Technical Notes

Technical Review of CAPRA Hurricane Vulnerability Estimation Process

Funded by:

1818 H Street NW
Washington, DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

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BACKGROUND

This technical note provides an overview for decision makers in the emergency management community who wish to build vulnerability assessments and must develop mitigation strategies and loss projections. It provides a peer-review of the advantages and challenges for the different vulnerability methodologies proposed to date, such as the current version of the ERN-Vulnerability module, and its vulnerability model.

This document has been produced by Gonzalo L. Pita, Ph.D., Senior Vulnerability and Risk Assessment Consultant, under the guidance and supervision of Fernando Ramirez-Cortés and Oscar A. Ishizawa, Senior Disaster Risk Management Specialists, as part of the Technical Notes developed under the World Bank LCR Probabilistic Risk Assessment Program (CAPRA).

Technical review by Antonio Zeballos, Senior Vulnerability and Risk Assessment Consultant.

INTRODUCTION

The hurricane-induced building damage in countries whose inventory is subjected to hurricane activity has been steadily increasing in the last decades. On the one hand, the main culprit of such damage rise is the increasing exposure in risk-prone regions, spearheaded by population moving and concentrating more wealth on the coast. On the other hand, there is no evidence indicating that the hurricane frequency and intensity will, at least, decline in the near future. Therefore the hurricane risk is expected to keep increasing.

With such a prospect, many international institutions and local government agencies have been enacting plans to analyze and reduce the risk that affects populations in order to protect human lives, protect the infrastructure and the investments, and guarantee sustainability. Measures including regulations, local ordinances, building codes, and mitigation projects have been enacted to reduce risk. Risk has been analyzed with computer simulations, sometimes called catastrophe models, to reproduce the interaction of the hurricane hazard with the building stock and its exposure, in order to estimate the effects produced upon a certain region of interest.

A vulnerability function is an analytical or empirical expression that relates the building damage to a hazard intensity measurement; these functions, used to assess the building damageability, are the basic constitutional elements of a catastrophe model. Building vulnerability assessment plays a crucial role in loss projections and mitigation strategies. Increasingly refined and accurate building vulnerability assessments are always needed. In order to develop appropriate vulnerability functions, it is important to survey the vulnerability methodologies proposed to date to be aware of the benefits and limitations of each approach. More sophisticated methodologies will render more reliable estimations of damage, and will benefit decision makers in the emergency management community.

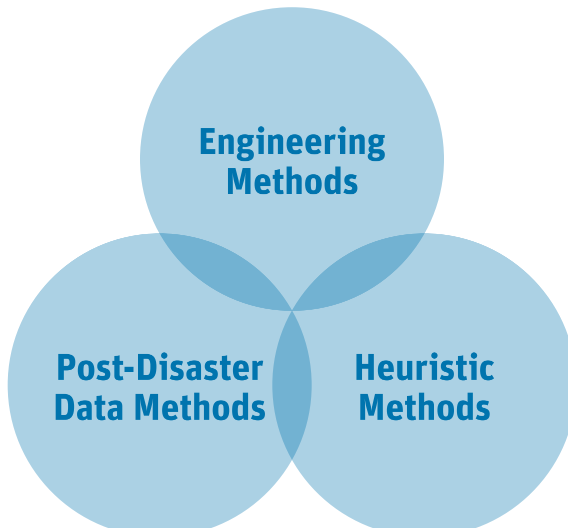
Objective and Organization of this Report

The objective of this report is to provide a peer-review of the hurricane vulnerability functions built in the CAPRA risk suite, to appraise the current user-interface, and to give suggestions for future developments. The documentation upon which this report has been based is: ERN-Vulnerability v.2.0, and *Informe Técnico* ERN-CAPRA-T1-5.

MAIN TYPES OF HURRICANE VULNERABILITY CURVES IN USE IN THE HURRICANE RISK ANALYSIS COMMUNITY

Many vulnerability estimation models have been proposed since the first were published in the early 1960's. Nowadays these models can be classified into three main groups namely: (1) post-disaster data based, (2) heuristic, and (3) engineering models (Figure 1).

Figure 1 **Classification of main hurricane vulnerability methodologies.**



The post-disaster based building vulnerability assessment methods where the first to appear and could either directly fit a curve to damage data, or also try differentiating between building types in the data by means of expert knowledge. Secondly, the heuristic models are used whenever none of the other two methods are practicable. One or many experts are asked to provide an estimate of damage probability for some predetermined wind speeds thresholds. The engineering methodologies include calculating the building damage either by standard engineering methods, or by simulations.

The coming paragraphs will succinctly mention the salient features of each vulnerability methodology, along with an appraisal of their advantages and limitations. An exhaustive and in-depth discussion of the characteristics of the vulnerability models exceeds the scope of this report, but can be found in (Pita 2012), and (Pita et al.2013b).

Post-disaster data-based methodology

In these methods the vulnerability curves are regressed against damage or claim data coming from surveys, or insurance companies respectively. Models belonging to this methodology were the first to be developed in the early 1960's, and are useful still today to government agencies, and modeling companies that have access to the availability of damage data.

While the first published models provided vulnerability curves of whole regions (e.g. counties, states), the latter models added the expertise of engineers and scientists in order to disaggregate the building types form the data, and to remove the intrinsic biases. The main advantages and challenges of this methodology include (see Pita et al. 2013a):

- **Advantages:** Simplicity and availability. Whenever it is possible to gather damage data by surveying a hurricane aftermath (in person or airplane imaging), or claim data, it is straightforward to have a ready estimate of the building stock vulnerability. If the data can be disaggregated by building type, the usefulness of the functions improves.
- **Shortcomings:** Absence of key building features information; representativeness of the data sample might be insufficient; claim data truncated because of the deductibles and limits; damage data represents the vulnerability of the past building stock; difficulty to quantify the wind speeds that caused the damage; damage data generally span a short interval of wind speeds.

Heuristic Methods

Heuristic methods were initially developed in the mid 1970's based on the opinion of experienced field engineers who provided subjective damage probabilities conditioned on hazard level. Experts in this methodology are also usually asked to assess the wind speeds that cause certain thresholds of damage based on their observations (see Table 1 for a typical damage probability matrix (DPM)). Other heuristic methods propose analytical vulnerability functions whose parameters are estimated by experts based on experience and data.

Table 1 Sample expert heuristic assessment of building vulnerability

Damage State	Hazard State of a 1-Story building in the USA			
A (17%)	0.90	0.75	0.12	0.10
B (50%)	0.10	0.18	0.65	0.20
C (83%)	0.00	0.07	0.20	0.50
D (100%)	0.00	0.00	0.03	0.20

- **Advantages:** These methods are particularly useful when damage data is unavailable, when a simulation model is in an initial stage, or when the information about the strength of building components is scarce. The heuristic vulnerability estimations might have good accuracy, depending on the expert's insight and experience.
- **Shortcomings:** The quality of the vulnerabilities is contingent upon the experts having considerable experience and data availability; even so, there is no true estimate of the uncertainty. The ability of any expert to assess the vulnerability of similar building types remains limited.

Engineering-based methods

These methods, unlike the previous, are predictive and encompass as many diverse approaches as their engineering techniques to assess damage. The two most relevant to this report perhaps are the component-based methods and the simulation-based methods.

Component-based vulnerability assessment

These methods estimate the hurricane damage of a building by (1) assessing the wind damage at each key component, and (2) tracking how damage propagates to the rest of the structure. Some tools that have been used to assess the component damage include: failure-tree analysis, and assigning fragility functions to key components and considering their interconnectedness with traditional engineering methods.

Simulation-based vulnerability assessment

Simulation methods convey the most sophisticated vulnerability functions today.

They run in a probabilistic framework built on Monte Carlo simulations that sample the resistance of the components, and compare each resistance with the wind-induced component stresses. If the loads exceed the components' capacity, the algorithm saves the damage value, and redistributes the loads. This procedure is repeated for thousands of Monte Carlo realizations, and for increasing wind speeds and varying angles of wind-attack. Later on the estimates for interior damage are included to account for the total damage ratio.

- **Advantages:**
  - Engineering methods: component-based methods are useful for a quick, evaluation of damage, as compared to simulation methods.
  - Simulation-produced present the most accurate vulnerability curves in the catastrophe modeling community today; they readily incorporate new research as it becomes available. The damage predictions of this method are based on structural analysis techniques. Besides, they can include estimates of interior damage, which, for the past-data methods, remains embedded into the input data.
- **Challenges:**
  - Engineering methods: component-based still rely on sometimes extensive expert input.
  - Simulation models are not always practicable. The computational resources, the expertise, and the time required to develop these models is significantly larger than for the previous methods. Precise strength estimates of the key components and their interconnectedness are required for the methodology to have any accuracy. These methods also rely to some extent on damage data for validating the predictions.

The advantages and challenges for each one these methods will be discussed in a section below, in the context of a continuing vulnerability assessment strategy (Table 3). The characteristics of the building inventory and the availability of damage data will lead the selection of the most appropriate mode. It is however very important when choosing a vulnerability model, that the modeler and the decision maker are aware of the advantages and limitations of each methodology and how they will affect the accuracy of the risk analysis results.

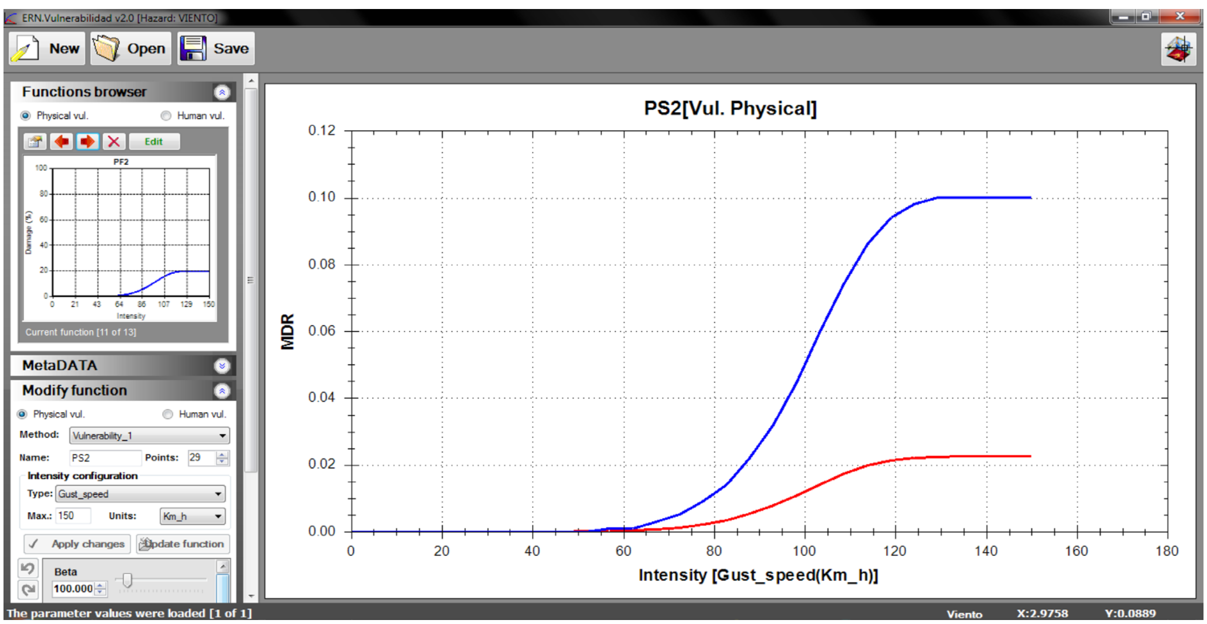
The following section details the characteristics of the current version of the ERN-Vulnerability module, and its vulnerability model.

DESCRIPTION OF THE CURRENT HURRICANE VULNERABILITY MODULE—ERN-VULNERABILITY

The CAPRA platform currently manages its vulnerability assessment framework from a twofold perspective: with a pre-defined analytical vulnerability function calibrated with expert-supplied parameters, and with a software interface called ERN-Vulnerability that allows the user to input other vulnerability functions. Specifically, ERN-Vulnerability is a tool for loading, editing, visualizing, and creating new vulnerability functions. The vulnerability functions processed with the user-interface are used in the risk analysis module to represent the building inventory hurricane damageability.

The tool currently has a library of 13 built-in vulnerability curves featuring buildings that are characteristic of Caribbean and Central America traditional construction. The user-interface consists mainly of two displays (Figure 2): a 'Modify function' dropdown menu (left) with an editable display of the governing parameters of each vulnerability function, and a display zone (right) to visualize the resulting functions. Additionally, the 'Functions browser' allows a quick view of the built-in function.

Figure 2 **Main interface of ERN-Vulnerability with vulnerability function (blue) and variance function (red) for a sample building type**

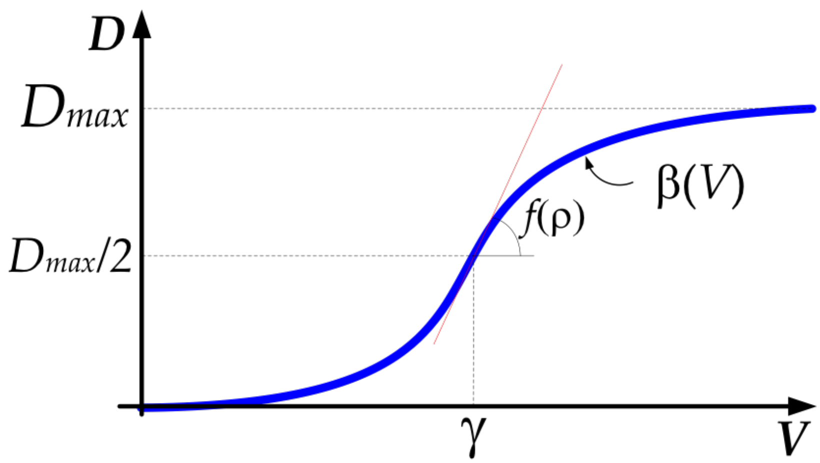


The current hurricane vulnerability curve used by CAPRA ERN-Vulnerability consists of a 3-parameter analytical model. According to the technical document ERN-CAPRA-T1-5 p. 2–17 (T1-5 hereafter) the analytical model is given by (omitting the D_{max} term):

$$ß = D_{max}\left[1 - 0.5^{\left(\frac{V}{\gamma}\right)^{\rho}}\right] \quad (1)$$

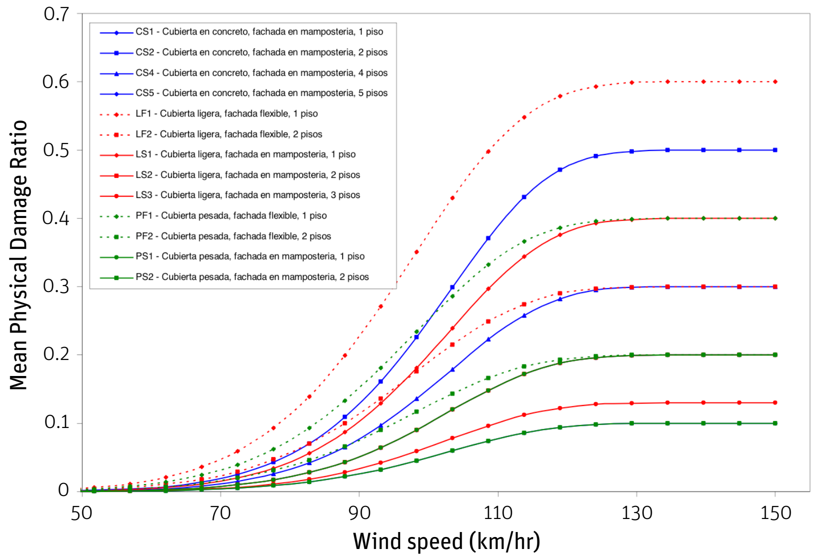
with expected physical damage ß corresponding to 5-sec gust wind speed *V* (km/hr), while γ denotes the wind speed causing half of the maximum damage (scale parameter) , and ρ denotes the steepness of the curve at γ (shape parameter) (Figure 3). The expected damage ß, or mean damage ratio (MDR), is defined as the repair building cost divided by the total building cost. The built-in function is related to a Weibull cumulative density function.

Figure 3 Parameters of the built-in vulnerability function



The 13 built-in functions in ERN-Vulnerability were built by varying the parameters in Eq. (1). Figure 4 displays all the currently available functions corresponding to the frequent building types.

Figure 4 Available functions in ERN-Vulnerability



The built-in vulnerability functions are defined by three main building components whose instances are listed in Table 2.

Table 2 Building features that define built-in vulnerability functions in ERN-Vulnerability

Roof type	Facade (envelope)	Number of stories
Concrete	Masonry	1–5
Light		
Heavy	Flexible	

In addition to displaying the vulnerability function (blue in Figure 2), ERN-Vulnerability also plots another curve (red) which affords an estimate of the variance of the damage estimates at each wind speed *V*. Document *T1-5* indicates that the variance at each wind speed has been adopted to follow a Beta distribution. The parameters for the variance curve are also defined by the user in the 'Modify Function' user-interface dropdown menu. See appendix for more details on the variance function (Beta distribution).

REVIEW OF THE CURRENT VULNERABILITY FUNCTIONS USER-INTERFACE

The ERN-Vulnerability interface is very user-friendly. The user has the complete information that defines the vulnerability function in front of him all at once. The definition of the functions based on the underlying model is uncomplicated.

The user-interface module has the useful capability of allowing the user to input vulnerability functions developed with any other methodology as the ones discussed in the previous sections. This can be done by loading .dat files.

Furthermore, the interface allows inputting the vulnerability function as tables—using the 'By_points' option—which are especially suitable for expert function assessments. The user in both cases can modify the function by clicking on the graph using the option 'By-points'.

The interface affords the useful capability to copy vulnerability and variance curves and paste it directly into Excel as column vectors.

The tool is mostly functional for working with a relatively reduced number of vulnerability functions. For larger numbers (as the ones produced by simulation techniques) the tool is still useful as a displaying interface. Alternatively, the vulnerabilities can be created in regular mathematical software and loaded into ERN-Vulnerability for comparison, modification, etc.

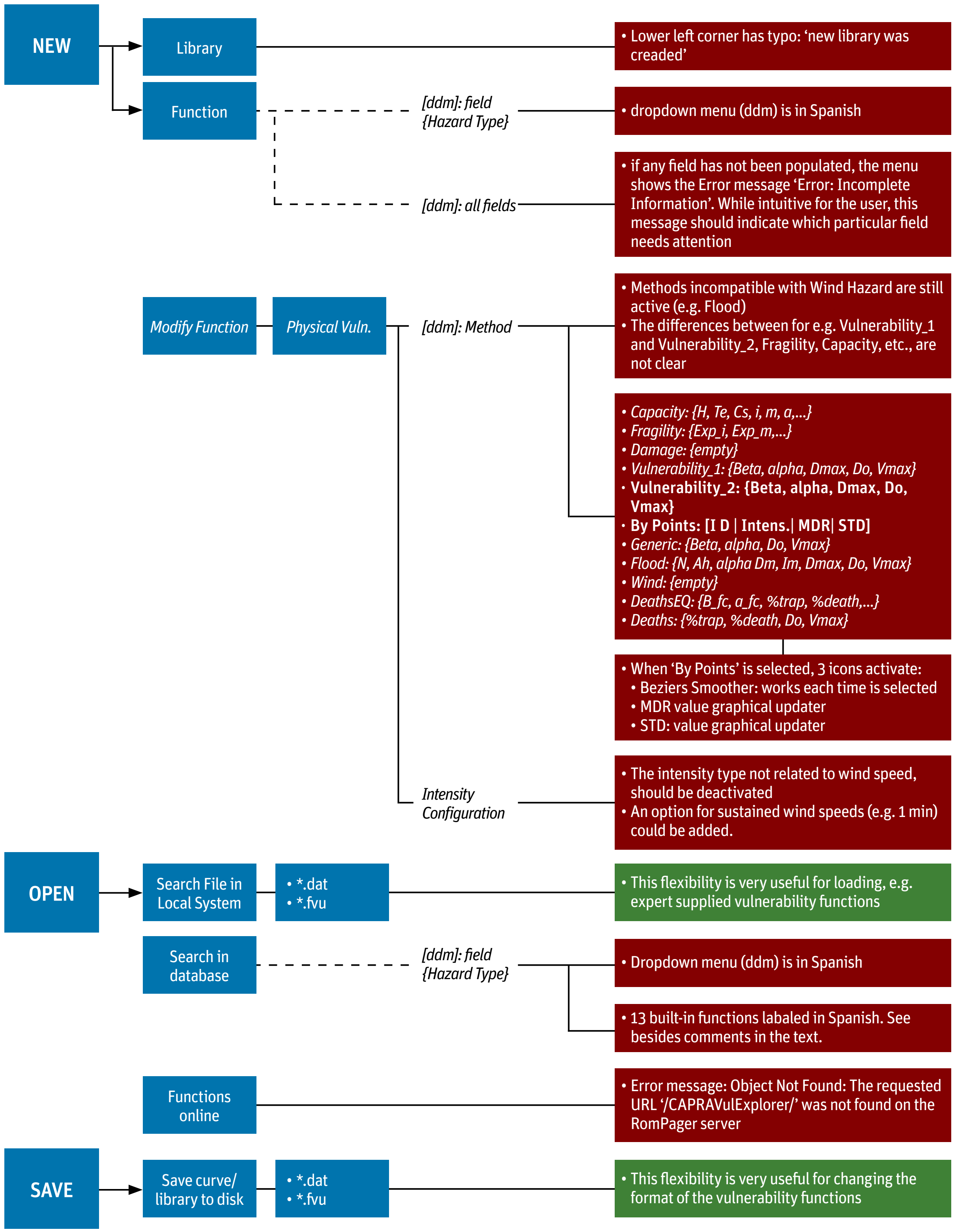
Suggestions for the user-interface

This section presents some suggestions that might enhance the user experience in ERN-Vulnerability. See also the diagram in the next page.

- The display will benefit from adding a legend to the display, and by allowing the user to define labels and fonts features.
- Consider allowing to input the user's own analytical models by defining the expression and number of parameters.
- Consider also adding an option in which the user can combine existing vulnerability functions with weighting coefficients from his experience.
- Consider adding to the user-interface the option to input damage probability matrices (DPM) in which an expert supplies probability estimates of damage for given intensity values.
- The label 'miles per hour' (mph) should be included in the dropdown menu options. Some countries in the Caribbean would benefit from it being available.
- The variable names in the user interface and the *T1-5* document differ. To avoid confusion, the terminology should be consistent between the user-interface and the User Manual.
- It might be worth considering replacing the hazard metric from 5 seconds wind gust, to 3 seconds wind gust to be in conformity with the widely adopted ASCE-7 (American Society of Civil Engineers) wind speed average time period.

- It might be helpful to display clearly in some part of the interface the analytic heuristic vulnerability functions adopted. Additional information of the background of such analytical model could also be included as a pop-up window.
  - It is very important that the user is aware of the assumptions associated with each model: for example the growth rate of the lower and upper tails of the curve. Some functions grow faster than others at lower wind speeds meaning that the integrated damage over an area will vary maybe significantly depending on the underlying function.

Some other aspects were identified that could increase the efficiency of the user-interface as shown in the following diagram:


NEW
Library
Function
[ddm]: field {Hazard Type}
[ddm]: all fields
• Lower left corner has typo: 'new library was creaded'
• dropdown menu (ddm) is in Spanish
• if any field has not been populated, the menu shows the Error message 'Error: Incomplete Information'. While intuitive for the user, this message should indicate which particular field needs attention
Modify Function
Physical Vuln.
[ddm]: Method
• Methods incompatible with Wind Hazard are still active (e.g. Flood)
• The differences between for e.g. Vulnerability_1 and Vulnerability_2, Fragility, Capacity, etc., are not clear
• Capacity: {H, Te, Cs, i, m, a,...}
• Fragility: {Exp_i, Exp_m,...}
• Damage: {empty}
• Vulnerability_1: {Beta, alpha, Dmax, Do, Vmax}
• Vulnerability_2: {Beta, alpha, Dmax, Do, Vmax}
• By Points: [I D | Intens.| MDR| STD]
• Generic: {Beta, alpha, Do, Vmax}
• Flood: {N, Ah, alpha Dm, Im, Dmax, Do, Vmax}
• Wind: {empty}
• DeathsEQ: {B_fc, a_fc, %trap, %death,...}
• Deaths: {%trap, %death, Do, Vmax}
• When 'By Points' is selected, 3 icons activate:
• Beziers Smoother: works each time is selected
• MDR value graphical updater
• STD: value graphical updater
Intensity Configuration
• The intensity type not related to wind speed, should be deactivated
• An option for sustained wind speeds (e.g. 1 min) could be added.
OPEN
Search File in Local System
• *.dat
• *.fvu
• This flexibility is very useful for loading, e.g. expert supplied vulnerability functions
Search in database
[ddm]: field {Hazard Type}
• Dropdown menu (ddm) is in Spanish
• 13 built-in functions labaled in Spanish. See besides comments in the text.
Functions online
• Error message: Object Not Found: The requested URL '/CAPRAVulExplorer/' was not found on the RomPager server
SAVE
Save curve/ library to disk
• *.dat
• *.fvu
• This flexibility is very useful for changing the format of the vulnerability functions

REVIEW OF THE CURRENT BUILT-IN VULNERABILITY FUNCTION

The analytical vulnerability model adopted in the module in ERN-Vulnerability is appealing. The model fits into two of the categories presented above. It could be heuristic if the function parameters are assessed by an expert engineer; or would be classified as past-loss data if the function is fitted to damage data surveyed from the field.

In both instances there is a twofold set of assumptions, one is explicit and directly related to the type of vulnerability methodology in use (i.e. heuristic, or post-disaster data); the other assumption is not self-evident and is related to the characteristics of the Weibull function itself and how it affects the overall risk analysis, e.g. by the rate of growth of the left tails. This latter point will be discussed in some more detail below.

For experts who might not be familiar with vulnerability functions, the structural interpretation of this particular function, unlike other alternatives, is easily accessible. Moreover, the fact that the function has few parameters allows the expert to quickly modify the curve to match his experience.

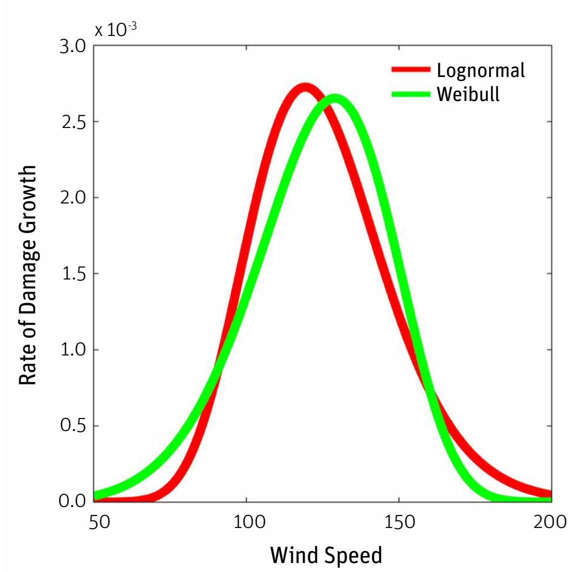
In addition, it is helpful that the model explicitly conveys the damage estimate variance. The loss estimations using only damage averages might prove misleading in risk analysis, while expressing losses as ranges might be more useful to the decision maker who thus might be able to better estimate of a utility scale.

Suggestions for the current vulnerability function

Some recommendations arising from the peer-review of the existing vulnerability model are listed below:

- It was not possible to identify in the documentation the height at which the reference wind speed is measured. Usually the measurement height is taken as 10 meters.
- The built-in hurricane vulnerability function seems to have been directly adopted from the seismic vulnerability function for buildings in the inelastic range. While there is no clear-cut set of criteria for preferring one model over another for competing vulnerability functions candidates, it might be useful to clarify the assumptions of this function. In the user-interface help or in a User Manual there might be a tutorial explaining the meaning and influence of the left and right tails growing rate, and how the selection of the underlying function influences the damage assessment outcome. Specifically for the Weibull function, its left tail grows faster than other commonly used models, such as the logistic, or the lognormal (Figure 5).

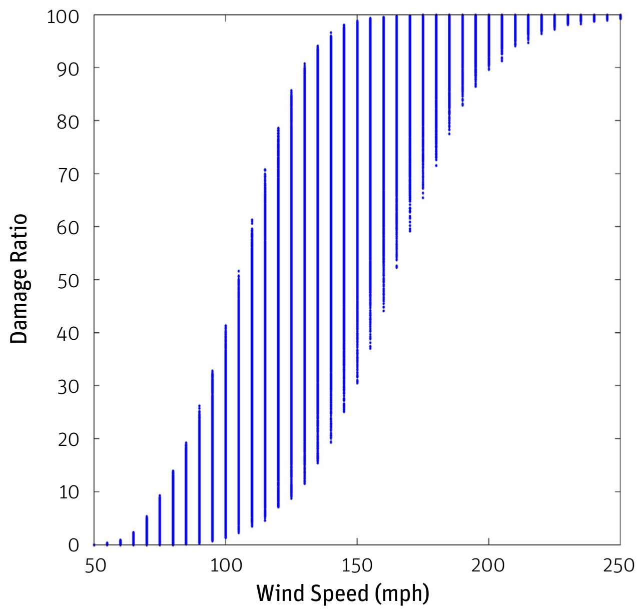
Figure 5 **Comparison of Weibull and Lognormal fitting the same cloud of damage points**



- By providing an expert with a certain function (now Weibull), an assumption is made as to the rate of growth of damage and consequently, to the geographical distribution of losses, and the expected average loss value, at the lower or higher tails. This assumption should not go unnoticed, but rather measures should be taken so that the assumptions, and their associated effects, are clear. It is important to know beforehand the properties because engineer expert might be unfamiliar with these properties of the functions.

- In regards to the variance law of the mean damage estimation (ß), it might be helpful to justify the adoption of the Beta model. In the Beta case, it is assumed that the values on the x-axis (in this case the mean damage ratio ß) is uncertain. As with any other distribution function, the Beta distribution imposes its assumptions to the damage distribution for a given wind speed and that directly impinges in the overall risk assessment. In other words, because of the skewness (to the right or the left) and dispersion (gathering around the mean), lower or higher values than the mean might prevail in a large scale analysis for thousands of buildings, thus affecting the overall average expected loss estimate. In the experience of the reviewer, it is difficult to prove that a single distribution function is able to accommodate the variability of damage around the mean for all wind speeds. The variance of the vulnerability functions (now a beta distribution) has to be appraised on a case by case basis. The user has to be aware of the options available (see Figure 6 for an example of where a single distribution might not work).

Figure 6 Example of where the distribution of damage around the mean value is not constant through the wind speed range



- It was not possible to find the data origin or any background information that justifies the selection of the building parameters for the vulnerability functions.

It might be interesting to provide a tutorial in a User Manual, on how these values are to be defined.

- It was not possible to find the justification that the vulnerability functions reach for maximum damage values sometimes well below 100% for high wind speeds. It is noteworthy that in US buildings, the interior and contents value of a building frequently exceed the value of the structure and envelope. Interior damage is mostly caused by water intrusion into the building after the openings have been breached. If buildings in Central America or the Caribbean, share a similar distribution of interior to exterior damage ratio, then interior damage might drive the losses up. More background information would be beneficial to clarify the adoption of these maximum damages values.

- Some of the built-in vulnerability functions are identical (i.e. CS1 ≡ PS2; CS5 ≡ LS2 ≡ PS1). It is necessary to check if this is an involuntary oversight or some justification can be provided.

- Likewise the previous point, some vulnerability functions cross with other functions (i.e. CS2/PF1; CS4/PF2; LS1/LF2). It might be necessary to check the validity of this behavior, i.e. that these buildings are more (less) vulnerable and then less (more) vulnerable after a certain wind speed.

The vulnerability functions are defined in Spanish, and are labeled using structural jargon that might not be unequivocal in some countries. Thus, the structural terminology designates roof structure instances as heavy (pesada) or light (ligera). Likewise, the designation of the envelope (fachada) as flexible should be updated.

- In the User Manual the vulnerability section should contain all the definitions and assumptions related to the vulnerability functions.

Some suggestions are presented herein for future updates of the ERN-Vulnerability module. These suggestions aim at representing the building inventory more accurately in kind and degree of features.

- Evaluate expanding the current pool of available of vulnerabilities. A survey of the region or country of interest will single out buildings types that might justify being included as a built-in function in ERN-Vulnerability.
- Provide vulnerability curves with further resolution, i.e. specifying the degree of strength (e.g. weak, medium, and strong) as a proxy to building age, construction quality, building code version (if any), and building regulation enforcement.
- It might also be useful to specify the base area of the buildings represented by the vulnerability functions.
- The surroundings of the buildings described by the vulnerability functions should be specified. Categories might include downtown, suburban, and open field. This designation is intended to specify whether the buildings are in risk of being damaged by flying debris, or also, if they might benefit from the shielding effect (or not) provided by neighboring constructions that reduce the wind gusts; or conversely if the building lay unprotected in the open field where the wind speed is maximum.

The level of detail and effort implied in some of the above suggestions might prove to be unattainable in situations when the structural information to model buildings, or even to select the proper vulnerability curve, is scarce or even absent. That fact must not prevent them being at least mentioned in this peer-review, since at the least it reminds the user about the uncertainties involved in the vulnerability estimation process.

POSSIBLE STRATEGIES FOR A CONTINUING VULNERABILITY ASSESSMENT FRAMEWORK

This section presents some thoughts about possible strategies for a continued effort to assess building vulnerability. Some ideas for discussion arise from the peer-review provided of what is currently available and the next steps as envisioned by the CAPRA developers.

CAPRA stands in a twofold role in regards to the development of a continuing vulnerability assessment: either as a 'provider' of a risk-analysis tool or as a 'user' of that same tool. The priorities and prospects for building strategies to further improve the vulnerability assessment depend on the perspective of the user.

As a 'provider', the relevant question is: *what tools, capabilities, and background knowledge is CAPRA willing to provide the user with in order to obtain sound and reliable risk estimates?*

This question involves matters of generality or specificity of what the vulnerability framework will be designed to offer. Among other issues:

- appraising the potential risk scenarios that a generic user might face;
- once the above are identified, decide on the cost/benefit ratio involved in developing specific vulnerability functions vs. the benefit that the user is going to get in the quality of his risk analyses.
- Furthermore, what will be left to the generic user to input, and what will be provided by the CAPRA tool. What amounts of expertise time is CAPRA willing to provide to the 'generic user' in the form of training, assistance to develop appropriate vulnerability functions, and other forms of guidance?

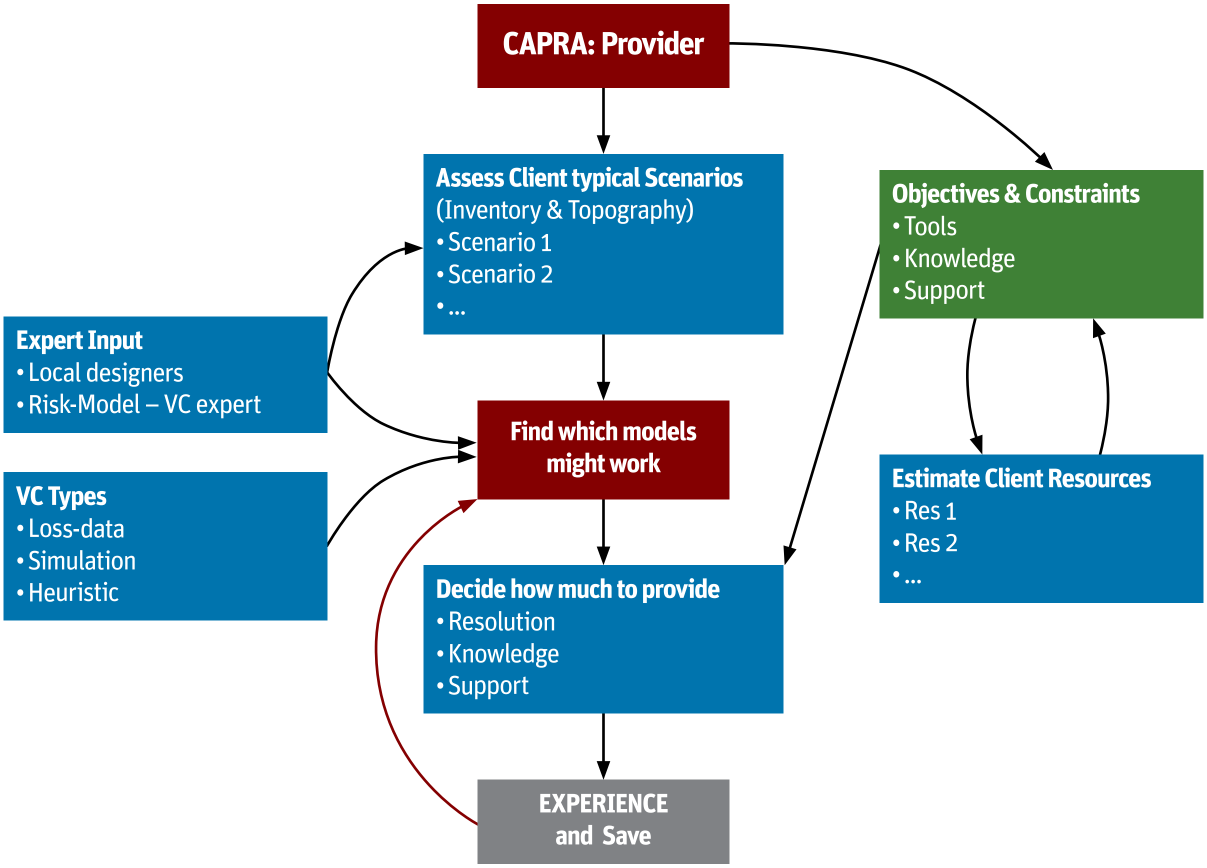
The answers to these and other questions will lead to decide which type of vulnerability is the most appropriate for a certain project given the characteristics of each vulnerability methodology (Table 3). See Figure 7 for a flowchart detailing some sketch stages in the continuing vulnerability assessment strategy with CAPRA as a 'provider'.

Table 3 **Appraisal of the features of vulnerability methodologies**

	Loss-data	Heuristic	Component-based	Simulation
Source	Regional loss data	Experience with individual building types	Individual building types computations	Individual building types simulations
Uncertainty	Loosely defined	Loosely defined	Somehow defined	Defined
Effort to produce	Low	Medium	Medium+	High
Extent of time to develop	Short	Short	Medium/Medium+	Medium/Long (unless previous experience)
Portability	Low—applies to local buildings	Medium—mostly local buildings	Medium+—depends on expert judgment	Medium+/high—general approach

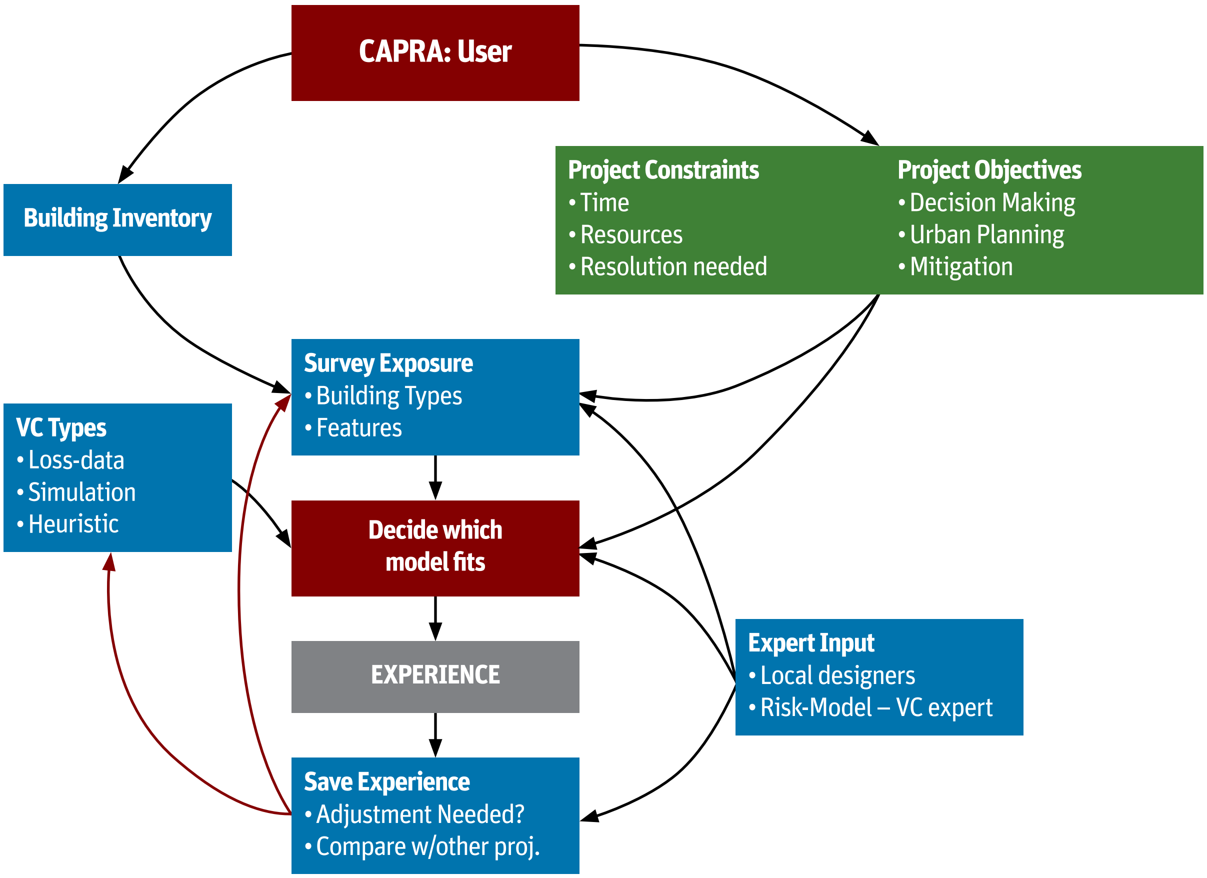
In view of a continuing vulnerability assessment effort, data and experience collecting is crucial. Local users could be encouraged to share in a CAPRA website vulnerability functions with a clear definition of the applicability and assumptions, damage data, and anecdotic evidence.

Figure 7 Flowchart of CAPRA's continuing vulnerability assessment strategy as a 'provider'



With CAPRA as a 'user' itself of the vulnerability methodology, particular decisions arise. In this case specific projects are involved, and so, specific vulnerability curves are produced as the project demands and the resources allow. The corresponding constraints associated to a specific project will enable CAPRA to decide from Table 3 which method is preferable. It must be remembered however that after a certain threshold, it's not obvious that an increase in vulnerability modeling resolution will produce an increase in the predictive accuracy. See Figure 8.

Figure 8 Flowchart of CAPRA's continuing vulnerability assessment strategy as a 'user'



Irrespective of CAPRA's particular role, either as a 'provider' or a 'user', the building vulnerability assessment benefits predominantly from continuity. Vulnerability functions represent an open problem as the inventory it describes changes with time (i.e. it depreciates, it gets older, it's retrofitted, it expands, etc). In addition the expert knowledge is expected to improve. Therefore the vulnerability estimation process must be viewed as a dynamic process with feedback, and updating. As such it must be considered part of the overall strategy, which involves keeping a pool with knowledge and damage database, adding new data as becomes available, actively pursue the survey of new data, and updating the vulnerability functions.

Level of resolution of vulnerability assessments

The resolution of the vulnerability assessment depends on the CAPRA role (as 'provider' or 'user') and the particularities of the project and resources.

The methodologies listed in Table 3 were designed to provide vulnerability estimates for individual building types, either as a curve or as a table with expert-supplied probabilities.

An alternative approach would be to assess the vulnerability of a geographically continuous group of buildings that share a common set of attributes, i.e. a patterned unit that repeats in space. By virtue of sharing the same features, it is assumed that the hurricane vulnerability of such unit might be representative of like building groups.

How to define such a group? The basic issue is to identify the basic characteristics, which account for making the group homogeneous in the vulnerability sense. Vulnerability estimation of 'building groups' needs a study that identifies common economic, demographic, and inventorial variables, and should also be complemented from an engineering expert appraise.

The first study indicates trends of the inventory features, but the second confirm those, and also add more details such as building code enforcement, construction quality, and anecdotic details that help in better defining a classification of a 'typical' area whose features/pattern repeat regularly in a given region, or are a more or less faithful representation of an area characteristic.

Approaches to identifying a group might be:

- If damage data is available: perform a spatial correlation analysis identifying clusters of building characteristics that share comparable damage. Such an analysis might rely on tools from the Spatial Statistics field such as kriging, variograms, spatial autocorrelation, cluster analysis, etc. Therefore, for similar levels of wind speed, which city zones sustained similar levels of damage? Here the 'contours' of the group will be identified along with the corresponding wind speed that caused the damage. The surroundings of the buildings (i.e. topography, land cover, etc.) should be used as explanatory factors. Successful analyses from past-loss data would provide the vulnerability for some wind speeds. This implies that the vulnerability would not be defined for the entire wind speed domain. In order to find the remaining wind speeds, some regression analysis (i.e. an extrapolation) must be performed. The question whether such 'units' are portable to other sites, has to be carefully analyzed on a case-by-case basis.
- In a simulation environment, the building inventory of the city of interest must be characterized with some level of vulnerability resolution. Then for each wind speed level, a similar analysis to the one described above must be performed until all the domain of wind speeds has been spanned. This approach involves more effort than the previous, but avoids the extrapolation and admits more simulation detail. In addition, if past-loss data is available, the results of a simulation analysis could be validated.

There are some building groups in a city that naturally lend themselves to being considered as 'patterned units' such as neighborhoods where all the houses were built by the same builders at the same time. Any analysis however must be performed by a civil engineer with experience in vulnerability estimations.

Hurricane vulnerability of critical infrastructure

The risk analysis of critical infrastructure, e.g. power lines, electric power distribution systems, transportation systems, water supply, and natural gas supply system has received considerable attention in the last years. The approaches to assess the risk of such facilities are multiple and include: statistical learning theory, (Guikema 2009) including Data mining such as CART, BART, and GAM (Guikema, 2010).

The resilience analysis of networked infrastructure, which includes some of the cases mentioned in the previous paragraph, has also received much attention. Researchers are proposing different metrics to measure resilience (e.g. Reed et al. 2009). The vulnerability analysis of critical infrastructure naturally requires a different approach to that of the building infrastructure.

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APPENDICES

Variability of damage estimation

The model in Eq. (1) represents the median value of the physical damage estimated at a given wind speed *V*. The model also provides an estimate of the spread of damage estimates at each median damage. Such variance is assumed to follow a Beta distribution (Figure 9):

$$\sigma_{\beta}^2 = Q[\beta]^{r-1}[1-\beta]^{s-1} \qquad \text{(A-1)}$$

where

$$Q = \frac{V_{max}}{D_0^{r-1}(1-D_0)^{s-1}} \qquad \text{(A-2)}$$

and

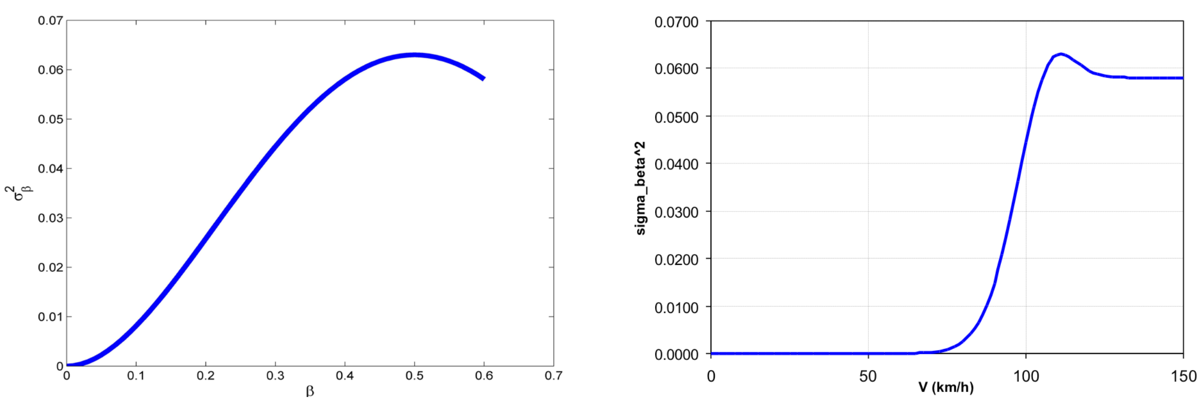
$$s = \frac{r-1}{D_0} - r + 2 \qquad \text{(A-3)}$$

and $r = 3$.

Table 4 Parameters of built-in vulnerability functions

Parameters (interface and Eq. (1))	CS1	CS2	CS4	CS5	LF1	LF2	LS1	LS2	LS3	PF1	PF2	PS1	PS2
Beta (γ)	100	100	100	100	95	95	100	100	100	95	95	100	100
Alpha (ρ)	8.1	8.1	8.1	8.1	7	7	8.1	8.1	8.1	7	7	8.1	8.1
Dmax	0.1	0.5	0.3	0.2	0.6	0.3	0.4	0.2	0.13	0.4	0.2	0.2	0.1
Do	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Vmax	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063

Figure 9 Beta distribution for a vulnerability curve with Dmax = 0.6 as a function of ß and *V*



Preliminary Comments on the Hazards user interface

This section lists some suggestions for enhancing the user experience of the hurricane hazard tool.

- Tutorial
  - While the voice in the tutorial is in English, all the images coming from the PC are in Spanish. Misleading for non-Spanish speakers.
  - The tutorial shows the roughness measured from 1 to 4. Maybe add the ranges of the coefficient z_0 for reference purposes.
- ERN-Hurricane interface
  - Interface has Spanish name 'ERN-Huracán'.
  - General Data Tab:
    - 'soil type' is confusing, should say 'roughness'.
    - A definition of how roughness (z_0) should be added, i.e. meters.
  - Analysis Zone Tab:
    - 'Points in shoreline' should say: 'grid points in shoreline to estimate storm surge'.
    - Tutorial voice says 'boundary geographic data' but should perhaps say 'domain of wind and rain estimation' or similar
    - Tutorial says 'distance between points' but may perhaps say something like 'domain of evaluation of wind field model' or similar.
    - In the interface, it is not immediately evident what the label 'Delta' means and what its units are. Maybe write grid spacing.
    - Likewise wit 'N'. Maybe write 'Number of grid points'.
    - Maybe replace 'Minimum' and 'Maximum' with 'South' — 'North', or 'Upper' — 'Lower'.
    - Do storm surge includes initial tide, or astronomical tide?
  - Hurricanes Tab
    - Tab lacks some details to guide the user.
    - Maybe add a label saying 'load hurricane tracks'. Also maybe include an 'Add' button as double clicking in white zone is not immediately evident.
    - See some suggestions for the hurricane track files below.
  - Simulations Tab
    - Specify what type of simulations are used.
    - Specify what 'Sigma' is.
    - Not clear what is the difference between 'Group of simulations', 'Pure Simulations', and 'No Simulations'. Besides, the 'No Simulations' option conflicts with the 'Simulations' tab label.

- The tutorial recommends keeping the same values as those already in the interface. Not clear what control over the simulations is afforded to the user.
- What is the role of the 'Coefficient of variation' options?

– Run

- There are four bars indicating the simulation progress, but are not labeled.

– Other suggestions

- Maybe add a visualization tool of the building features.

– Hurricane track file (see below for sample):

- For the sake of portability with other risk platforms, maybe consider the adoption of 'NOAA Best Track' nomenclature, or similar, for the hurricane track files.
- Change 'Número de Avisos' to 'Stations' or 'Measurements'
- Add the units for each table heading.
- Explain if 'Velocity' is Intensity, i.e. maximum velocity, and specify the time averaging used, i.e. 3-sec gust, 5-sec gust, 10-min sustained, 1-hr sustained, other. Is it located at the radius of maximum winds (RMW)?
- Specify projection system for GIS?

The .atl files structure for inputting the hurricane trajectory has the following format:

Nombre: Huracan-01-Tutorial

Oceano: Atlantico

Número de avisos: 81

Frecuencia anual: 0.020

Longitud	Latitud	Fecha	Hora	Velocidad	Presión
-70.83126204	11.36318608	15/10/2005	04:00:00 p.m.	46.3	1004
-71.03126204	10.76318608	15/10/2005	10:00:00 p.m.	46.3	1003
-71.03126204	10.76318608	16/10/2005	01:00:00 a.m.	55.56	1003

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