Aeroelastic Preliminary-Design Optimization of Communication Tower Structures

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An aero-structural optimization framework is presented to derive cost-optimal designs for communication tower structures. Preliminary designs are sought given certain high-level requirements such as tower height, wind speed and antenna loading. In order to rapidly search the design space, low-order modeling is emphasized for computational efficiency. Accordingly, appropriate engineering assumptions are enforced where applicable. Simplified finite-element methods are employed to model structural behavior. Aerodynamic loading on the structure is built-up from drag coefficients that are estimated for various tower elements. Re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) is used to derive a worldwide 3-sec gust distribution for a 50 year return period. To bound the design space, optimization constraints are obtained from a commonly used design standard in the US for antenna structures: TIA-222-G. Validation results are provided comparing tower deflections with those obtained from higher-fidelity tools. Finally, a country-wide tower deployment planning case-study is illustrated utilizing this sizing approach.

I. Introduction

The demand for communications towers has notably increased in recent times on account of the rapid surge in worldwide data traffic. With the introduction of advances in wireless communication technology, such as 5G, global mobile traffic is set to grow eight times in the next four years[1]. The global telecom tower market that is currently valued at USD 39 billion is expected to reach USD 114 billion by 2026[2]. Although, much of the investment focus is trending toward smaller towers in urban areas, significant investment has also been made in rural areas. The US Department of Agriculture recently invested USD 85 million for improving internet connectivity in rural areas[3]. Such investments are expected to catalyze the rural economy and lower unemployment rates.

Innovations in tower design, construction and maintenance have a direct impact not just in accelerating the growth of the tower industry, but ultimately, on the state of worldwide connectivity. As an example, carbon-fiber is making an entrance to the steel-dominated tower industry. Edotco, a telecommunications infrastructure services company based in Asia, reported a 20% reduction in TCO when using carbon fiber for towers installed in Malaysia[4]. Innovation in tower design methods and software analysis tools is another potential means of impact. Many tower design software packages currently exist, however, the primary use-case is for detailed design and comprehensive structural analysis. Currently, no tools exist for preliminary tower design and analysis that may be useful for decision-making at the conceptual design/planning stage. In emerging markets, where specialized tower expertise (eg: tall guyed towers) may be lacking, such a tool may assist in quickly producing preliminary designs given high level requirements or to quickly check the structural integrity/capacity of existing structures. Ref. 5 notes that nearly 30% of tower failures are attributed to designs with insufficient loading capacity and another 30% due to lack of expertise in construction and maintenance. This capability will also be useful for network planning tools with the ability to rapidly trade structural capacity with deployment cost and coverage.

Tower design follows standardized procedures regulating telecom infrastructure. The TIA-222-G is an example of a widely followed standard in the US. Prior to design, the type of tower is specified. Communication towers typically found in the industry are of the following types: 1) Monopoles 2) Self-supported and 3) Guyed. Monopoles are cantilevered hollow structures that extend for heights upto 60m. Self-supported structures are lattice towers that are used for taller tower designs upto 120m. Guyed towers feature a slender mast with lateral stability provided by tensioned guy cables that are anchored to the ground. These towers are cost-effective for tall towers and sometimes extend to heights upto 500m. Both monopoles and self-supported are typically used in urban settings where land leasing costs are not cost-optimal. Guyed towers are more often used in rural areas since a large area of land may be required. In addition to tower type, height and antenna loading, classifications for structural reliability/hazards and terrain (to account for wind exposure) would also need to be specified for design. These requirements are detailed in the TIA-222-G standard [6]. A rapid-design tool is proposed that seeks to capture this process. Preliminary designs are obtained using 1) a simplified finite-element representation of the structure to model structural behavior and 2) a heuristic optimization method to minimize tower cost while satisfying design constraints. Section II details the optimization and analysis framework. Section III provides results validating the modeling approach with higher-fidelity tools, sample optimization results and an application case-study for optimizing a country-wide network deployment.

II. Optimization and Analysis Framework

The optimization framework is illustrated in Fig. 1. Frame3DD[7], an open-source software for static and dynamic analysis of 3D truss structures, is used to build a finite-element representation of the tower structure. The mast is modeled as an interconnected lattice structure or an equivalent slender-beam. The axial, bending and torsional stiffnesses of this equivalent beam are provided in Section A for various bracing patterns. Aerodynamic loading on the structure is developed based on TIA-222-G standards for communication structures. Local wind speeds are estimated from a worldwide wind model using extreme value distribution statistics. The tower structure is first built-up using a set of macro design variables such as face width, bracing angle, etc. Frame3DD returns with an estimate of the structural response in terms of distributed stresses and deflections.

To size the tower given design constraints, MIDACO[8], an optimization routine based on the ant colony optimization method is used to derive minimum cost designs. With user-defined material costs (steel and concrete) and the material weight computed using Frame3DD, the total cost of the tower is estimated which is then provided to the optimizer as an objective. Constraints including material failure, buckling limits, guy slack, etc. are sent to the optimizer as constraints. The input variables are mixed continuous-discrete in nature (width of monopole, no. of guy levels, etc). Accordingly, heuristics-based optimization algorithms targeted at mixed-integer nonlinear optimization (MINLP) problems are considered for this purpose.

The flow of data is described as follows: High-level design parameters such as tower height, tower type and windspeed are fixed by the user as a set of requirements. Based on guess design variables (no. of guy levels, leg sizes, etc) determined by MIDACO, Frame3DD returns with the tower cost and a set of structural constraints related to failure criteria and stiffness requirements. Based on the objective and constraints, the final optimized design is produced. This procedure is therefore useful to quickly determine the tower costs for business modeling purposes for varying requirements (tower height, location, etc).

A. Modeling: Structures

As aforementioned, the structure is modeled using a simplified finite-element method. The user is provided the option to model the entire structure as a truss network or to model the mast with equivalent beam elements. Typically, monopole structures are modeled using beam elements, self-supported with a full truss network and tall guyed towers using the equivalent beam method.

Modeling monopoles and self-supported structures using Frame3DD is straight-forward. This involves building up the geometry, defining elements, connections and element properties. However, modeling guyed towers involve significant complexity. The slenderness of the structure along with the significant flexibility makes them inherently sensitive to dynamic external excitation such as wind turbulence. In addition, the

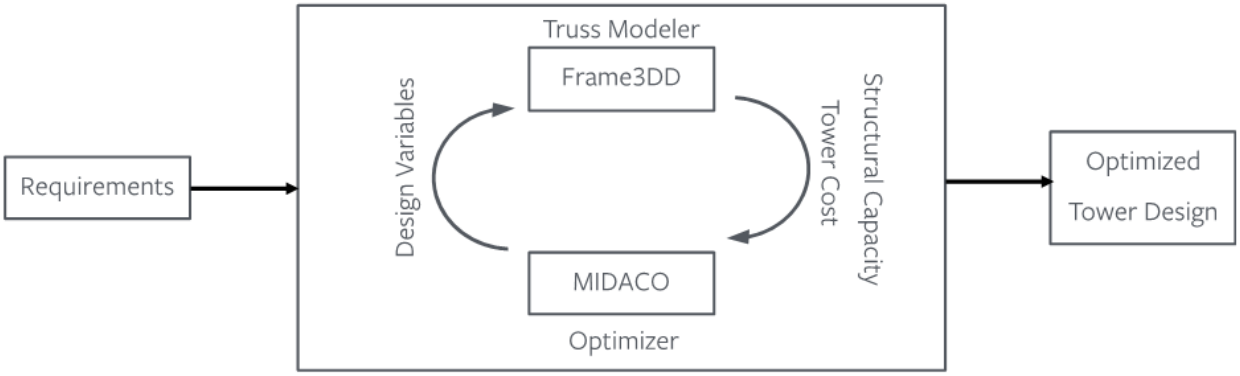

Figure 1. Optimization Framework

guy cable sag due to self-weight lends itself to nonlinear behavior under normal service conditions. Guyed towers also manifest dynamic aeroelastic behavior such as aeolian vibrations (high-frequency, low-amplitude oscillations) due to vortex shedding and galloping (large-amplitude, low-frequency oscillations)[9].

A typical analysis of a guyed tower involves a large degree of freedom finite-element representation of the truss mast and guy cables taking into account nonlinear behavior. A complex structural model implies a detailed tower representation as an input. The design process therefore is time-consuming with many variables and requires engineering judgment to produce cost-optimized tower designs. Low-order representations of the tower behavior are sought to simplify the design process for rapid design validation and cost analysis.

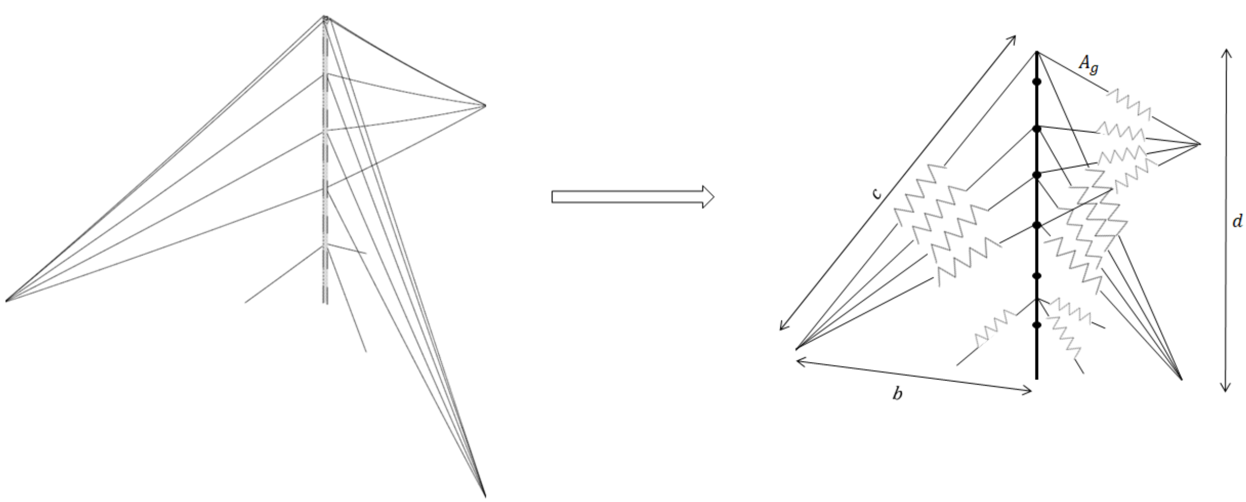

Figure 2. Low-Order Representation: Truss Network of Mast idealized as Equivalent Beam Elements, Guy Cables idealized as Equivalent 3D springs

A full-order analysis for the truss involves idealizing every truss member (vertical, horizontal, diagonal) as beam elements. As a simplification, owing to the slenderness of the mast, the truss as a composite may be idealized using equivalent beam elements. The number of beam elements should be large enough to accommodate property variations in the mast. Typically, around 10 beam elements between guy levels are

Equivalent Property	Pattern 1	Pattern 2	Pattern 3
EA	$3EA_c$	$3EA_c$	$3E\left(A_c + \frac{2A_sA_d\cos^3(\theta)}{A_s + 2A_d\sin^3(\theta)}\right)$
EI_x, EI_y	$\frac{EA_c\,a^2}{2}$	$\frac{EA_c\,a^2}{2}$	$\frac{E\,a^2}{2}\left(A_c + \frac{A_sA_d\cos^3(\theta)}{2(A_s + 2A_d\sin^3(\theta))}\right)$
GA_x, GA_y	$\frac{1}{2/(3EA_d\sin^2(\theta)\cos(\theta) + (2\tan(\theta)/(3EA_s))}$	$\frac{3EA_d\sin^2(\theta)\cos(\theta)}{2}$	$\frac{3EA_d\sin^2(\theta)\cos(\theta)}{2}$
GJ	$\frac{1}{(4/(Ea^2))(1/(A_c\tan^2(\theta))) + 1/(A_d\sin^2(\theta)\cos(\theta)) + \tan(\theta)/A_s}$	$\frac{Ea^2A_d\sin^2(\theta)\cos(\theta)}{2}$	$\frac{Ea^2A_d\sin^2(\theta)\cos(\theta)}{2}$
Wind Area per Unit Length	$\left(3\frac{\sqrt{3}}{4}\tan(\theta)\right)D_s + \left(\cos^2(\theta) + \frac{2}{\cos(\theta)}\left(1 - \frac{1}{4}\sin^2(\theta)\right)^{3/2}\right)D_d + 3D_c$	$2\left(\cos^2(\theta) + \frac{2}{\cos(\theta)}\left(1 - \frac{1}{4}\sin^2(\theta)\right)^{3/2}\right)D_d + 3D_c$	$\left(3\frac{\sqrt{3}}{4}\tan(\theta)\right)D_s + \left(\cos^2(\theta) + \frac{2}{\cos(\theta)}\left(1 - \frac{1}{4}\sin^2(\theta)\right)^{3/2}\right)D_d + 3D_c$

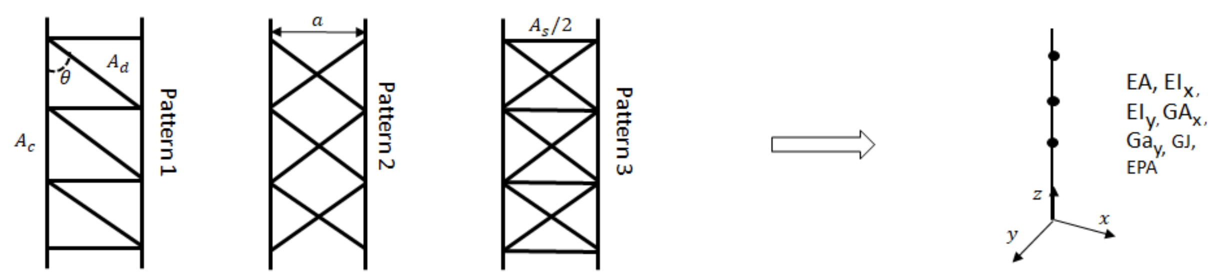

Figure 3. Equivalent Beam Method for Triangular Slender Masts[10]

considered adequate. Depending on the bracing pattern of the mast (shown in Fig.3), equivalent properties of the substitute beam may be derived. Shown in the table is the equivalent axial stiffness (EA), bending stiffness (EI), shear stiffness (GA) and torsional stiffness (GJ). In Frame3DD, given material properties for steel: E,G, the beam elements are modeled as truss links with areas and inertias computed from the equivalent stiffnesses: EA, EI, GA and GJ.

In a similar manner, the guy cables may be idealized as linear springs (see Fig. 2). An expression for the cable stiffness considering cable geometry, self-weight and initial pre-tension (T_P) is provided as follows[11]:

$$EA_{eq} = \frac{EA_g}{1 + (mgb/T_P)^2 \frac{EA_g}{12Tp}} \tag{1}$$

where b is the distance of the ground attachment point from the mast, A_g is the guy cross-sectional area and mg is the weight per unit length. This expression is accurate for low in-service loads compared to the pre-tension forces. Similar to idealization of beam elements in Frame3DD, with modulus, E, known, cross-sectional areas can be computed for the truss link. For multiple cables at the same attachment points (at mast and ground), the computed areas are appropriately scaled.

The tension (T) in the cables is given by:

$$T = T_P + EA\frac{u}{c} \tag{2}$$

where u is the linear displacement at the mast attachment point and c is the length of the cable. The calculated tension is necessary to evaluate cable failure or slack. The vertical download due to cable initial-tension is given by:

$$T = T_P\frac{d}{c} \tag{3}$$

Vertical dead loads (gravity, downward load due to initial cable tension) are applied as vertical axial loads at different mast elevations. Forces due to wind are applied as horizontal shearing loads on the mast. A pinned boundary condition is enforced at the mast bottom.

A finite-element representation is constructed (equivalent beam elements for mast and spring elements for cables) in Frame3DD and with the applied dead and wind loading, the system of equations is solved for to obtain internal reactions and displacements. Given internal loads developed in the mast (idealized as an equivalent beam), member stresses are then estimated.

Vertical members are assumed to carry compression loading due to downloads and bending moments. For the vertical leg members, axial stress is computed as follows using mast axial and bending moment loads[11]:

$$F_{leg} = \frac{1}{3}F_{mast_{AX}} + F_{mast_{BM}}\frac{2}{\sqrt{3}a} \tag{4}$$

Bracing members are assumed to carry shearing loads. With shearing loads, F_x, F_y and torsional moments M_z, F_1, F_2 and F_3 are calculated assuming static equilibrium(see Fig. 4)[12]:

$$F_1 = \frac{2M_z}{\sqrt{3}a} + \frac{2}{3}F_y \tag{5}$$

$$F_2 = \frac{2M_z}{\sqrt{3}a} - \frac{F_y}{3} + \frac{F_x}{2\sin(60\,\mathrm{deg})} \tag{6}$$

$$F_3 = \frac{2M_z}{\sqrt{3}a} - \frac{F_y}{3} - \frac{F_x}{2\sin(60\,\mathrm{deg})} \tag{7}$$

The TIA standard specifies procedures to estimate allowable member strengths from material yield strengths in order to evaluate member failure for calculated internal loads.

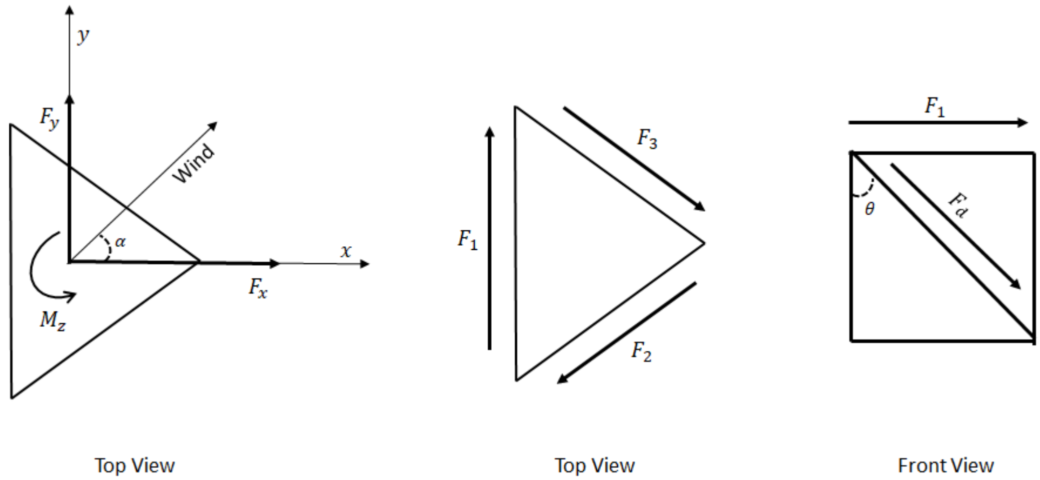

Figure 4. Stress recovery in Members given Mast Loads [12]

B. Modeling: Aerodynamics

The wind model utilized to determine applied loads follows the method outlined in TIA-222-G. To specify aerodynamic loading on the structure, dynamic pressure, aerodynamic coefficients and area of obstruction are required. The dynamic pressure (or equivalently wind speed) is a function of geography and altitude. ASCE prescribes design wind speeds in terms of maximum 3-second gusts at 10m height above ground level. Wind speed data with this specification (3-second gusts) is available worldwide (given lat/long) from the European Centre for Medium Range Weather Forecasts (ECMWF)[13]. Wind data is taken for a period of 20 years at 2 hr intervals.

50 year returns are calculated using extreme value statistics as follows[14]. First, maximum annual wind speeds in miles per hour is estimated and sorted (lowest to highest). A linear fit is now found between $x = -ln(-ln(Pv))$ and the sorted windspeeds, y, such that

$$y = \alpha x + \beta \tag{8}$$

where,

$$P_v = \frac{m - 0.44}{N + 0.12} \tag{9}$$

and m is the one-based index of the sorted windspeed distribution and N is the total number of annual observations. For a return period of R (typically, 50 years), the design speed over the return interval is calculated as:

$$V_{max} = \alpha(-ln(-ln(1 - 1/R))) + \beta \tag{10}$$

Aerodynamic coefficients for the antennas and guy cables are found in TIA-222-G. Aerodynamic coefficients are dependent on the shape of the obstruction and wind direction. Tables are provided in the standard for various antenna shapes indexed with wind direction to determine loading. Such coefficients may also be derived for the mast structure depending on the bracing pattern as shown in Fig. 3 for a drag coefficient of one for individual members (legs and bracing)[10]. Here, only round members are considered, i.e., steel pipes or solid rods. A drag coefficient of 1.2 is accordingly assumed. Note that for round mast members, wind direction does not significantly change the resultant wind load.

In addition to aerodynamic coefficients, the TIA standard specifies several load factors to account for reliability and terrain. The structure class criteria specifies load factors for varying degrees of hazard to property in case of structural failure. The exposure category adjusts wind loading to account for varying terrain: shorelines, open areas or urban. Wind speed variations in height are also specified in TIA-222-G depending on the local terrain profile. The wind direction probability factor accounts for uncertainty in nominal local wind directions. The gust effect factor adjusts wind loads to account for wind turbulence. This factor is dependent on the tower choice: guyed vs self-supported and tower height. Load combinations are also specified to simulate limit states. A common load combination is a 1.6 multiplier on wind loads and a 1.2 multiplier on dead loads.

C. Design Methodology

Depending on the structure type (monopoles, self-supported or guyed), certain design rules are imposed to make the search through the design space efficient. For instance, for the guyed tower, the site radius is fixed at 80% of tower height. Guy sizes are chosen such that there is minimum slack and cables are always in a state of tension. Anchor locations are chosen such that the distance from the mast equals the average attachment height of the associated guy cluster. Buckling criteria for the mast (segmented by guy levels) and leg members (segmented by bracing members) are specified per Ref. 15.

Tower Type	Design Variables	Constraints
Monopole 	1. Mast Width (continuous) 2. Mast Width Taper (continuous) 3. Wall Thickness (continuous)	1. Compression Failure 2. Max. Thickness Ratio 3. Max. Twist/Sway at Antenna Location
Self-Supported	1. Leg Diameter (discrete) 2. Bracing (Diagonals, Horizontals) Diameter (discrete) 3. Mast Width (discrete) 4. Mast Width Taper (continuous)	1. Compression Failure (leg) 2. Compression Failure (bracing) 3. Slenderness Ratio (leg) 4. Slenderness Ratio (bracing) 5. Max. Twist/Sway at Antenna Location
Guyed 	1. Number of Guy Levels (discrete) 2. Mast Width (discrete) 3. Leg Diameter (discrete) 4. Bracing (Diagonals, Horizontals) Diameter (discrete) 5. Guy Diameter (discrete) 6. Guy Initial Tension (discrete)	1. Compression Failure (leg) 2. Compression Failure (bracing) 3. Slenderness Ratio (leg) < Slenderness Ratio (mast) [15] 4. Slenderness Ratio (bracing) 5. Max. Twist/Sway at Antenna Location 6. Guy Tension Failure and Slack 7. Torque Arm Attachment near Antenna Location 8. Buckling Criteria of Mast (idealized as beam) [15]

Figure 5. Optimization Design Variables and Constraints

Constraints are taken from the TIA-222-G standard imposing limits on member slenderness ratio, member stress failure and angular displacements at antenna locations. In addition, for guyed towers, a constraint is added to ensure a torque arm with double the number of guys is present near an antenna location to augment local stiffness. Design variables are specified as continuous or discrete. Discrete variables include number of guy levels as well as member sizes to reflect their availability in standard dimensions. This is summarized in Fig. 5.

The optimization objective to be minimized is total tower cost. This includes both material and non-material costs (construction, logistics, etc). Non-material costs are scaled with tower height or applied as an overhead percentage on material costs. Unit costs for both material and non-material costs are provided by the user.

For the foundation, the pad footing is sized such that tension is prevented within the concrete block which could cause the pad to crack. This is done by checking if the shear planes pass through the lower corners of the pad strip. The shear planes are assumed to be 45 deg from the base which implies that the pad thickness will equal the pad projection (D=P, Fig. 6). The pad area is determined from the soil bearing capacity. Given the maximum download force, F_a, soil bearing capacity, σ_b, the pad area is then given by: $A_p = \frac{F_a}{\sigma_b}$. Assuming a square pad footing, the width is then determined, based on which the pad thickness is also obtained.

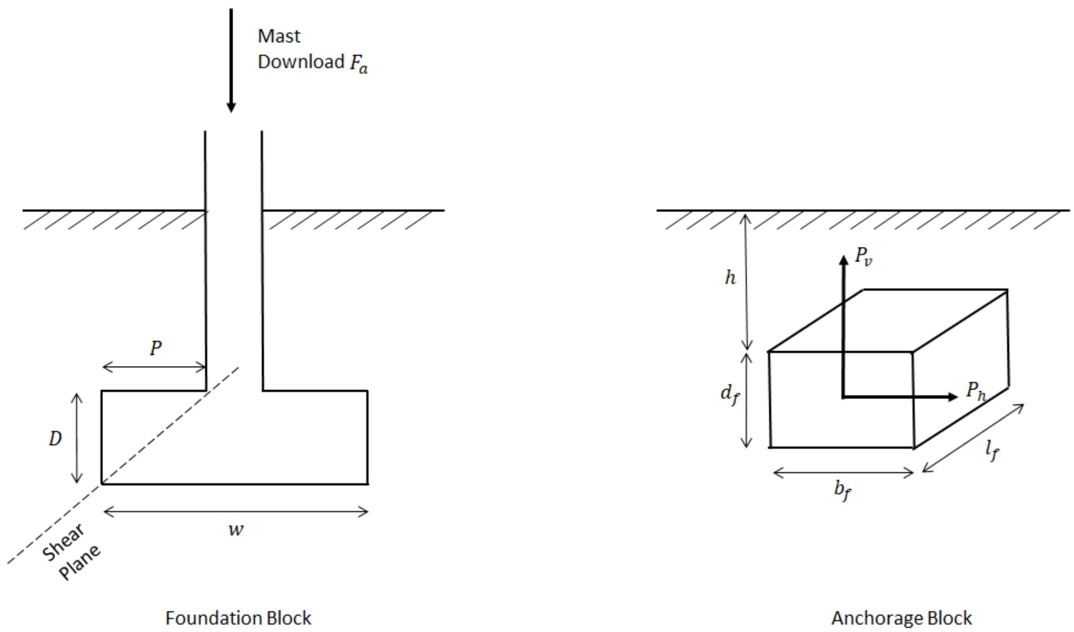

Figure 6. Foundation and Anchor Sizing

The anchor block dimensions sizes are similarly determined based on anchor reactions and soil properties using methods described in Refs. 12 and 16. The results are summarized as follows:

$$d_f = 2h\frac{\gamma_s}{\gamma_c} \tag{11}$$

$$l_f = \frac{3P_h}{k_p {d_f}^2(\gamma_s + \gamma_c)} \tag{12}$$

$$b_f = \frac{P_v}{d_f l_f \gamma_c} \tag{13}$$

where γ_s and γ_c are the densities of soil and concrete respectively. P_h and P_v are the horizontal and vertical components of the guy cable tension acting on the anchor block. In this study, the height of soil, h is assumed as 1m.

Figure 7 illustrates a web-based GUI interface that was developed for the tool to facilitate rapid trade studies. Two modes of operation are shown. In the analyze mode, the tower design specified by the user in the design tab is checked for available structural capacity. In the design mode, a new tower is designed based on user-defined requirements. The interface allows for the input of several parameters such as unit costs, material properties, local topographic and environmental conditions. Post-analysis, a structural report containing stress distributions is provided to the user.

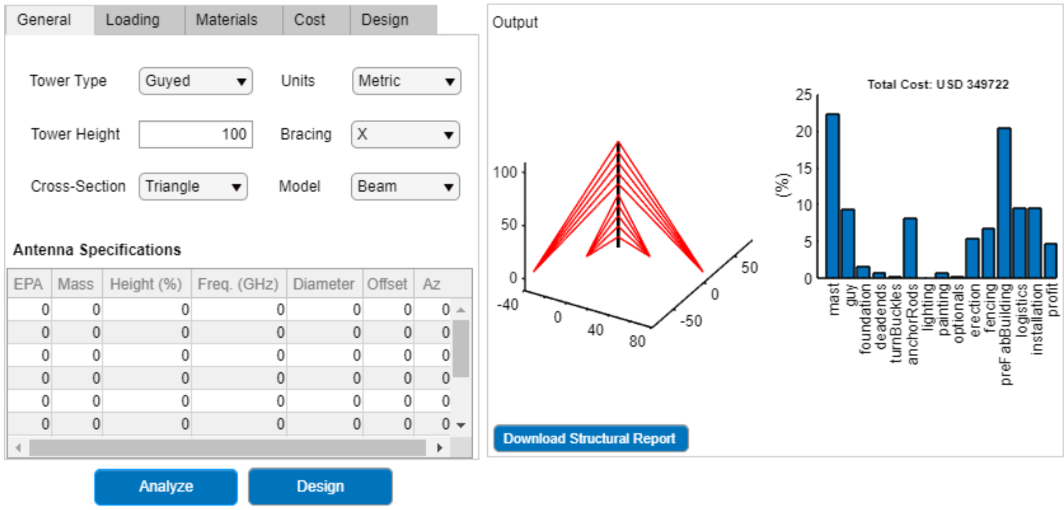

Figure 7. GUI Interface

III. Results

A. Validation

Results evaluating the accuracy of the predicted structural response are shown here. The responses were validated against tnxTower, an industry-standard tower analysis software. A standard triangular self-supported tower design with a 1.5m mast width is used as a basis for these studies. Diagonal bracing along with horizontal braces (Pattern 1) are included. The bracing angle is set at 45 deg. All bracing members are solid rods of 1 in. Leg dimensions are of standard 4.5x0.337 size. Four heights are considered: 10m, 20m, 30m and 40m. For each tower height, four windspeeds are considered: 20m/s, 30m/s, 40m/s and 50m/s. An antenna with an effective projected area (EPA) of 1 sq.m weighing 300 kg is fixed at the tower top. EPA is defined as reference area x drag coefficient, i.e., $F_{aero} = q$.EPA, where q is the dynamic pressure. Three outputs are considered for comparison: tip deflection, tip tilt angle and structural capacity.

Figure 8 shows the comparison of the tip deflection predictions of tnxTower vs Tower Planner. Tip deflections are an important measure of predicting structural stiffness. Note that the maximum error is on the order of an inch. Figure 9 shows the comparison of the tip tilt angles. Tip tilt angles are an important measure of whether constraints on 10db degradation in radio frequency signal level are violated. Note that the maximum error is on the order of 0.15 deg. Also, note that the TIA standards indicate that working with measures less than 0.25 deg is not practically feasible.

Figure 10 shows the comparison of the structural capacity estimations. Structural capacity here is defined by:

$$Structural\ Capacity = max\left(\frac{stress\ in\ member}{allowable\ stress\ for\ member}\right) \times 100 \tag{14}$$

Stresses are checked for both tension and compression failure modes. Correctly predicting structural capacity indicates that loads, stiffness and stress recovery are modeled accurately. Average prediction error is on the order of 10%. Reasons for the discrepancy include modeling differences. For instance, tnxTower includes girt members that were not included in Tower Planner. In general, predictions by Tower Planner lean toward conservative estimates and overall good agreement is observed with tnxTower.

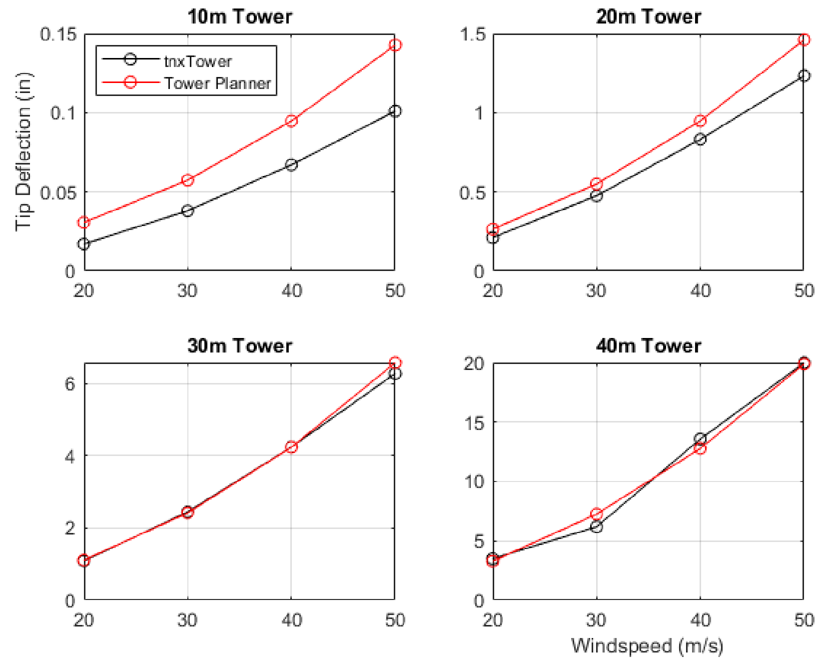

Figure 8. Validation: Self-Supported, Tip Deflection

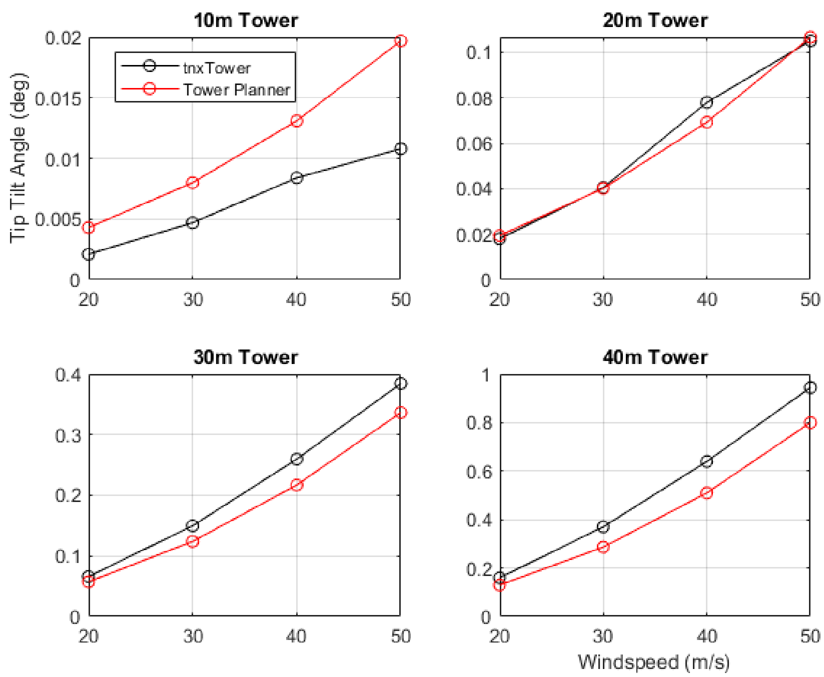

Figure 9. Validation: Self-Supported, Tip Tilt Angle

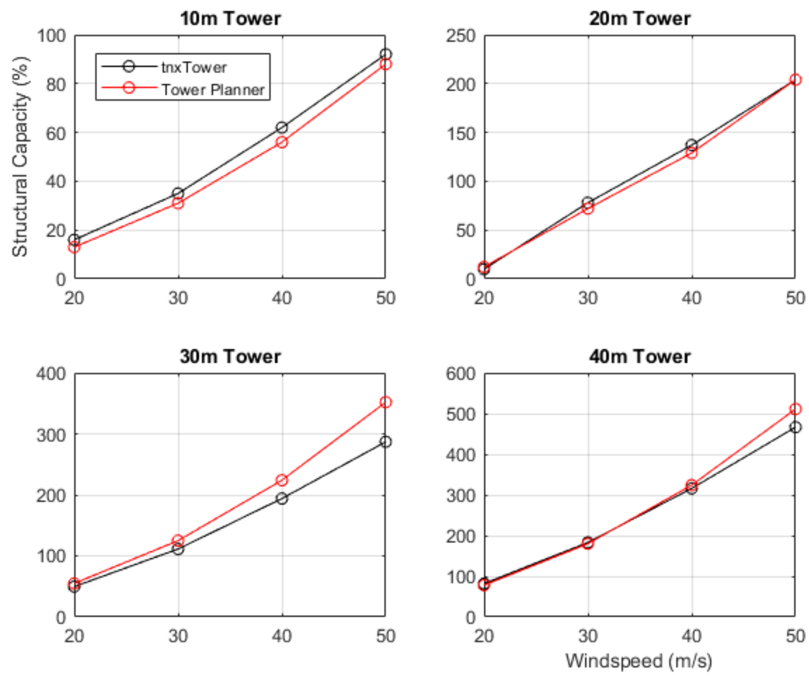

Figure 10. Validation: Self-Supported, Structural Capacity

Similar validation studies are performed for guyed towers. An 80m tower with five guy levels is considered for this purpose (see Fig. 2). The mast width is set at 1m. 6.35mm is specified for the guy and leg diameter and 1.56mm diameter is specified for the bracing. The leg member is a pipe with thickness ratio 10 and the bracing members are solid rods. Cross-bracing (Pattern 2) is utilized with a bracing angle of 45 deg. The site radius is set at 80% of tower height. Antenna loading conditions are similar to the previous self-supported case.

Recall, for guyed towers, significant simplifications are introduced, i.e., guy cables are modeled with linear springs and the truss network is modeled as an equivalent beam. Deterioration in agreement is expected as a result. Fig. 11 shows the agreement for several metrics: max. deflection, max. tower tilt, available capacity in the legs, bracing and guys for varying windspeed. Good agreement is noted for lower windspeeds. At higher windspeeds, discrepancies increase for leg and guy capacity. The maximum errors for tip deflection is on the order of 5cm. This is insignificant considering the the height of the tower (0.06%). Figure 12 shows the variation of predicted structural responses with elevation at a given wind speed. Note the trends with elevation are correctly captured for shear loads, bending moments, deflections and angular displacements. The calculation procedure in tnxTower involves a comprehensive analysis taking into account nonlinear behavior. As a result of the nonlinear guy behavior calculations are repeated until convergence is achieved. Figure 12 illustrates that the linear approach is able to satisfactorily predict structural behavior to a first-order approximation. This capability is therefore useful for preliminary structural analysis and design.

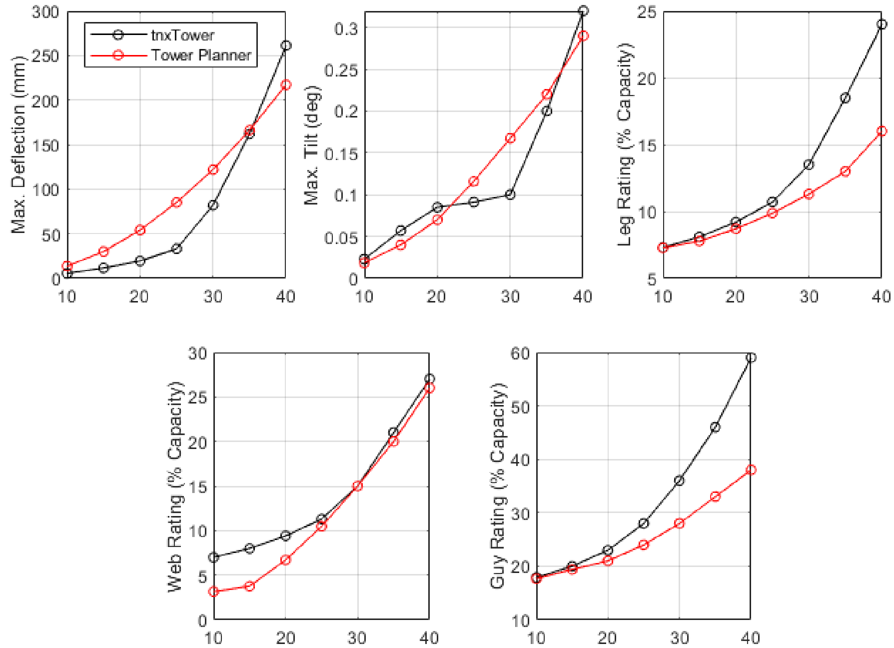

Figure 11. Validation: Guyed, Variation with Windspeed

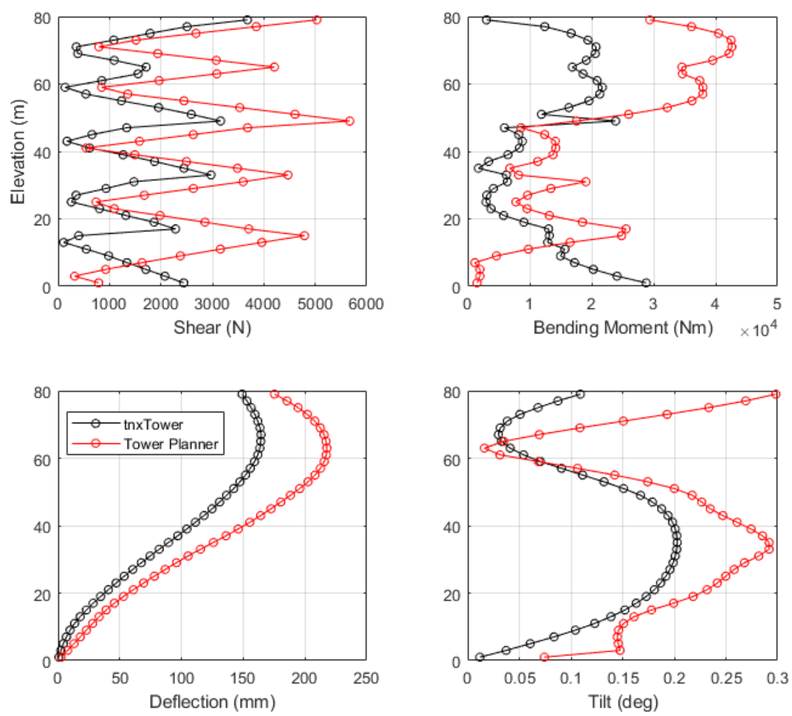

Figure 12. Validation: Guyed, Variation with elevation. Windspeed = 40m/s

B. Design Optimality

Optimality of designs produced are compared with available reference designs. For this purpose, a published catalog of designs from Rohn Tower is used [17]. The catalog specifies a design given a tower height, wind speed and antenna loading for over 200 cases. With these requirements (illustrated in Fig. 13), tower designs are generated using the optimization framework. Designs are compared using total costs as an optimality metric with the same unit material costs for both cases. This provides a measure of "closeness" of tower designs. Figure 13 demonstrates that 95% of cases are within 10% cost difference with reference designs indicating that most designs produced are near optimal per a commonly used design reference.

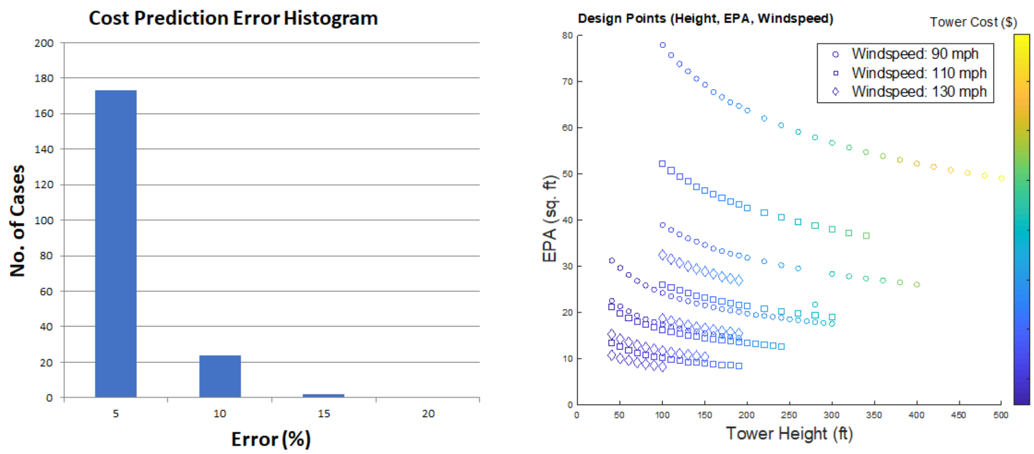

Figure 13. Design Optimality Study

C. Cost Trends

Figure 14 illustrates how tower cost varies with height for different tower types – monopole, self-supported and guyed using the optimization framework. Note that guyed towers show the least increase in cost with height. However, the costs shown here do not include costs associated with land area. Adding this contribution will reduce cost difference with self-supported towers. Nevertheless, these trends reveal the reason why most tall towers today are guyed.

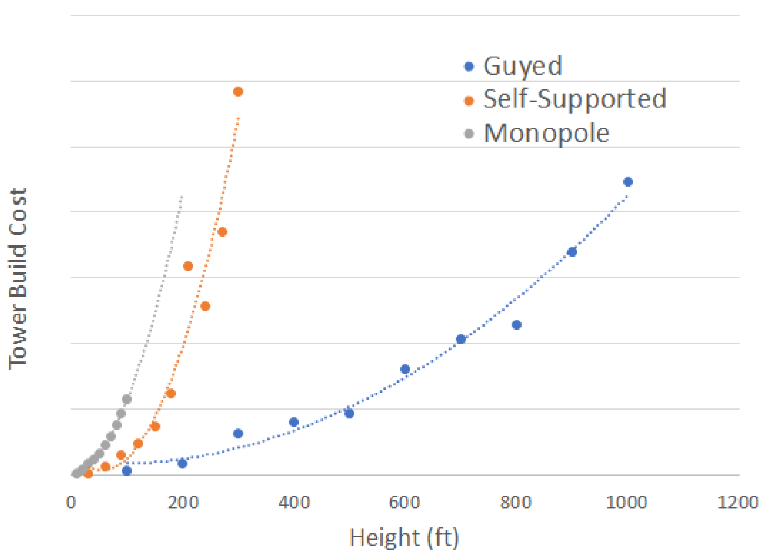

Figure 14. Cost Trends: Guyed vs Self-Supported vs Monopole

D. Application : Cell Tower Inventory Demand Forecasting

Tower companies face the problem of forecasting demand and/or optimizing their inventory – i.e. the number of various types of towers that they will need to build and supply. The suitability of a tower for any particular communication network use-case will depend on the implied cost and benefit trade-off. Put simply, taller towers are generally more expensive while also being more powerful as a communications platform, due to being better from an RF (Radio Frequency) coverage perspective. Network operators are concerned with reducing their infrastructure cost and would like to utilize towers that provide the best return on invested dollar.

The current tower cost optimization model can help with this use-case by providing insights into the distribution of cost-optimized towers across large and diverse topographies and population densities. Furthermore, this distribution can be made to depend on an end-to-end network optimization, where the benefits of tower height for line-of-sight (LOS) based microwave backhaul connectivity, in addition to RAN (Radio Access Network) coverage, are traded-off with cost.

These cost-optimized tower height (and, in general, tower type) distributions can be sliced and diced by country, market segment, etc., enabling the tower company to either maintain or be prepared to supply appropriate volumes of diverse tower stocks in different markets. As an example, in Figure 15, we illustrate the final statistics obtained after running a hypothetical country-wide greenfield network plan for a large and expanding incumbent network operator. Here, we show one cut of the statistics across the urban-rural dimension. Other similar cuts are possible based on province, existing market and device penetration, etc. This type of result can then guide the appropriate stocking of tower inventory – for e.g., if the urban build-outs are to be prioritized in upcoming roll-outs, a 50 meter tower stock would suffice to solve for 90-th percentile of the builds.

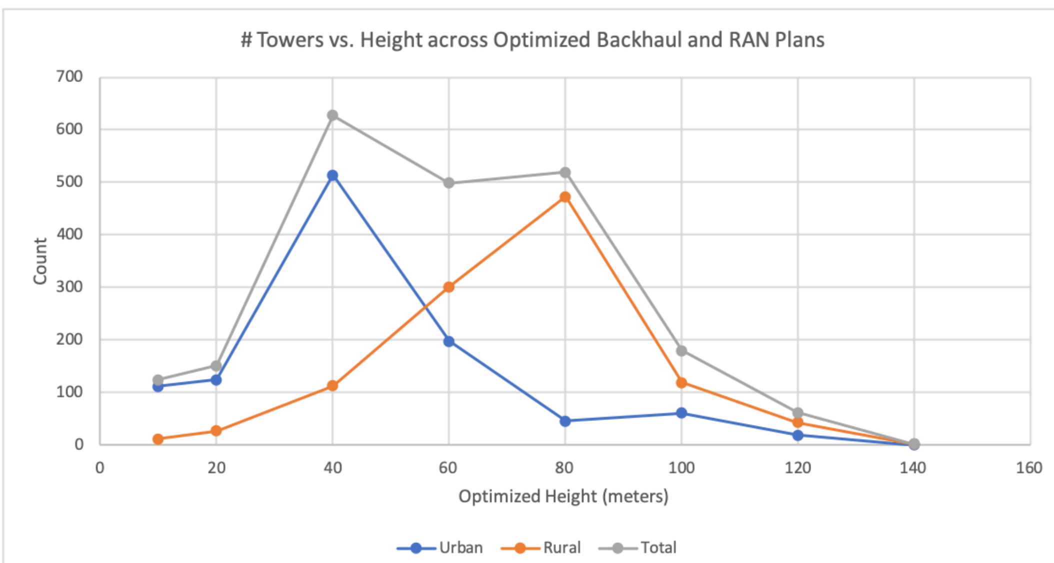

Figure 15. Optimized Tower Height Distribution

IV. Conclusion and Future Work

A computational framework for preliminary analysis and design of communication towers is presented. Computational efficiency is achieved by invoking several engineering assumptions without significantly sacrificing accuracy. Design is performed using an optimization framework that seeks to minimize tower build cost while satisfying constraints imposed by civil infrastructure design standards. The modeling procedure is compared with industry-standard, higher-fidelity tools with satisfactory agreement. Design optimality is evaluated against a commonly used design reference. Applications of this approach towards business cost modeling and network planning were explored.

Future improvements include expanding the member database to include other commonly used shapes such as steel angles. Further studies evaluating the design optimality of self-supported and monopole designs are necessary. In addition, the tool will be integrated with GIS-based capabilities to directly provide users the impact of tower design on site economic viability, site planning/logistics and LOS-based coverage.

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