table”. The generated table has a feature that exports the table into an MS Excel spreadsheet. The spreadsheet can then easily be imported into the AutoCAD layout created by the lift study AutoCAD plug-in.

4 VALIDATION

The Rapid Lift Study Generation system was used to recreate the graphical portion for a total of 34 pre-existing lift studies from a project by NCSG Crane & Heavy Haul Services. The project was located in Fort McMurray, Alberta and involved the assembly of prefabricated pipe racks that had been transported to the site by trucks. The crane featured in the lift studies was the Manitowoc 18000. The 55A configuration was used with a boom length of 280 ft. The studies featured 18 pipe racks weighing up to 211,974 lb with lengths up to 120 ft. All lifts featured were single-crane lifts. The transport truck, pipe racks, custom rigging, and crane blocks had been created by the drafts-people at NCSG for use in traditional lift studies. The blocks were then modified for use with the Rapid Lift Study Generation Program. Information relevant to the insertion of the blocks was measured using existing AutoCAD tools and entered into spreadsheets. Use of the program substantially reduced the time needed to insert the blocks into the drawing. Because of the level of automation offered by the plug-in it was possible to create lift studies with less effort and drafting knowledge. Tedious tasks such as manually inserting, rotating, and aligning the blocks were mitigated. During the process of creating lift studies, it should be noted, it is often necessary to explore multiple crane position options. Through use of the program it is possible to create many versions of the same lift study in a short period of time, making the planning phase more efficient. For a few of the 34 lift studies created the table of crane information was constructed through use of the SLP. The SLP was tested against existing software, “Crane Support Design”, developed by Hasan et al. (2010). A sample comparison between the two programs is provided in Table 1. For actual industrial implementation of the developed system, further and more rigours validation is necessary.

Table 1: Comparison between SLP and crane support design

Calculation	SLP	Crane Support Design
Boom Side Front Pressure	8,284 psf	8,010 psf
Boom Side Rear Pressure	2,570 psf	2,732 psf
Counter Side Front Pressure	6,697 psf	6,429 psf
Counter Side Rear Pressure	1,982 psf	2,169 psf
Horizontal Angle For Max Pressure	30°	30°
Min. Mat Length	47.7 ft	42.7 ft
Mat Depth	12 in	12 in
Mat Width	3.8 ft	3.8 ft

Differences between values are assumed to be due to minor differences in the implementation of formulas in creating the respective programs and the way the programs handle values. The difference in mat length is due to the fact that SLP takes into account the bending and shear strength of the wood, whereas the Crane Support System does not.

5 CONCLUSION

In this paper, an automatic system has been introduced for rapid lift study creation for heavy industrial projects. The system has been proven efficient in engineering planning and the design stage for heavy lifts. Many design factors have been considered in the calculations, such as the lifting capacity and ground bearing pressure. The crane is inserted to its predefined pick and set locations in an AutoCAD system using a plug-in developed by researchers at the University of Alberta; lift drawings (2D and 3D views) are automatically generated, which shortens the drafting time and reduces the human component involved. The designed graphical system has been tested by recreating documents for an actual industrial project in Fort McMurray, Alberta, and the SLP results have been compared with the system previously developed by Hasan et al. (2010).

Acknowledgements

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References

Al-Hussein, M., Niaz, M.A., Yu, H., and Kim, H. 2006. Integrating 3D visualization and simulation for tower crane operations on construction sites. *Automation in Construction*, Elsevier, **15**(5): 554-562.

Chang, Y.C., Hung, W.H., and Kang S.C. 2012. A fast path planning method for single and dual crane erections. *Automation in Construction*, Elsevier, **22**: 468-480.

Hanna, A.S. and Lotfallah, W.B. 1999. A fuzzy logic approach to the selection of cranes. *Automation in Construction*, Elsevier, **8**(5): 597-608.

Hasan, S., Bouferguene, A., Al-Hussein, M., Gillis, P., and Telyas, A. 2013. Productivity and CO_2 emission analysis for tower crane utilization on high-rise building projects. *Automation in Construction*, Elsevier, **31**: 255- 264.

Hasan, S., Al-Hussein, M., Hermann, U. H., and Safouhi, H. 2010. Interactive and dynamic integrated module for mobile cranes supporting system design. *Journal of Construction Engineering and Management*, ASCE,**136**(2): 179-186.

Huang, C., Wong, C.K., and Tam, C.M. 2011. Optimization of tower crane and material supply locations in a high-rise building site by mixed-integer linear programming. *Automation in Construction*, Elsevier, **20**(5): 571-580.

Juang, J.R., Hung, W.H., and Kang, S.C. 2013. SimCrane 3D+: A crane simulator with kinesthetic and stereoscopic vision. *Advanced Engineering Informatics*, Elsevier, **27**(4): 506-518.
Lei, Z., Taghaddos, H., Hermann, U., and Al-Hussein, M. 2013a. A methodology for mobile crane lift path checking in heavy industrial projects. *Automation in Construction*, Elsevier, **31**: 41-53.
Lei, Z., Taghaddos, H., Olearczyk, J., Al-Hussein, M., and Hermann, U. 2013b. Automated method for checking crane paths for heavy lifts in industrial projects. *Journal of Construction Engineering and Management*, ASCE, **139**(10): 04013011.
Lien, L.C. and Cheng, M.Y. 2014. Particle bee algorithm for tower crane layout with material quantity supply and demand optimization. *Automation in Construction*, Elsevier, **45**: 25-32.
Lin, Y., Wu, D., Wang, X., Wang, X., and Gao, S. 2012. Statics-based simulation approach for two-crane lift. *Journal of Construction Engineering and Management*, ASCE, **138**(10): 1139-1149.
Olearczyk, J., Al-Hussein, M., and Bouferguene, A. 2014. Evolution of the crane selection and on-site utilization process for modular construction multilifts. *Automation in Construction*, Elsevier, **43**: 59-72.
Safouhi, H., Mouattamid, M., Hermann, U., and Hendi, A. 2011. An algorithm for the calculation of feasible mobile crane position areas. *Automation in Construction*, Elsevier, **20**(4): 360-367.
Tantisevi, K. and Akinci, B. 2009. Transformation of a 4D product and process model to generate motion of mobile cranes. *Automation in Construction*, Elsevier, **18**(4): 458-468.
Wu, D., Lin, Y., Wang, X., Wang, X., and Gao, S. 2011. Algorithm of crane selection for heavy lifts. *Journal of Computing in Civil Engineering*, ASCE, **25**(1): 57-65.
Zhang, C. and Hammad, A. 2012. Multiagent approach for real-time collision avoidance and path replanning for cranes. *Journal of Computing in Civil Engineering*, ASCE, **26**(6): 782-794.
"AutoCAD", AutoDesk, accessed January 14, 2015, http://www.autodesk.com/products/autocad/overview
"Visual Basic", Microsoft, accessed January 14, 2015, http://msdn.microsoft.com/en-us/library/2x7h1hfk.aspx