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Optimal Design of Distribution Overhead Powerlines using Genetic Algorithms

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***Abstract*—As the design of distribution overhead power lines becomes increasingly standardized in the 21st century, the reduced search space of its design parameters allows for increasing opportunities to automate the design process. It involves specifying the distribution utility pole heights and classes, pole-top attachments, and conductor span tensions. A successful algorithm must be able of generating designs that are compliant with applicable codes and utility standards, achieve construction labour and material costs that are commensurate to that of a human-created design, and require a reasonable computation time.**

A design automation algorithm is created for ATCO Electricity, Alberta, Canada. Based on provided requirements and constraints, it uses the genetic algorithm to optimize the design parameters, including a completed design staking list, material loading file, and relevant calculation reports for use by the design department. Evaluation of the developed tool is based on five samples of real design scenarios. Within a reasonable amount of computation time, the tool produces results free from major design errors, comparable in material and construction costs to those of human-created designs. Furthermore, the design automation tool makes rigorous use of design decisions that result in small cost savings but that are not commonly found in human-created designs.

***Index Terms*—Power distribution lines, overhead, genetic algorithms, design automation, optimization.**

I. Introduction

In response to increasing pressure to reduce the cost associated with distribution overhead powerline (DOP) installations, distribution facility operators (DFOs) are increasingly standardizing the design of DOP [1]. With increased standardization, the state space associated with the design parameters of a DOP design decreases and more easily allows for the application of computational optimization techniques to the design process. The possibility to fully automate the design of DOP provides DFOs with the potential to realize considerable design labour, construction labour, and material savings on new designs.

To maximize the benefits of DOP design automation, it is essential that any proposed algorithm can produce accurate designs that are comparable in cost efficiency to human-created designs while not requiring an unreasonable amount of computation time. To address these needs, this paper sets out to achieve three primary objectives in automating DOP design.

Firstly, the proposed algorithm must be capable of generating DOP designs that are free of major errors that violate applicable utility codes and DFO standards. Examples of applicable utility codes include the Alberta Electric Utility Code [2] and the CSA Standard for Overhead Systems [1]. Utility codes prescribe legal design and construction requirements for DOP safety that must be met. A DFO standards manual is a structure library that is created and maintained by a DFO and encapsulates the safety requirements of the utility codes with structure-specific standards prints that can be directly utilized within new DOP designs.

Secondly, the proposed design automation algorithm must be capable of producing DOP designs that are comparable in cost to those of a typical human-created design. The primary costs for new DOP installations that are sought for optimization in this paper are construction labour and material cost. While the use of a design automation algorithm also avails considerable savings in terms of design labour, design labour savings are not explored in detail in the paper.

Finally, the proposed algorithm must be capable of performing DOP design automation for moderately large designs within a reasonable timeframe on a personal desktop computer. While no hard time limit is set for satisfying the third objective, the expectation is for the design automation algorithm to be able to optimize a moderately large DOP design within a few hours of computation time. A 40 structure DOP new extension typically results in a 4km expanse of new line in rural areas and is considered to be a moderately large project [2].

This paper presents a noncommercial DOP design optimization tool, referred to herein as AutoDesigner, for use by the distribution design department of ATCO Electricity (referred to as the DFO). AutoDesigner seeks to fully automate the DOP design process using, as input, a survey Comma Separated Value (CSV) file of pole and crossing locations. The presented software package addresses the three primary objectives outlined above. It is custom-designed to fit seamlessly within the DFO's existing design practices so as to require minimal human intervention in the design automation process once it is deployed to the end-user.

The key contributions made by this paper are:

- Development of a software package suitable for use by the DFO in automating the design of DOP,
- improvement of optimization speed through the use of memory to save computationally intensive operations while generating candidate solutions,
- introduction of graduated constraint violation mechanisms to expedite the learning process, and
- evaluation of otpimizer performance and identification of unique design constructs that are not commonly observed

in human-created designs.

This paper contains five sections. Section II provides an introductory background of some fundamental DOP design concepts followed by a review of available literature and commercial software offerings. Section III lays out the methodology of AutoDesigner. Section IV provides the results of the hyper-parameter search analysis performed on AutoDesigner. Section V provides the final evaluation of AutoDesigner by comparing its results against those of several human-designed DOP designs. Section VI provides concluding thoughts on AutoDesigner's performance.

II. Background

A. Distribution Overhead Powerline Design Concepts

DOP provides a reliable conducting path for supplying electrical power from a substation to a customer's service by suspending open-air electrical conductors on powerline structures [3]. Typically, a new DOP design either involves extending a new DOP from an existing DOP mainline to serve a new customer or rebuilding an existing DOP mainline with a new line and structures while tying in the existing services [2]. The first case involves limited interaction between new and existing powerline structures; however, the latter case requires significant interaction between new and existing design components. DOP rebuild designs pose a specific challenge for design automation software, as existing powerline facilities cannot necessarily be assumed to adhere to the DFO's standardized design practices, so significant human customization of existing structures is typically required. Figures 1 and 2, respectively, illustrate the samples of a DOP new extension and rebuild design.

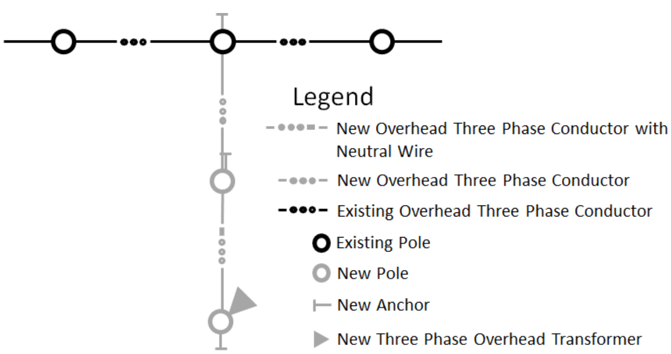

Fig. 1. Design View of DOP New Extension

Each pole structure in a DOP design contains one or more pole-top structure attachments that enable a utility pole to safely support powerline conductors or equipment, provide a tap-off connection for a new powerline extension, specify a downhaul guy wire or provide a ground connection. Figure 3 illustrates a sample of common pole-top attachments encountered in DOP designs.

The pole-top attachments that are present on each pole in Figure 3 are denoted below each illustration using three or four character alphanumeric labels and are separated by commas in cases where multiple structure prints are present. Each label refers to a structure print name of a standard that is contained

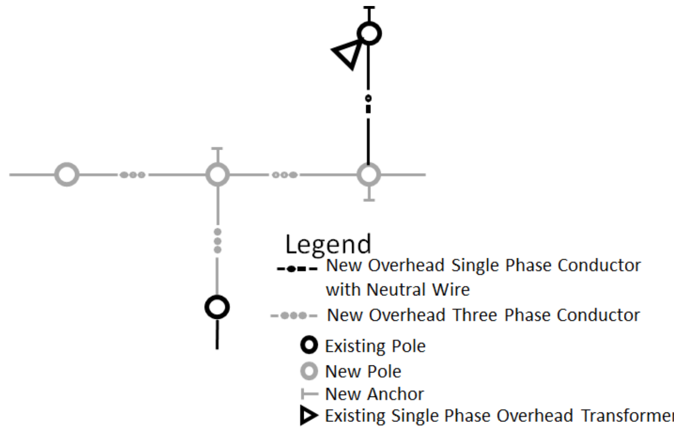

Fig. 2. Design Overview of a Sample DOP Rebuild

in the DFO's standards manual. Labels that begin with an "R" character denote single phase pole top attachment standards such as the R112 structure illustrated in the top-left corner of Figure 3. Labels that begin with an "N" character denote three phase pole top attachment standards such as the N11, N32 and N52 structures shown in the remaining three panes of Figure 3. Labels that begin with a "G" denote down-haul guy wire standards that are needed to provide pole-top force cancellation for accompanying three phase or single phase structures. Attachment labels that contain a numerical value of 0, such as the N0A structure, refer to neutral conductor attachments that support a single neutral connection point approximately 2.0 m below phase conductors.

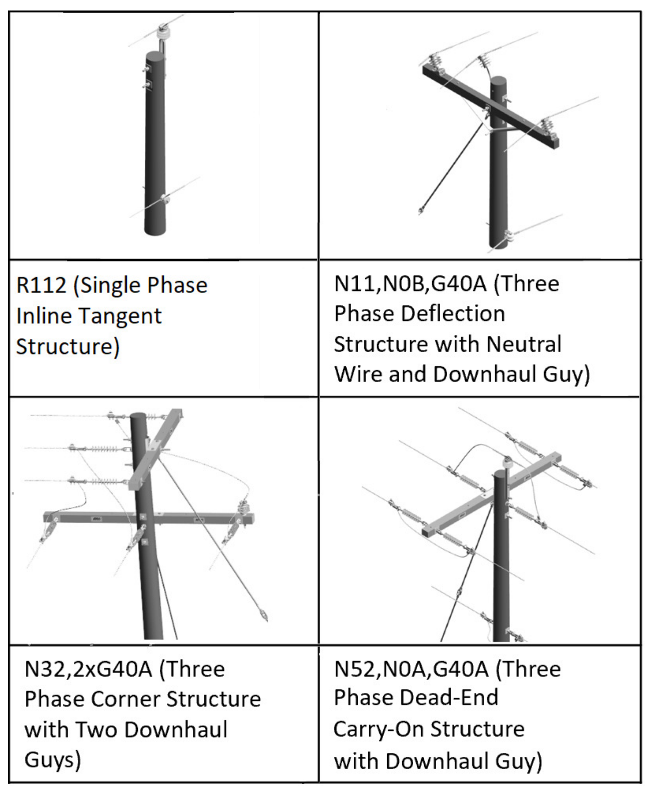

Fig. 3. Sample of Common Three Phase DOP Pole-Top Attachments

Additional design parameters that must be determined when designing DOP include the tension of each new span, the height and class of each new pole structure, the set depth of new pole structures, and the presence of an overhead neutral wire. Short spans may be strung as a low-tension slack span in cases when it is not desirable to install a downhaul guy wire at an adjacent pole structure. Wood pole heights typically range from 40 to 60 ft. for new DOP designs, in 5 ft. increments, while the pole class may range from 1 (representing the thickest pole) to 5 (representing the thinnest structure). In cases where slack spans are installed and unbalanced forces are present at the supporting pole structure, a minimum of 1.0 m pole deep-set must be applied on top of the nominal pole set depth. While pole deep-sets are typically performed to support slack spans, deep-setting may also prevent conductor uplift conditions from being created on adjacent pole structures. Finally, The DFO may use an overhead neutral wire as a return path for ground current or, alternatively, use the earth as a return path. In the latter case, the presence of an overhead neutral wire may be treated as an optimizable design parameter where short runs of neutrals can be used to provide redundant ground connections for pole-top equipment.

The optimization of DOP design is subject to numerous design constraints, which must be satisfied to ensure the structural stability and safety of a DOP installation. First is the need for individual DOP pole structures to be able to withstand the applied force loading exerted by conductor tension, wind-loading effects, ice-loading, and attachment weight. Second, DOP spans must maintain adequate vertical clearance over crossings such as ground that may be traversed by pedestrians, roadways, agricultural areas, and railways. Third, DOP designs must account for conductor uplift due to large changes in elevation between structures on DOP pole-top structures that use pin-style insulators, which may fail when exposed to upward vertical force [3].

B. Related Work

A large selection of literature addresses the problem of optimizing powerline design. It is challenging, however, to find discussions of DOP design optimization at the specific scope and scale that is considered by AutoDesigner. For example, a significant portion of the literature deals strictly with the design of transmission overhead powerlines [4][5][6][7][8]. Articles that do address DOP often consider high-level planning activities such as the coordination of protection devices, line routes or energy loss minimization [4][9][10]. The studies that consider planning components of a DOP design generally forego detailed design activities – such as the placement of pole-top attachments – that are specified by AutoDesigner.

On the other hand, Ciconi et al. [11] lay out a DOP optimization scheme that is exceptionally relevant to the operation of AutoDesigner. The method they suggested is capable of realizing a cost-optimized DOP design by selecting design parameters that are very similar to those optimized by AutoDesigner and is based on a similar set of input data. Their tool differs from AutoDesigner in that it makes use of commercially available software to perform much of the design automation activity as opposed to being a custom-made software package as with AutoDesigner. The advantages of using custom-made software in the automation of DOP are further discussed in the following subsection.

C. Commercially Available Software Offerings

A number of commercially available software packages address the challenge of DOP design optimization. PowerLines Pro and Automated Utility Design both enable a form of DOP design automation by allowing users to seamlessly place poles within a convenient user interface while automatically identifying design issues such as substandard clearances or pole loading violations [12], [13]. Similarly, PLS-CADD (the most well-established DOP design software in North America) allows for the optimal placement of DOP poles within the right of way to minimize costs while satisfying constraints such as conductor clearance, pole loading and conductor uplift [14], [15].

While commercial software allows for significant steps toward automating DOP design, some DFO-specific design practices such as using deep-sets to support slack spans, optimizing the placement of ground rods in earth-return grounding systems and making decisions around the replacement of existing structures are difficult to fully automate without customized software. Furthermore, commercial software also struggles to automatically account for the variability in the attachment heights of older DOP structures that may not comply with DFO standards. As a result, when using commercial design automation software, human intervention is inevitably required to augment portions of the optimization process, which adds to the total design effort hours. In some cases, the need for human intervention may also inhibit the design automation software from realizing a truly optimal design. AutoDesigner seeks to fully optimize the DOP design process based on the survey-specified locations of poles and anchors as well the attachment heights of existing structures. It is composed of custom-made design software that is adapted specifically to the practices of the DFO.

III. Methodology

AutoDesigner accepts as input a survey Comma Separated Value (CSV) file that contains geographical coordinates specifying the locations of existing and new proposed poles, anchor locations, and DOP crossing locations relevant to the DOP design being optimized. Next, AutoDesigner preprocesses the supplied data, constructs a linked list data structure that complements the physical configuration of the DOP, and finalizes the non-optimizable design parameters through rule-based analysis. Once the design's non-optimizable components are determined, AutoDesigner makes use of the genetic algorithm to optimize the remaining design parameters, which include the heights and classes of new poles, pole-top attachment configurations, span tensions, pole deep-sets and deciding whether or not to upgrade existing pole-top attachments or existing pole structures. Note that the optimization of design parameters is subject to five constraint modules that enforce DOP design compliance with applicable codes and DFO standards: pole

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loading calculations, conductor clearance calculations, conductor uplift calculations, low-tension span calculations, and neutral and ground rod usage. Finally, once the optimization process is complete and a final DOP design is realized, AutoDesigner generates a battery of output design reports and documents in a format that is directly usable by the DFO's design department. Note that Figure 4 illustrates the flow of data through the various modules that comprise AutoDesigner.

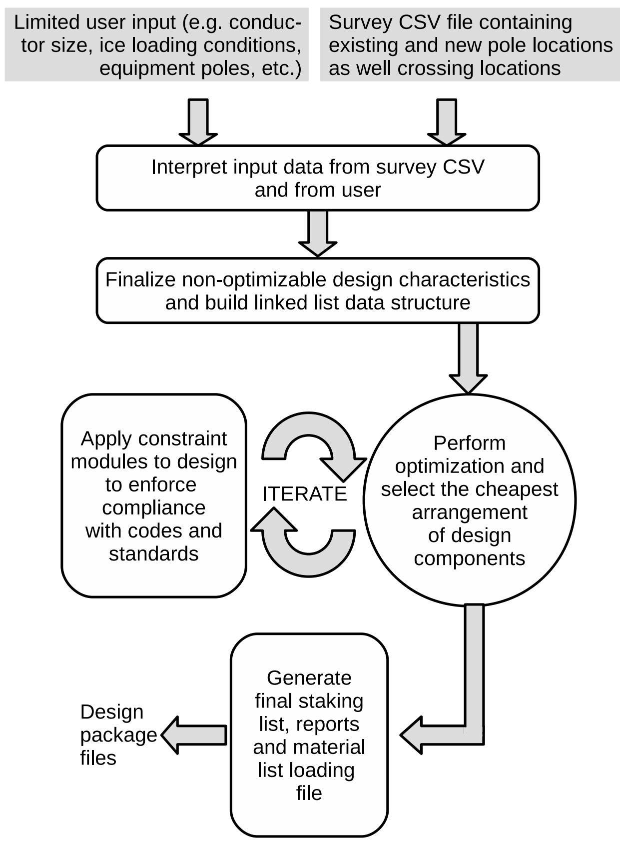

Fig. 4. Flow of DOP Design Automation Process in AutoDesigner

The discussion on the methodology used by AutoDesigner is divided into five categories based on the modules illustrated in Figure 4. Note that AutoDesigner is implemented using Python version 3.6.4 within the Jupyter Notebook development environment on a personal computer with a Windows 10 operating system.

A. Survey CSV File Interpretation

The first stage in the operation of AutoDesigner is the interpretation of a CSV file produced by the DFO's survey department. The CSV file lists the geographical coordinates of new and existing pole structures, down-haul anchor locations, and the locations of relevant conductor span crossings. A sample survey CSV file is shown in Figure 5. The first column can denote either new poles (three digit numerical values), existing pole asset identification (six digit numbers), crossing locations (four digit numbers) or anchor locations (numbers ending with "A" or "B" suffixes). The survey CSV file also contains additional columns specifying the existing pole-top

Survey Pt No.	UTMNorthing (m)	UTM Easting (m)	Elevation (m)	Crossing Type / Existing Pole Height, Class and Year	Ex. Pole Structure Attachments	Ex Pole Asset ID	Ex Structure Height of Attachment (m)
475127	6452357	585346.2	284.883	EXPP_35_5	R252_	475127	
475127A	6452353	585346.4	284.808	EXANC_	G10_		
475126	6452347	585346.7	285.056	EXPP_35_6	R240	475126	
142	6452345	585380.4	284.698	PP_	N42_N390_E12_G40_		
142A	6452345	585373.4	284.749	ANC_	7M_		
143	6452345	585390.6	284.752	PP_	N12_R390_E12_		
144	6452345	585458.7	284.804	PP_	N12_		
145	6452346	585526.9	285.038	PP_	N12_		
8100	6452347	585576.3	285.899	RDSHL_			
8101	6452347	585579.9	285.994	RDCL_			
8102	6452347	585584.2	285.799	RDSHL_			
146	6452347	585595	285.559	PP_	N12_R258_G1_		
147	6452349	585688.3	285.514	PP_	N12_		
148	6452350	585781.5	285.207	PP_	N12_		
7131	6452352	585842	285.243	P/L_	GAS COOP_		
149	6452352	585874.8	285.394	PP_	N42_N390_E12_G40_		
149A	6452352	585881.8	285.349	ANC_	7M_		
146	6452347	585595	285.559	PP_	N12_R258_G1_		
799409	6452358	585594.9	285.671	EXPP_40_5	R252_	799409	HOA=9.95
799409A	6452351	585595	285.526	EXANC_	G40_		
799410	6452440	585593.6	285.355	EXPP_40_5	R212_	799410	HOA_9.49
799411	6452518	585592.5	284.993	EXPP_40_5	R212_	799411	HOA_9.47

Fig. 5. Sample of Survey CSV File

structure standards present on the pole as well as the height of attachment (HOA) of the actual field-measured attachment points on the pole. Figure 5 lists the attachment standards and the HOA values for the existing poles 7994029, 799410 and 799411 in the seventh and eighth columns of the CSV file. AutoDesigner has the capability to automatically read in and interpret the text strings contained within the two columns. It then extracts the physical attachment dimensions of the existing pole structure from the DFO's standards library with an adjustment adder that maps the attachment heights to the supplied HoA values. The ability to automatically interpret DFO standards and HOA data of existing pole structures from the CSV file enables AutoDesigner to automate a significant portion of the DOP design process that would normally need to be manually entered by the designer when using commercial design-automation software [14].

B. Construction of the DOP Design Data Structure

After all input data is successfully interpreted, AutoDesigner generates a linked list data structure to contain all physical parameters associated with a DOP design. The linked list data structure is doubly linked and comprises alternating pole and span objects, where each pole object contains references to up to four span objects and each span object contains references to two adjacent pole objects. Figure 6 illustrates a small sample of a linked list data structure for a series of poles and spans within a DOP design.

Immediately after constructing the data structure, AutoDesigner populates the attributes of each pole and span object with values that can be determined prior to design optimization. Attributes that can be determined without optimization include design span lengths, conductor deflection angles at pole structures, and conductor span crossing locations. The

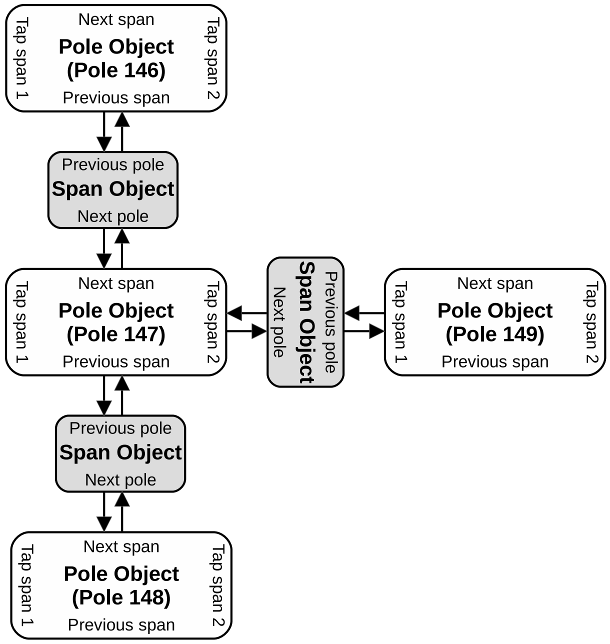

Fig. 6. Sample of Linked List Data Structure

remaining attributes that cannot be determined prior to optimization are assigned an asterisk value, which is to be overwritten after the optimization is complete. Upon populating the design attributes associated with each pole and span object, a preliminary staking list file is generated, which is in the format of the staking lists used by DFO's design department. Figure 7

ELEV (m)	STR. NO.	ASSET ID#	DEFLN	SPAN (m)	HEIGHT/C	TYPE
2 x #4 ACSR Pollock OVERHEAD - MEDIUM						
284.97	475121	475121	R 000°00'		0/0	Ex. Pole: 35/5,R140(L),R180,E12,G10
				67.69		
285.20	475120	475120	L 000°22'		0/0	Ex. Pole: 35/6,R252, R0,E12,G10
1 x #4 ACSR Pollock OVERHEAD - MEDIUM						
285.20	475120	475120	L 000°22'		0/0	Ex. Pole: 35/6,R252, R0,E12,G10
				6.48		Slack-Span
285.39	475119	475119	L 084°31'		0/0	Ex. Pole: 35/6,R240
1 x 1/0 ACSR Raven OVERHEAD - MEDIUM						
285.39	475119	475119	L 084°31'		0/0	Ex. Pole: 35/6,R240
				29.61		*Potential Slack-Span
285.0	150		L 002°28'		_>=_40/*	,*
3 x 1/0 ACSR Raven OVERHEAD - MEDIUM						
285.0	150		L 002°28'		_>=_40/*	,*
				32.66		*Potential Slack-Span
284.83	151		L 000°02'		*/*	,*
				106.50		
284.53	152		R 000°01'		*/*	,*
				106.49		
284.33	153		L 000°00'		*/*	,*
				106.49		
284.20	154		L 000°00'		*/*	,*
				106.49		As-Built P/L ___ m at ___ °C 70 m from STR#154
283.77	155		R 000°00'		*/*	,*
				106.70		
284.25	156		L 000°00'		*/*	,*
				99.00		As-Built RD ___ m at ___ °C 7 m from STR#156 As-Built RD ___ m at ___ °C 9 m from STR#156 As-Built RD ___ m at ___ °C 12 m from STR#156
284.14	157		R 000°00'		*/*	,*
				99.01		
1 x #4 ACSR Pollock OVERHEAD - MEDIUM						
284.25	156		R 106°07'		0/0	Material Already Called For
				9.89		Slack-Span
284.25	475109	475109	L 016°09'		0/0	Ex. Pole: 35/6,R252, R0,E12,EXANC

Fig. 7. Sample of Preliminary Staking List

illustrates a small sample of a preliminary staking list, where each pole and span within the DOP design is represented by a row on the list. Note that the preliminary staking list contains asterisk values in all fields that must be finalized by the optimization process. Furthermore, contained to the right of the preliminary staking list main body are additional columns, not shown in Figure 7, that display a substantial portion of the attribute values contained in each pole and span object. AutoDesigner provides advanced functionality by allowing the user to constrain the optimization process by entering specific constraint operators into the supplemental data fields. After generating the preliminary staking list, AutoDesigner reloads the preliminary staking list along with any user-entered optimization constraints.

C. Genetic Algorithm Optimization

Genetic algorithm (GA) is a metaheuristic optimization method based on the mechanics of natural selection and genetics [16]. Suitable for a broad range of problems across numerous application domains, GAs have also found use in the area of power systems [17], including distribution system planning [18], design [19], and operation [20]. Metaheuristic optimization methods fit the problem of optimal DOP design well in general. Compared to classical optimization, they require lower computational effort and provide better solutions for large-size dsitribution systems [17]. The specific choice of GA metaheuristic is driven by the discrete nature of the DOP design problem. It corresponds well to the representation and search operations of the standard GA, as opposed to the real number representation and floating point operations of other metaheuristic approaches, such as differential evolution or particle swarm optimization [21].

After reloading the contents of the preliminary staking list into the linked list, AutoDesigner proceeds to construct a chromosome for use in the GA optimization process. As discussed in the previous subsection, each field denoted with an asterisk on the preliminary staking list corresponds to an optimizable parameter that is determined by the GA. In particular, each new pole object requires optimization to determine pole height, pole class, pole-top attachment structures, and pole set-depth. Each new span object that is short enough to accommodate a slack span tension must undergo optimization to determine if the span is classified as tight or slack. Finally, AutoDesigner may replace attachments or completely replace existing pole structures through the optimization process, provided that sufficient information detailing adjacent existing pole structures is present so that a constraint violation is not created with the upgrade.

AutoDesigner uses a chromosome composed of genes that are integer-valued and range between 0–100. Each gene within the chromosome maps to a single optimizable design attribute. To construct a mapping, AutoDesigner determines a complete set of potential values that each optimizable design attribute may validly assume. Pole heights may assume ranges between 40 and 60 ft poles and pole classes may have a maximum value of 1 and a minimum of 5, while pole deep-set levels may assume values of 0.0 m, 0.5 m, 1.0 m or 1.5 m. AutoDesigner determines the set of potential pole-top attachments that may be installed at a particular pole structure location based on an extensive library of possible pole attachment combinations derived from the DFO's construction standards manual and contains over 400 possible pole-top attachment combinations [2]. That said, for a given structure, AutoDesigner removes many pole attachment combinations from consideration while

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constructing the chromosome based on the state of available design parameters that are known prior to optimization. Note that pole-top attachments, both with and without neutral attachments, are mapped to the GA chromosome unless the user specifically constrains a neutral to be present; if the user does not, the optimization process determines the presence of a neutral wire indirectly through the pole-top attachment selection process. Figure 8 illustrates a sample mapping between the potential values that may be assumed by the attributes contained within the GA and a chromosome to be used in the optimization process.

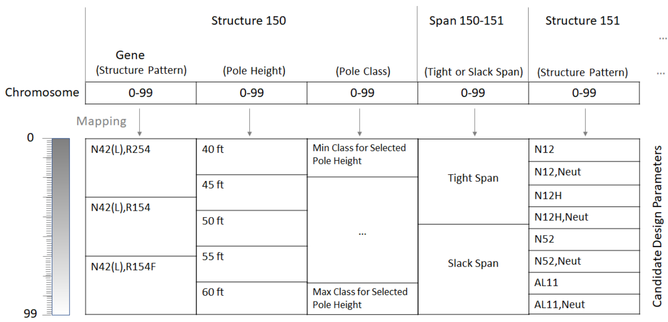

Fig. 8. Sample Mapping Between GA Chromosome and Potential Design Attributes

The GA fitness function is the sum of the total DOP design material and construction labour cost with the addition of penalty factors to represent constraint violations produced by the constraint modules, which are discussed in the next subsection. Each constraint violation is modelled as a minimum of a 1 million dollar penalty factor, which is added to the total fitness function cost. Equation 1 denotes the fitness function used by AutoDesigner.

$$F = M_{\text{tot}} + L_{\text{tot}} * H_{\text{rate}} + \$1,000,000 * C_{\text{viol}}, \quad (1)$$

where M_{tot} is the total material cost for the DOP, L_{tot} is the total labour effort hours required to construct it, H_{rate} is the burdened hourly rate for a DFO powerline technician, and C_{viol} is the total number of constraint violations present in the DOP design.

The GA continues the optimization process until the best-performing individual yields a fitness function value that falls under 1 million dollars, indicating that the design is free from constraint violations. Once the fitness function evaluates below this value, the GA continues further optimizing until the best-performing individual from 20 consecutive generations achieves no further reduction.

The cross-over rate, mutation rate, and population size of the GA are determined by means of a hyper-parameter search that is discussed in Section IV of this paper. Mating parents from a given generation are determined by means of a tournament that selects each parent from a group of three individuals. Once an individual is selected for mutation (using the mutation rate determined by the hyper-parameter search), pairs of genes within the chromosome are further subject to a 0.05 probability of a mutation operation, where the genes are swapped within the chromosome.

D. Constraint Modules

AutoDesigner uses five distinct constraint modules to constrain the GA optimization process to adhere to the electric utility code requirements or DFO best practices that exceeds the scope of a specific structure and that may not be satisfied by applying individual structure prints from the DFO's standards manual. Each constraint module enforces a specific code requirement or best practice. The constraint module returns a value of 0 for a compliant DOP design and a value of 1.0 or higher for designs that contain a constraint violation. The relationship between the output of the five constraint modules and the C_{viol} value in (1) is calculated as follows

$$C_{\text{viol}} = \sum_{i=1}^{N} (C_{\text{PoleCheckD1},i} + C_{\text{PoleCheckD2},i}) + \sum_{i=1}^{K} C_{\text{ClearCalc},i} + \sum_{i=1}^{M} C_{\text{FloatCheck},i} + \sum_{i=1}^{L} C_{\text{DeepSet},i} + \sum_{i=1}^{J} C_{\text{NumGnd},i}, \quad (2)$$

where N is the total number of new structures or existing structures being modified as a result of the DOP design, M is the total set of crossing locations under spans that are a part of a new DOP design or are attached to structures that are being modified as part of the DOP design, K is the total number of modified or new pole structures that are susceptible to conductor uplift, L is the total set of new or modified pole structures supporting slack-spans that do not have adequate pole-top force cancellation, and J represents the total set of new or modified structures that are supporting equipment such as pole-top transformers or underground cable risers.

A floating point value that is higher than 1.0 may be returned in modules that use a graduated constraint violation. This is intended to reward the GA optimization process for incremental movement along the error surface that approaches a compliant design, even if a constraint violation remains. Figure 9 illustrates the potential benefit of using a graduated constraint violation on the learning process during GA optimization. Note that the first four constraint modules discussed below use graduated constraint violations.

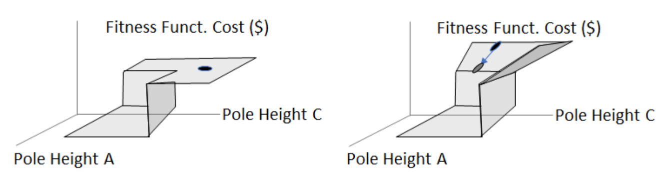

Fig. 9. Benefit of graduated constraint violation in facilitating GA learning process (left - no graduated information is provided for design improvement; right - the slope established by the graduated constrain violation guides the optimization process towards regions without constraint violation)

Furthermore, to reduce the computation time associated with the generation of individuals, the results of the PoleCheck and ClearanceCalc constraint modules discussed below are stored in sparse lookup tables, where the constraint module outputs for a particular pole height, class, pole-top attachment and span tension configuration can be retrieved with minimal computational effort. The lookup tables serve as a memory database

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that enables AutoDesigner to carry out fewer computationally intensive operations while generating individuals. Figure 10 illustrates how the applicable row number in the memory lookup table for the PoleCheck constraint module is addressed in a direct manner without the use of search algorithms. Addressing the row numbers in the memory lookup tables is conceptually similar to navigating a decision tree where the branches present at each node are known beforehand [9].

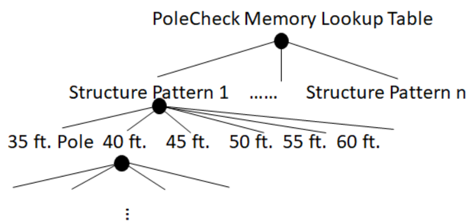

Fig. 10. Sample of PoleCheck memory lookup table row addressing

The first constraint module, referred to as PoleCheck, is responsible for performing a finite element analysis check of all new or modified existing pole structures in a DOP design as per code requirements [3]. PoleCheck assigns pole utilization percentages to each pole structure from a database of relevant scenarios. Pole utilizations that fall under 100% correspond to a constraint violation value of 0.0 returned to AutoDesigner, while utilizations over 100% correspond to values of at least 1.0 being returned. The relationship between the pole utilization and the resulting constraint violation value is expressed by the piece-wise formulas in (3) and (4). Note that percent utilization for a pole structure is obtained from one of the two PoleCheck databases where (3) is the constraint penalty implementation for the first database within AutoDesigner while (4) is the implementation for the second database [22], [2]

$$C_{\mathrm{PoleCheckD1,i}} = \begin{cases} 0.0 & \text{for } p_{u,i} \leq 100\%, \\ p_{u,i}/100.0 & \text{for } p_{u,i} > 100\%, \\ 2.0 & \text{for } p_{u,i} \notin \mathbb{R}, \end{cases} \tag{3}$$

$$C_{\mathrm{PoleCheckD2,i}} = \begin{cases} 0.0 & \text{for } p_{u,i} \leq 100\%, \\ 1.0 & \text{for } p_{u,i} > 100\% \text{ or } p_{u,i} \notin \mathbb{R}, \end{cases} \tag{4}$$

where $p_{u,i}$ represents the percent force utilization of pole structure i. Note that the first PoleCheck database uses graduated constraint violation, while the second database uses static constraint violation response due to the secondary cost optimization procedure within the database query [22].

The second constraint module used by AutoDesigner is referred to as ClearanceCalc. It ensures that conductor spans maintain adequate vertical clearances over ground, roadways and other categories of conductor crossings. Conductor clearances are modelled by ClearanceCalc and evaluated against the DFO's minimum prescribed clearance values, which exceed the requirements mandated in code [23][2]. ClearanceCalc adapts a tool created by the DFO's designers to measure the conductor clearance of spans for use by AutoDesigner. Each new or modified conductor span is assessed for adequate clearance within ClearanceCalc. Spans that are found to meet or exceed the minimum clearance receive a constraint violation value of 0.0. Alternatively, the violating spans are given a constraint violation value of 1.0 or greater for each clearance violation that exists underneath the span. Each clearance violation is modelled using a graduated penalty factor proportional to the difference between the minimum span height and the required height

$$C_{\mathrm{ClearCalc,i}} = \begin{cases} 0.0 & \text{for } C_{\mathrm{d},i} \geq C_{\mathrm{req},i}, \\ 1.0 + \frac{(C_{\mathrm{req},i} - C_{\mathrm{d},i})}{10} & \text{for } C_{\mathrm{d},i} < C_{\mathrm{req},i}, \end{cases} \tag{5}$$

where $C_{\mathrm{d},i}$ is the designed worst-case clearance, in metres, of the DOP at a particular crossing location. $C_{\mathrm{req},i}$ specifies the required clearance of the line at the crossing location as per applicable utility code rules and DFO practices [22][23].

The third constraint module, FloaterCheck, measures the conductor uplift condition on poles that support the conductors using pin-style insulators. FloaterCheck is similar to ClearanceCalc in that it is adapted for use by AutoDesigner based on an existing tool the DFO's designers use. FloaterCheck returns a constraint violation value of 0.0 for pole structures that do not contain any conductor uplift violations. Poles that contain uplift hazards receive a constraint violation of at least 1.0. The magnitude of the constraint violation is proportional to the degree of uplift at the pole under investigation to provide graduated feedback to the GA

$$C_{\mathrm{FloatCheck},i} = \begin{cases} 0.0 & \text{for } W_{s,i} \geq 0.0 \\ 1.0 - \frac{W_{s,i}}{200} & \text{for } -1 \leq W_{s,i} < 0.0 \\ 2.0 & \text{for } W_{s,i} < -1 \end{cases} \tag{6}$$

where $W_{\mathrm{s,i}}$ denotes the sum of the maximum expected uplift forces, referred to as weight span, that is contributed from each pole-top span attached to the pole. It is a non-physical parameter, expressed in metres. The total weight span at a pole with a pin-style attachment must be greater than or equal to 0.0 m, otherwise an uplift violation is present [22][2].

The fourth constraint module assesses new and modified poles that contain slack spans and ensures that the poles are adequately deep-set. All poles that are attached to unsupported or unanchored slack spans must per DFO standards have a minimum of 1.0 m deep-set[2]. Poles that contain unsupported slack spans receive a constraint violation of 1.0 or 1.2 depending on whether the pole has an inadequate 0.5m deep-set or no deep-set, respectively. The constraint formula expresses the graduated thresholds generated at poles with unsupported slack-spans

$$C_{\mathrm{DeepSet},i} = \begin{cases} 0.0 & \text{for } D_{\mathrm{s},i} \geq 1.0, \\ 1.0 & \text{for } D_{\mathrm{s},i} = 0.5, \\ 1.2 & \text{for } D_{\mathrm{s},i} = 0.0, \end{cases} \tag{7}$$

where $D_{\mathrm{s},i}$ is the degree of deep-set that the pole under investigation has been assigned by the GA optimizer.

The fifth constraint module ensures that the overhead neutral wire and interconnected ground rods are appropriately configured. It issues constraint violations of 1.0 if poles with equipment such as transformers fail to have at least two ground rods either at the equipment pole or interconnected through an overhead neutral wire (8). The constraint module also specifies

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ground rods to be placed along the overhead neutral wire at intervals of 400 m and at neutral termination points.

$$C_{\text{NumGnd},i} = \begin{cases} 0.0 & \text{for } N_{g,i} \geq 2, \\ 1.0 & \text{for } N_{g,i} = 1, \end{cases} \tag{8}$$

where $N_{\mathrm{g},i}$ is the number of ground rods electrically interconnected to the equipment structure under investigation.

E. Final Output Reports

Once the GA process is complete and compliant and cost-optimal DOP design is achieved, final output reports are produced. The most important output report is the final staking list, which contains a list of all new and existing pole structures including pole heights, classes, deep-sets, slack spans, and structure attachments; excerpts of the final staking list are shown in Figures 11–15. A material list loading file is also generated, which can be directly loaded into the DFO's material management software. Finally, a series of calculation reports and a summary text file are generated, which fully justify all individual pole and span calculations from the PoleCheck, ClearanceCalc and FloaterCheck constraint modules to assist with engineering validation of the design.

IV. Hyper-Parameter Search Results

Population size, cross-over rate, and mutation rates used in the GA optimization process are determined by means of a hyper-parameter search. The hyper-parameter search is run on three separate DOP designs of varying sizes and complexity. Mutation rate and crossover rate ranges are determined based on the findings from Patil and Pawar [24] and range from 0.001 to 0.5 and 0.6 to 0.95, respectively . Population sizes range from 20 to 5,120 for the 9 and 17 pole DOP design cases and from 20 to 15,360 for the 32 pole case. These ranges are based on empirical observations indicating that very large population sizes result in better GA performance, especially for larger DOP designs. Approximately 10 samples are explored within the range of each investigated hyper-parameter. Table 1 lists the best-performing combination of hyper-parameters for each of the test cases.

Note that the population sizes identified in Table 1 represent the minimum population sizes for which optimal material and construction labour costs are attained. Due to the non-deterministic nature of GA optimization, larger population sizes than those shown are often selected for use in the evaluation to ensure that optimal results are more consistently achieved.

V. Evaluation of AutoDesigner

The evaluation of AutoDesigner is performed using five sample DOP designs of varying complexity. The performance of AutoDesigner for each evaluation case is compared against human-created designs in terms of the overall construction labour and material costs, design errors contained in the design, and nonoptimal design decisions within each design that may not reach the threshold of being considered an error. Table II indicates the relative percent difference in material and construction labour costs between the AutoDesigner output and the human-created design, as well as the number of design errors and nonoptimal design decisions made by both AutoDesigner and the human designer for each evaluation case. Table III illustrates the benefit of AutoDesigner's use of constraint module memory for the first evaluation case in addition to listing the total computation time for case 3. Finally, Figures 11 to 15 illustrate some noteworthy design decisions made by AutoDesigner that are not typically found in human-created designs.

TABLE I
A Summary of the Hyperparameter Tuning Results

Design configuration	Hyperparameter values that lead to the best performing designs		
	Population size	Crossover rate	Mutation rate
[9/3/N]	320	0.8	0.03
[17/3/R]	640	0.8	0.005
[32/3/N]	10240	0.75	0.025

Design configurations are described in terms of their complexity [number of poles / number of phases / New extension OR Re-build].

TABLE II
A Comparison of Evaluation Case Outputs from AutoDesigner and Human-Created Designs

Test Case	Cost	# of design errors		# of non-optimal designs	
		Human	AutoDesigner	Human	AutoDesigner
1 [10/3/N]	4.23 %	1	0	0	0
2 [15/3/N]	-4.35 %	1	0	0	0
3 [39/3/N]	0.208%	0	0	3	2
4 [9/1/N]	-0.927%	4	0	0	3
5 [25/3/R]	0.306%	0	0	1	0

Test cases are numbered (1-5) and their complexity described in terms of [number of poles / number of phases / New extension OR Re-build]. Cost describes the construction labour and material cost as percent difference of AutoDesigner cost with respect to human-created design cost. Numbers of design errors and non-optimal design decisions/borderline errors are compared for DOP designs created by a human designer and AutoDesigner.

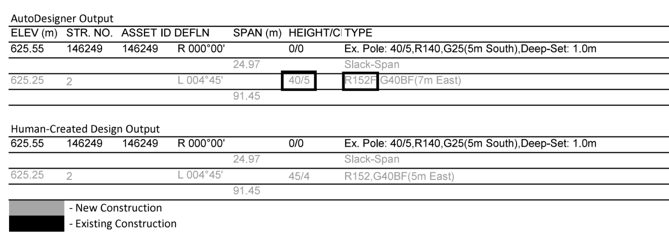

Fig. 11. Sample of AutoDesigner Utilizing Single Phase Flat-Spacing to Enable Shorter Pole Height at New Structure Location in Evaluation Case 4

During optimizing the five evaluation cases, AutoDesigner demonstrates its ability to make numerous design decisions that are not common for human designers. In evaluation case 4, AutoDesigner makes rigorous use of flat spaced structure configurations that bring the neutral wire up to the same attachment height as the single phase wire to avoid using higher and more costly poles. Furthermore, in case 5, AutoDesigner uses

TABLE III
Computation Time with Constraint Module Memory Functionality Turned On versus Constraint Module Memory Turned Off.

Evaluation Case	Computation Time with Constraint Module Memory Turned On	Computation Time with Constraint Module Memory Turned Off
1	1 Minute	13 Minutes
3	170 Minutes	N/A (case not investigated)

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AutoDesigner Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
3 x 1/0 ACSR Raven OVERHEAD - MEDIUM						
				100.47		
796.45	4		R 090°00'		45/3	N32(S<L),G40AF(7m North),Deep-Set: 1.0m
				23.93		Slack-Span As-Built RD ___ m at ___ °C 4 m from STR#4 As-Built RD ___ m at ___ °C 9 m from STR#4 As-Built RD ___ m at ___ °C 13 m from STR#4
797.61	104		L 090°01'		40/4	N32(S<L),G40AF(7m South),Deep-Set: 1.0m
				55.55		

Human-Created Design Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
				100.47		
796.45	4		R 090°00'		45/4	N32,G40BF(7m North),Deep-Set: 1.0m
				23.93		Slack-Span As-Built RD ___ m at ___ °C 4 m from STR#4 As-Built RD ___ m at ___ °C 9 m from STR#4 As-Built RD ___ m at ___ °C 13 m from STR#4
797.61	104		L 090°01'		45/4	N32,G40BF(7m South),Deep-Set: 1.0m
				55.55		

Fig. 12. Sample of AutoDesigner Utilizing Reversed Vertical Placement of Three Phase Corner Structure Cross-Arms to Allow Shorter Pole Structure Supporting Span Over Road Crossing in Evaluation Case 5

AutoDesigner Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
3 x 1/0 ACSR Raven OVERHEAD - HEAVY						
876.19	19		L 003°10'		40/3	N12H
				95.98		As-Built P/L ___ m at ___ °C 87 m from STR#19
878.86	20		R 000°00'		40/3	N12H,Deep-Set: 1.0m
				66.53		As-Built PED ___ m at ___ °C 21 m from STR#20
877.19	21		L 000°01'		40/4	N12H

Human-Created Design Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
876.19	19		L 003°10'		45/4	N12H
				95.98		As-Built P/L ___ m at ___ °C 87 m from STR#19
878.86	20		R 000°00'		40/4	N12H
				66.53		As-Built PED ___ m at ___ °C 21 m from STR#20
877.19	21		L 000°01'		45/4	N12H

Fig. 13. Sample of AutoDesigner Utilizing Pole Deep-Set to Allow Shorter Pole Structures while Not Creating Conductor Uplift at Middle Structure in Evaluation Case 3

AutoDesigner Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
3 x 1/0 ACSR Raven OVERHEAD - HEAVY						
664.76	1		L 000°16'		45/3	N12,N55,G40AF(7m East)
				96.43		As-Built RD ___ m at ___ °C 5 m from STR#1 As-Built RD ___ m at ___ °C 8 m from STR#1 As-Built RD ___ m at ___ °C 12 m from STR#1 As-Built AG ___ m at ___ °C 68 m from STR#1 As-Built AG ___ m at ___ °C 82 m from STR#1
665.16	2		L 000°00'		40/3	N12H

Human-Created Design

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
664.76	1		L 000°16'		45/2	N12,N55,G50AF(7m East)
				96.43		As-Built RD ___ m at ___ °C 5 m from STR#1 As-Built RD ___ m at ___ °C 8 m from STR#1 As-Built RD ___ m at ___ °C 12 m from STR#1 As-Built AG ___ m at ___ °C 68 m from STR#1 As-Built AG ___ m at ___ °C 82 m from STR#1
665.16	2		L 000°00'		45/3	N12H

Fig. 14. A sample of AutoDesigner utilizing a precise application of ClearanceCalc to meet minimum required clearances with a shorter pole as opposed to the human designers decision to use a taller pole to save on computational effort in Evaluation Case 1.

AutoDesigner Output

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
3 x 1/0 ACSR Raven OVERHEAD - HEAVY						
1019.42	2		L 000°00'		40/4	N12H
				54.67		
1016.25	3		R 090°00'		40/3	N32,G50AFF(8m NE),Deep-Set: 1.0m
				7.00		Slack-Span
1016.36	4		L 090°00'		40/3	N32,G50AFF(8m SW),Deep-Set: 1.0m
				55.20		
1014.81	5		R 090°00'		40/3	N32,G50AFF(8m NE),Deep-Set: 1.0m
				33.21		Slack-Span
1015.15	6		L 046°18'		40/5	N42,N55,Deep-Set: 1.0m
				13.81		Slack-Span
1015.43	7		L 046°18'		40/3	N42,N55,G50AFF(8m SW),Deep-Set: 1.0m

Human-Created Design

ELEV (m)	STR. NO.	ASSET ID	DEFLN	SPAN (m)	HEIGHT/C	TYPE
1019.42	2		L 000°00'		45/5	N12H
				54.67		
1016.25	3		R 090°00'		45/4	N32,G50AFF(8m NE),Deep-Set: 1.0m
				7.00		Slack-Span
1016.36	4		L 090°00'		45/4	N32,G50AFF(8m SW),Deep-Set: 1.0m
				55.20		
1014.81	5		R 090°00'		45/4	N32,G50AFF(8m NE),G50AFF(8m NW)
				33.21		
1015.15	6		L 046°18'		45/4	N42,N55(S<L),G50AF(8m SE), Deep-Set: 1.0m
				13.81		Slack-Span
1015.43	7		L 046°18'		45/4	N42,N55,G50AFF(8m SW),Deep-Set: 1.0m

Fig. 15. Additional example of AutoDesigner utilizing precise ClearanceCalc calculations to select minimum acceptable pole height instead of the human designers decision to select uniformly taller poles due to ease computational fatigue Evaluation Case 2.

a reversed cross-arm arrangement on two corner structures to boost the conductor clearance over a roadway, allowing shorter poles to be used. Finally, AutoDesigner regularly uses pole deep-sets even when no slack spans are present to avoid having to use higher poles at another location to prevent a conductor uplift condition from occurring, such as in Figure 13. Although none of these design decisions are necessarily novel and are used by designers when trying to avoid using very tall or expensive pole structures, AutoDesigner finds regular application in these design decisions – even when using standard pole heights. The reason for this may be that the marginal savings in costs afforded by these design decisions are typically not worth the additional computational effort for a human designer to devote to an investigation. Conversely, such computational effort is not a consideration for AutoDesigner, since it performs a complete design analysis on all structures. As a result, AutoDesigner applies numerous small cost savings to a DOP design, unaffected by the burden of greater computational complexity, to achieve an overall cheaper design.

VI. Conclusion

In the five evaluated cases, the proposed system has been successful at achieving the set objectives. In all cases, it proposes designs that are free from major design errors. While on a few occasions, AutoDesigner makes design decisions that are less than optimal, such as calling for superfluous double-guy strain down-hall anchors, in the fourth evaluation case, these nonoptimal decisions do not compromise the safety of the DOP design and can be easily remedied in future projects by adjusting the rule-based criteria within AutoDesigner.

Furthermore, AutoDesigner succeeds in consistently producing designs that are comparable in material and construction labour costs to those of human-created designs. Evaluation cases 1, 2 and 4 represent designs where the human designer is less experienced, while cases 3 and 5 are designs created by the DFO's most experienced design engineers. In cases 1, 2 and 4 AutoDesigner is able to produce designs that are measurably more economical than those created by the human designer (note that the lower cost of the human-created design in case 1 is only made possible by means of a significant design error). Furthermore, in evaluation cases 3 and 5, AutoDesigner is able to produce designs that are almost identical in cost to designs that are produced by the DFO's most experienced design engineers. Overall, AutoDesigner succeeds in producing very efficient DOP designs and can assist the DFO in reducing construction labour and material costs. Furthermore, while AutoDesigner is still undergoing debugging and testing, the software provides the DFO with the promise to save close to 100% of design time on new DOP designs. This is made possible by the fact that the software accepts the input survey CSV files and outputs the design documents in the exact format that is utilized by the DFO.

AutoDesigner also requires reasonable amount of computation time to produce designs, requiring 170 minutes of computation time to generate a design for the highly complex third evaluation case. Further improvements in design computation time may be realized by using multicore functionality in the generation of individuals during the GA optimization.

In conclusion, AutoDesigner succeeds in its three objectives relating to the optimization and automation of DOP design. It demonstrates numerous unique design decisions to make small, incremental reductions in construction and material costs. It provides cost-saving opportunities in material and construction labour expenses as well, providing the eventual possibility of saving close to 100% of human design time that is inherent through the use of customized design automation software fully adapted to the DFO's design practices.

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