Ploto

D4.3

Multi-Hazard Vulnerability Modules for IWW and connected hinterland infrastructures 1st version

Project name
Deployment and Assessment of Predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against Climate change and other extremes

Horizon Innovation Actions | Project No. 101069941
Call HORIZON-CL5-2021-D6-01

Co-funded by
the European Union

Dissemination level	Public (PU) - fully open
Type of deliverable	OTHER
Work package	WP4 – Vulnerability and Resilience Assessment of the IWW and the connected hinterland infrastructures
Deliverable number	D4.3 Multi-Hazard Vulnerability Modules for IWW and connected hinterland infrastructures 1st version
Status - version, date	Final – V1.0, 14/02/2024
Deliverable leader	NTUA
Contractual date of delivery	29/02/2024
Keywords	Inland Waterways, natural hazards, models, climate change

Quality Control

	Name	Organisation	Date
Peer review 1	Carmen Costache	RRT	29/01/2024
Peer review 2	Fotios Barmpas	AUTH	23/01/2024

Version History

Version	Date	Author	Summary of changes
0.1	18/12/2023	NTUA	First version of the document
0.2	18/01/2024	NTUA	Complete draft version for internal review
0.3	05/02/2024	NTUA, RRT, AUTH	Revised version based on the comments made during the internal review process
1.0	14/02/2024	NTUA	Final submitted version

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List of definitions, abbreviations and acronyms

Abbreviation	Meaning
C	Capacity
D	Demand
DM	Damage Measure
COP	Common Operational Picture
DS	Damage State
Dx.x	Deliverable x.x
EC	European Commission
EDP	Engineering Demand Parameter
EU	European Union
GA	Grant Agreement
IM	Intensity Measure
IMS	Incident Management System
IWAT	IWW Assessment Tool
IWW	Inland WaterWays
LS	Limit State
MHVM	Multi-Hazard-Vulnerability-Modules
MSA	Multi-stripe Analysis
Mx	Month x
PGA	Peak Ground Acceleration
S_a	Spectral acceleration
Tx.x	Task x.x
WP	Work Package

Executive Summary

PLOTO project aims at increasing the resilience of the Inland WaterWays (IWW) infrastructures and the connected hinterland- infrastructures, thus ensuring reliable network availability under unfavourable conditions, such as extreme weather, accidents and other kind of hazards. PLOTO's main target is to combine downscaled climate change scenarios (applied to IWW infrastructures) with simulation tools and actual data, so as to provide the relevant authorities and their operators with an integrated tool able to support more effective management of their infrastructures at strategic and operational levels. The PLOTO integrated platform and its tools will be validated in three case studies in Belgium, Romania, and Hungary.

The aim of this report is to:

a. present the methodology behind the development of the Multi-Hazard-Vulnerability-Modules (MHVM) as described in Task 4.2 of Work Package WP4;
b. index the IWW and hinterland infrastructure elements (assets) that constitute the exposure model of PLOTO;
c. present the structure of MHVMs.

1. Introduction

1.1 Project information

The project entitled **"Deployment and assessment of predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against climate change and other extremes (PLOTO)"** aims at increasing the resilience of the IWW and the connected hinterland infrastructures, especially under adverse conditions, such as extreme weather, accidents and other kinds of hazards. In doing this, downscaled climate change scenarios will be combined with simulation tools and actual data, to provide operators an integrated tool able to support more effective management of their infrastructures at strategic and operational levels.

PLOTO project consists in the deployment and assessment of predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against climate change and other extremes. An integrated tool is set up to allow relevant authorities to improve the efficiency of their infrastructure management. This tool is a combination of downscaled climate change scenarios with simulation tools and actual data. Six complementary avenues will be considered to achieve this integrated tool that will support relevant authorities and their operators for more effective management:

- Measure and use high-resolution modelling data for the determination and assessment of the climatic risk of the selected transport infrastructures and associated expected damages.
- Use existing data from various sources with new types of sensor-generated data (computer vision) to feed the used simulator.
- Utilise tailored weather forecasts (combining seamlessly all available data sources) for specific hot spots, providing real-time early warnings with corresponding impact assessment.
- Develop improved multi-temporal, multi-sensor UAV- and satellite-based observations with robust spectral analysis, computer vision and machine learning-based assessment for diverse transport infrastructures.
- Design and implement an integrated resilience assessment platform environment as an innovative planning tool that will permit a quantitative resilience assessment through an end-to-end simulation environment, running "what-if" impact/risk/resilience assessment scenarios. The effects of adaptation measures can be investigated by changing the hazard, exposure and vulnerability input parameters.
- Design and implement a Common Operational Picture (COP), including an enhanced visualisation interface and an Incident Management System (IMS).

The PLOTO integrated platform and its tools will be validated in three case studies in Belgium, Romania and Hungary.

1.2 Purpose of the deliverable

Deliverable D4.3 “Multi-Hazard Vulnerability Modules for IWW and connected hinterland infrastructures 1st version” is one of the two (2) deliverables of WP4 related to Task 4.2 “Development of vulnerability modules”. In more detail, the scope of T4.2 is:

Characteristic ‘index’ IWW elements (e.g., channels, banks, slopes, bridges, etc.) and interconnected non-IWW components (e.g., power transmission lines, communication towers, etc.) that influence the infrastructure performance are selected using expert opinion and formal statistical clustering methods to best represent the vast portfolio of structures at threat. Highly detailed models are developed, together with corresponding fast-running simplified surrogate models that can be employed via available simulation software tools to provide near-real-time assessment of the vulnerability of IWW infrastructures.

To this end, advanced but easily programmable algorithms are currently being developed, that will correlate measured data (e.g., from meteorological stations or instrumentation) with the expected failure patterns of IWW elements assuming various scenarios (e.g., drought, extreme rainfall, high precipitation levels etc.). Inverse analysis methods are also being implemented in cases where monitoring data are available. The aim is to assess the current state and accurately predict future response needs. Data from conventional sensors along the IWW and the hinterland infrastructure combined with measured climate related data (i.e., snow height, wind speed, temperature differences) are used for validation and verification purposes of the numerical modelling results. Hence, the calibration of both detailed and surrogate structural models as well as structural and geotechnical engineering (NTUA) is assured. Environmental model inputs, field data and material (e.g., steel, concrete) parameter uncertainties based on diverse sources, e.g., experimental data, long-term monitoring, regular inspections, and expert knowledge, will be encoded to provide fully probabilistic age-dependent models of each infrastructure. The epistemic uncertainty due to the detailed model’s reduction to surrogacy will also be quantified and incorporated. A large number of future CC-related weather scenarios will be created from the regional climate models employed in WP3. Climate related loads (snow height, rain rate, wind speed and local consecutive pressure etc.), geo-hazard intensities (e.g., earthquake acceleration) and man-made hazard (e.g., fire load or explosive weight and stand-off distance) are utilized to develop the entire potential range of stressors on each index structure.

These loads are integrated into the numerical models in order to predict their response and the relevant damage at the detailed level of individual elements. This way, a high-resolution assessment of vulnerability, whereby loss, functionality and downtime become directly tied to rehabilitation/emergency action planning is enabled. Any proposed adaptation and mitigation measures, together with the temporal evolution of material properties, is also included in the multitude of simulations for the evaluation of their effect and effectiveness over time. Results are encoded in software libraries, termed Multi-Hazard Vulnerability Modules, which enable a seamless integration of hazard simulators and vulnerability results into the IWAT model of the IWW system.”

To summarize, D4.3 aims to:

a. present the methodology behind the development of the Multi-Hazard-Vulnerability-Modules (MHVM) as described in Task 4.2 of Work Package WP4;

b. index the characteristic IWW and interconnected non-IWW elements (assets) that consist the exposure model of PLOTO;
c. present the typical structure of MHVMs.

Attainment of the objectives and explanation of deviations

This Deliverable is related to PLOTO Objectives STO-5 and STO-8. The MHVMs are standardisable software libraries that feed the Risk Assessment Engine. They provide data in a human-readable format regarding the fragility and vulnerability of IWAT assets against natural hazards. The objective is to acquire vulnerability assessment for assets related with IWW. This involves evaluating the impact of multiple hazards, including climate-related loads (such as, rain, wind, etc.), geo-hazard intensities (e.g., ground acceleration), and man-made hazards (e.g. traffic and impact loads).

1.3 Intended audience

Deliverable 4.3 is public and thus it will be openly available to all stakeholders, such as public authorities, IWW and other hinterland infrastructure owners and operators, researchers and technology providers, as well as decision and policy makers who interested in a report presenting Inland Waterways end-user needs and requirements towards the design and development of a system that improves the resilience of IWW against Climate change and other extremes.

1.4 Structure of the deliverable and its relation with other work packages/deliverables

The Deliverable has been structured as follows:

Section 1. Describes PLOTO's aim as well as this document's purpose, intended audience and structure.

Section 2. Describes the methodology followed in this Deliverable.

Section 3. Describes the theoretical background that is adopted for the development of MHVMs.

Section 4. Describes the assets that consist the exposure model per Demonstration Case.

Section 5. Describes the typical structure of MHVMs.

Section 6. Concludes the Deliverable by summarising the main outcomes.

2. Methodology

This deliverable is linked to Task 4.2 "Development of vulnerability modules (M6-M24; NTUA)". In more detail, it includes: (a) indexing of the IWW and non-IWW assets that are selected for the development of the exposure model of PLOTO demonstration cases (b) presenting the methodology employed for assessing the vulnerability of assets under natural or man-made hazards, and (c) presenting the development of MHVMs libraries (T4.2).

Figure 1 presents the WP4 high-level architecture where the Physical Vulnerability Assessment module (related to T4.2) is depicted. Also, Figure 1 illustrates the interconnection of T4.2 with the rest of the modules of WP4. Essentially, MHVMs are generated offline using structural and geotechnical safety assessment simulators. To elaborate, hazard simulators analyse inputs for selected hazard scenarios and transfer their outcomes to IWAT. Then, IWAT forwards the hazard input to MHVMs to conduct risk and resilience assessments. The outcomes are then sent back to the middleware for storage.

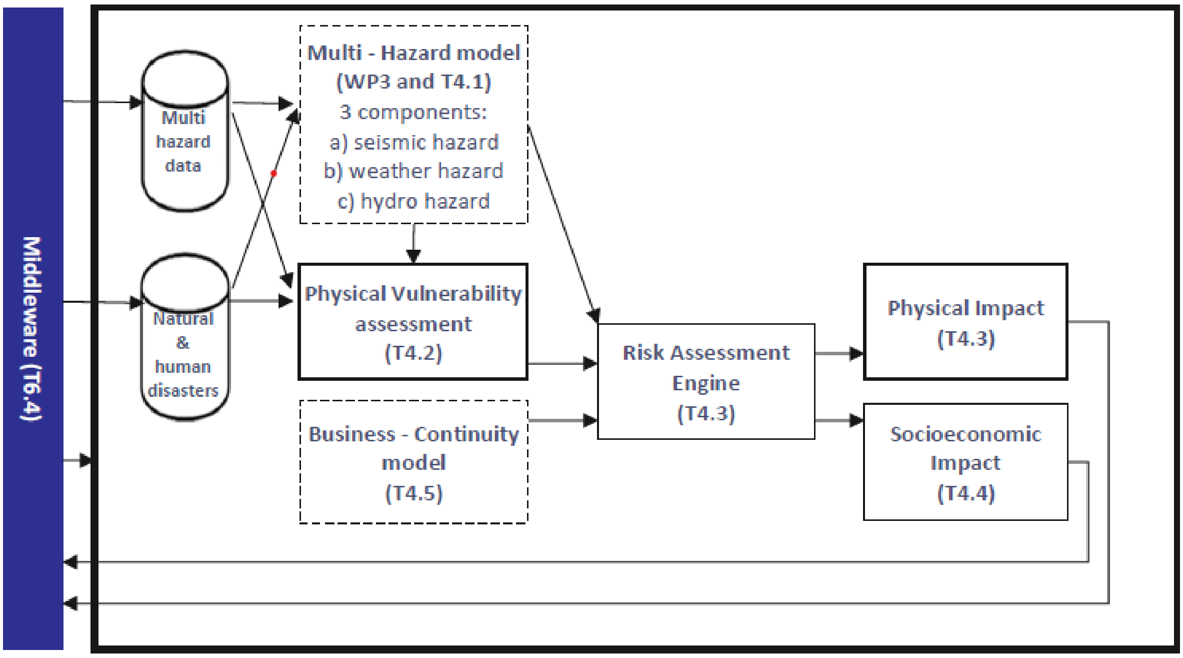


Figure 1: WP4 high-level architecture (adopted from D2.2)

To meet the objectives of the Deliverable, the contributing partners of T4.2 have worked together, cooperated closely and communicated via WP4 coordination meetings and dedicated bilateral meetings with the end-users. The time plan and milestones of the ongoing work on T4.2 is schematically illustrated in Figure 2. Technical partners cooperated towards achieving STO-5 "Improved vulnerability analysis and resilience assessment, including digital winning tools to simulate IWW.", STO-8 "To establish long-term data platforms securing open, consistent data points…" and the relevant KPIs.

The methodology that was implemented followed four steps as below:

1) Definition of the assets (IWW and non-IWW elements) that consist of the exposure model of PLOTO demonstration cases based on experts opinion and the relative data provided by the relevant (local) technical partners per demonstration case.
2) Preliminary design of the PLOTO's exposure model.
3) Preliminary design of MHVMs based on state-of-the-art tools that can be employed for assessing resilience of structures/infrastructures against natural and/or man-made hazards.

The work in T4.2 is progressing with the finalization of the exposure model of PLOTO and the corresponding finalization of MHVMs libraries (based on the work made on T4.1). Hence, results up to D4.3 will be finalized, updated and refined until M26 when D4.4 will be submitted. All the work employed for the development of D4.3 and D4.4 was made in coordination with the technical partners of the relative WPs and Tasks.

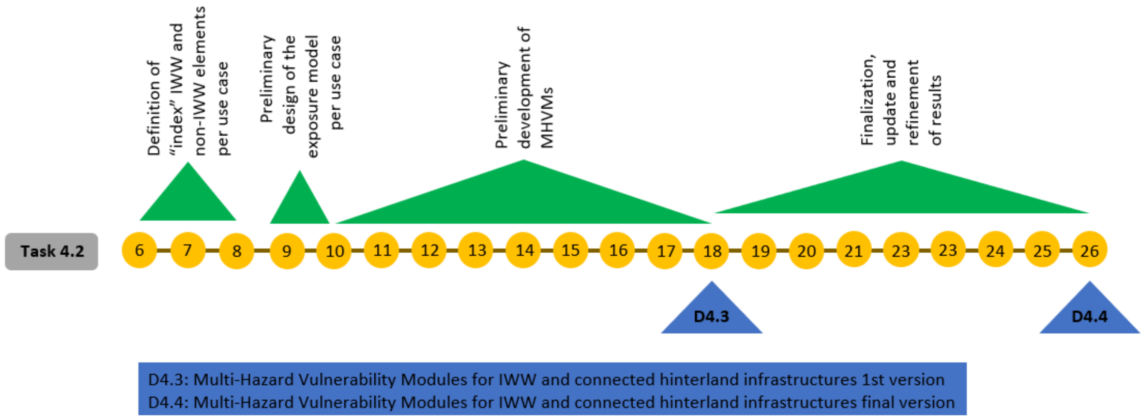


Figure 2: Time plan and milestones of T4.2

3. Theoretical background

3.1 Definitions

Hazard: stressors associated with a threat whose occurrence may affect the normal activities of people and the integrity and functionality of IWW and non-IWW assets, including, for example, ground shaking for earthquakes or wind action for storms.

Intensity Measure: Interface variable that links the hazard analysis and the structural analysis.

Engineering Demand Parameter: Quantity of structural response that is used to measure the response and to estimate damage to structural and non-structural components and systems.

Fragility curve: Function that provides for a structure the probability of exceeding a given limit state, or equivalently of being in a damage state or worse, given the intensity measure.

Vulnerability curve: Function that provides the distribution of a loss measure given the level of the intensity measure.

Exposure model: Contains information on the assets at risk, their location, taxonomy, etc.

3.2 IM approach

The analytical estimation of losses involves the combination of hazard (climate-related, geo-hazard and man-made hazard) with the results of (geo)structural analyses. The former is performed by experts per field (e.g., seismologists, environmental engineers etc.), whereas the latter is performed by engineers. Typically, an intensity measure (IM) is employed as the interface variable between the hazard analysis and (geo)structural analysis. IM serves as a point of contact between the different disciplines aiming to incorporate all complexity of the hazard-specific loading into a single quantity that can be used for the (geo)structural analysis. The aim is to avoid considering all the diverse characteristics of the loading. For instance, considering earthquakes, seismologists estimate the statistical properties of the IM through Probabilistic Seismic Hazard Analysis (Cornell 1968), while engineers calculate the structural response for given levels of the IM without taking into account a complex combination of earthquake magnitude, source-to-structure distance and other relevant seismological parameters within structural analysis. The desirable dissociation is achieved by selecting an appropriate IM that is efficient and sufficient with respect to the characteristics of the type of hazard examined (e.g., Vamvatsikos and Cornell 2005; Luco and Cornell 2007; Kazantzi and Vamvatsikos 2015; Lachanas et al. 2023). Efficiency of an IM means that the selected IM should be a good predictor of the (geo)structural response, as measured by the structure’s selected Engineering Demand Parameter (EDP). This enables achieving the desirable level of accuracy on the numerical analysis results with a relatively small number of time-history analyses. IM sufficiency means that the selected IM should show low dependency on the other inherent characteristics of the hazard and thus rendering an asset’s response independent of these specific characteristics. For instance, regarding the seismic risk assessment, a sufficient IM would remove any bias from considering the magnitude, distance and other seismological parameters of the ground motion records rather than the IM. Efficiency and sufficiency goals do not inherently align, as efficiency targets a decrease in variability within dynamic analysis results, while sufficiency focuses on diminishing reliance on hazard characteristics rather than the IM. It's crucial to recognize that by using a more efficient IM, despite reducing the dispersion in response, it doesn't necessarily mean an overall reduction in risk variability. Instead, it might involve shifting part of the variability to a different level within the risk estimation assessment.

In the PLOTO framework, for each type of hazard an appropriate IM is selected, as presented in Table 1. In the case of geo-hazard (earthquake), PGA is the peak ground acceleration and $S_a(T)$ is the elastic spectral acceleration for a vibration period T.

Table 1: Natural hazards considered in PLOTO and pertinent intensity measure (IM)

Hazard	IM
Weather	Wind speed/direction/gust factor, temperature, precipitation, etc.
Flood hazard	water level
Seismic hazard	$PGA, S_a(T)$

3.3 IM – EDP relationship approach

In the context of structural analysis, each dynamic analysis produces a simple pair of IM and the corresponding EDP demand values. Given the inherent uncertainties, multiple analyses involving a considerable number of inputs per intensity level are required. For example, for the case of seismic hazard, multiple ground motion records are employed as inputs for the analysis at each discrete IM level. There are many ways to group the aforementioned IM-EDP pairs in order to adequately characterize the IM-EDP space and estimate the seismic demand, such as single-stripe analysis (Jalayer 2003), multi-stripe analysis (Jalayer 2003; Jalayer and Cornell 2009), cloud analysis (Jalayer 2003; Mackie and Stojadinović 2001; Padgett and DesRoches 2008), or incremental dynamic analysis (Vamvatsikos and Cornell 2002). In the PLOTO framework, the multi-stripe analysis (MSA) method is employed for grouping IM-EDP pairs as it facilitates the post-processing procedure without the need for fitting regression models. MSA consists of a group of stripe analyses, each of which is performed at a different IM level. A single stripe includes the EDP results of the structure at hand when subjected to n time-histories of the hazard with each of them being scaled at the certain IM level of the stripe. A characteristic example of single-stripe analysis is shown in Figure 3, where, for a structure, each point (star) indicates the result of the non-linear time-history dynamic analysis under a ground motion record scaled to $S_a(T)$= 0.94g. For this example, the first-mode spectral acceleration $S_a(T)$ is employed as IM, where T is set equal to the fundamental vibration period of the structure. By performing non-linear dynamic analyses for multiple intensity levels (multiple stripes), the MSA results are obtained, as indicatively illustrated in Figure 4. Moreover, state-of-the-art tools are used to select time-histories in order to overcome any IM insufficiency issues and better represent each IM level. For example, regarding the seismic hazard, the ground motion records are selected to be site-specific and hazard-consistent (Lin et al. 2013; Kohrangi et al. 2017;).

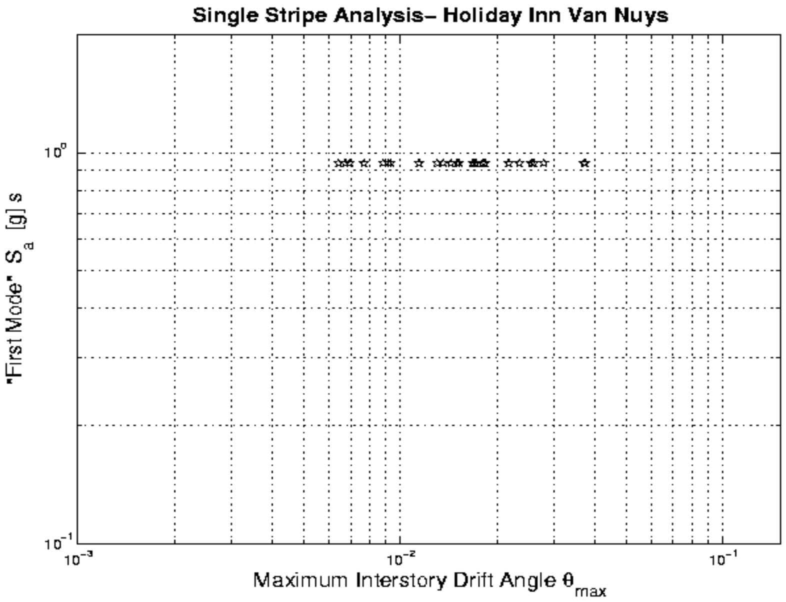
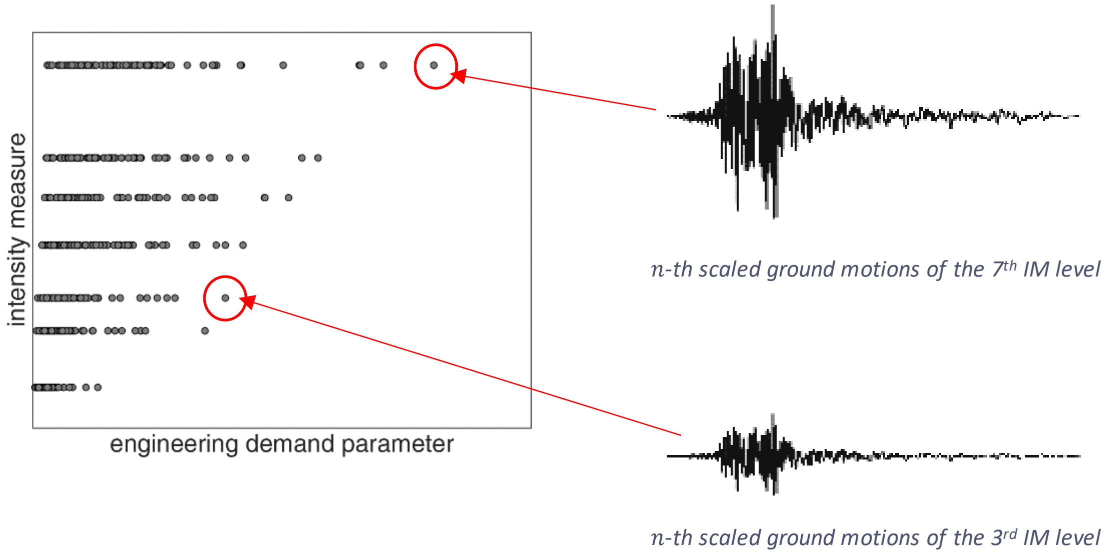


Figure 3: Single-stripe analysis results (adopted from Cornell and Jalayer 2002).



n-th scaled ground motions of the 7th IM level

n-th scaled ground motions of the 3rd IM level

Figure 4: Multi-stripe analysis results of an asset subjected to multiple ground motions and indicative time-histories of scaled ground motion records that are used as the input for the analysis to get the IM-EDP pairs.

3.4 Framework for performance assessment: fragility and vulnerability functions

The Performance-Based Earthquake Engineering (PBEE) framework as originally developed by Cornell and Krawinkler (2000) for the Pacific Earthquake Engineering Research Center, is employed for risk assessment in PLOTO. The PBEE methodology can be summarized as an implementation of the total probability theorem for calculating the mean annual frequency of violating (exceeding) a decision variable (DV), $\lambda(DV)$ as:

$$\lambda(DV) = \int_{DM}\int_{EDP}\int_{IM} G(DV \mid DM)\left|\mathrm{d}G(DM \mid EDP)\right|\left|\mathrm{d}G(EDP \mid IM)\right|\left|\mathrm{d}\lambda(IM)\right| \tag{1}$$

where IM is the intensity measure, EDP is the engineering demand parameter (e.g. maximum roof/interstory drift ratio for a building), DM is the damage measure, DV is the decision variable and $G(var_1|var_2)$ is the probability that specified values of var_1 are exceeded given the level of var_2. The final product of Eq.(1) is the mean annual frequency of exceeding the decision variable $\lambda(DV)$. Hence, risk can be estimated in terms of DVs that are also familiar with non-engineers, such as monetary loss, repair cost, casualties, downtime. Figure 5 illustrates this risk assessment approach schematically. The five steps from exposure data to decision making as shown in Figure 5 are:

- Exposure model: it contains information on the assets at risk. Specifically, per asset of PLOTO information are provided about their location, taxonomy, value, vulnerability, etc.
- Asset analysis: MSA analysis is performed per asset considering all potential hazards affecting it to define its response and then to calculate the corresponding fragility curves.
- Hazard analysis: all the potential hazards to which assets are vulnerable are considered. The relationship between the severity (intense) of the excitation and the frequency with which each level of excitation is exceeded, is defined.
- Loss analysis: the vulnerability function is defined for each asset given the environmental stressor intensity as measured by the pertinent IM. Vulnerability functions describe the distribution of a loss measure given the level of the IM. The loss is quantified in terms of repair cost, downtime and functionality.
- Decision making: the results of risk assessment assist authorities and decision makers to establish prioritization protocols and to manage associated incidents, facilitating the rapid assessment of the state of the assets.

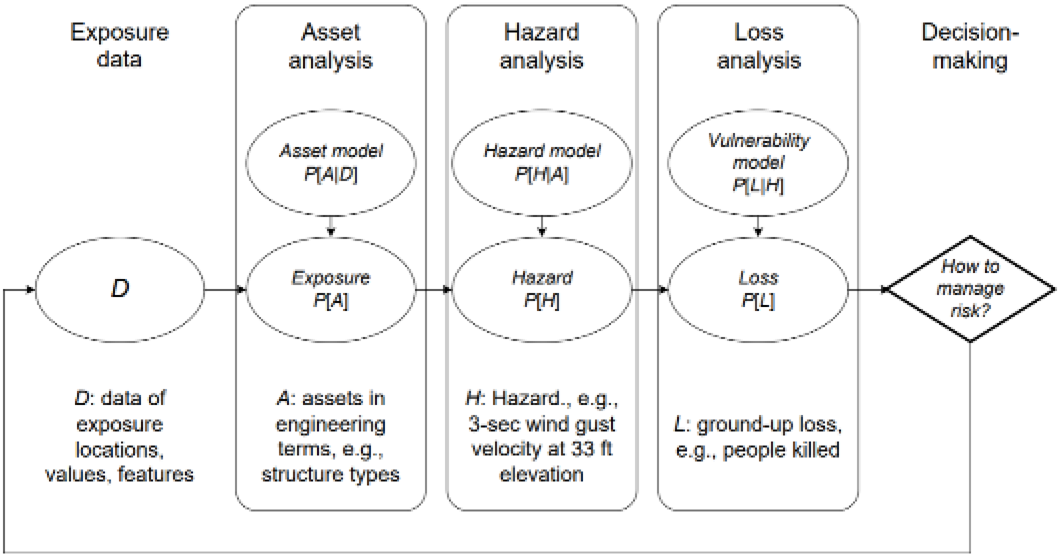


Figure 5: Natural catastrophe risk analysis framework (adopted from Porter 2019).

3.4.1. Fragility functions

Per asset, the continuous damage measure (DM) is discretized into a finite number of N damage states DS_i ($i = 0 \dots N-1$), separated by $N-1$ associated limit-states LS_i, $i = 1 \dots N-1$. Each limit-state is associated with a predefined level of expected damages and typically is determined by a specific EDP threshold. The EDP threshold for exceeding LS_i indicates the appearance of DS_i until the EDP threshold for exceeding LS_{i+1} that indicates DS_{i+1} etc. This way, fragility curves arise as continuous functions that provide the probability of exceeding a given LS_i, or equivalently of being in DS_i or worse, given the IM. A fragility function is defined as:

$$F_{LSi}(IM) = F_{LSi}(IM = x) = P\left[LS_i \text{ violated} \mid IM = x\right] = P\left[D > C_{LSi} \mid IM = x\right] \quad (2)$$

where limit state LS_i violation is typically defined as the case where the seismic demand, D, exceeds the associated limit-state capacity, C_{LSi} (typically defined by a single EDP threshold). Typically, fragility curves are assumed to follow the lognormal distribution. In this way, if θ_i is the median value and β_i is the dispersion (logarithmic standard deviation) of LS_i, the probability of exceeding LS_i is calculated as:

$$F_{LSi}(IM) = F_{LSi}(IM = x) = \Phi\left(\frac{\ln(x/\theta_i)}{\beta_i}\right) \quad (3)$$

where $F_{LSi}(IM)$ is the probability of exceeding LS_i given $IM = x$ and $\Phi(\cdot)$ is the standard normal cumulative distribution function. Then, the probability of being in each DS_i can be calculated as:

$$P(in\,DS_i \mid IM) = F_{LSi+1}(IM) - F_{LSi}(IM) \quad (4)$$

Damage states can be sequential, mutually exclusive or simultaneous. Sequential damage states are the norm meaning that DS_{i+1} always succeeds DS_i, as damage/consequence in the structure increases. Usually damage states escalate from the no-damage DS_0 to the total failure DS_N. Moreover, there are cases where a damage state can be defined as a mutually exclusive or simultaneous occurrence of higher-detail damage states (two or more). In the case of mutually exclusive DSs the occurrence of one DS precludes the occurrence of another. One the other hand, simultaneous DS may occur simultaneously, which is typical in a complex subsystem where different components may sustain damage simultaneously (e.g., the cabin and counterweight of an elevator). A typical example of fragility curves for three sequential limit state (four damage states) is presented in Figure 6.

Nonlinear dynamic analysis of numerical models is the basis for the most comprehensive analytical methods for assessing fragility. In PLOTO MSA is used as the basis for analysing the response of the assets. Then, for given predefined EDP thresholds the corresponding fragility curves are calculated through MSA results per structure. Each fragility curve corresponds to a specific limit state of the structure. A typical example of the construction of a single fragility curve is presented in Figure 7. Specifically, a predefined EDP-threshold is set equal to 0.08 in the Peak Story Drift Ratio (8%, typical collapse level). Then, working per stripe (horizontal line in the IM-EDP space) the probability of exceeding the EDP-threshold (number of records that produce EDP demand higher than 0.08 / total number of records per single stripe) is calculated. The probability values per IM level structure the empirical cumulative distribution function (CDF) of the corresponding fragility function for the collapse limit state. Then, a statistical distribution (typically lognormal) is employed for fitting the empirical CDF in order to cover also the higher IM-levels (extremely rare events) where no analyses are performed.

Thus, the full CDF of the collapse fragility curve is computed. Moreover, fragility curves can also be obtained directly via standardized tools that are available in the literature (e.g. HAZUS, FEMA 2003).

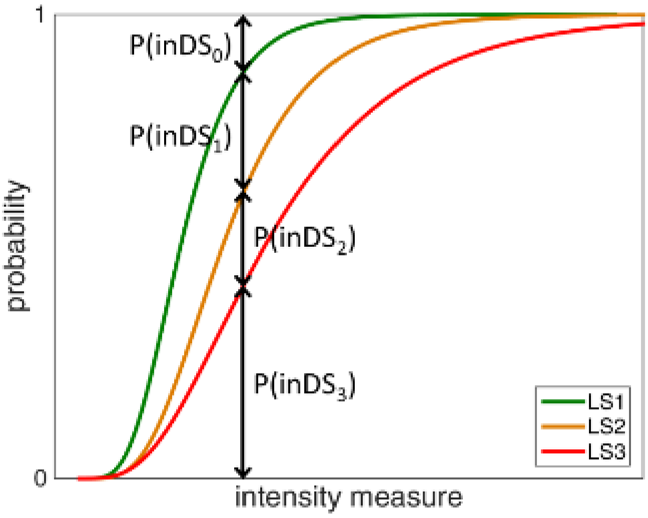


Figure 6: Example of fragility curves for three sequential limit states. The black arrowed lines indicate the probability of being in each damage state for a given value of the intensity measure.

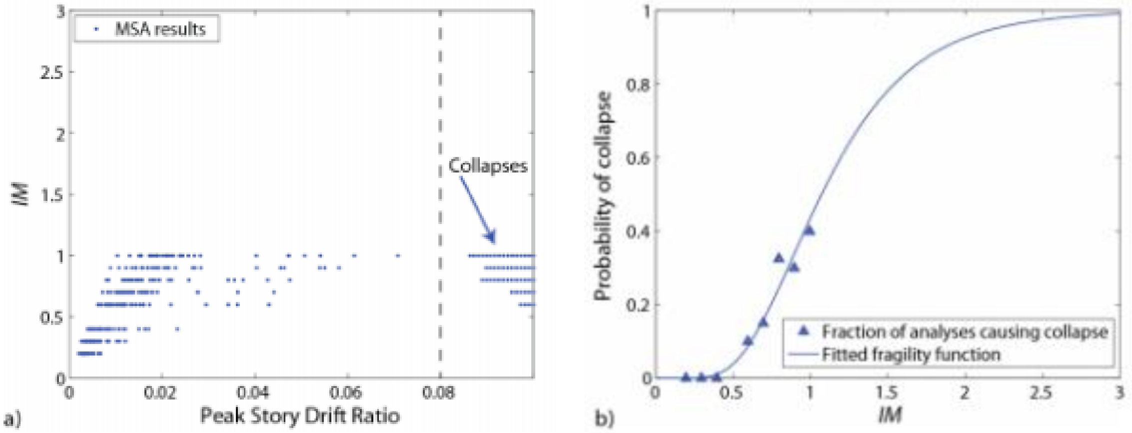


Figure 7: Example of MSA results (left) and discrete versus fitted collapse fragility function (right). (Adopted form Baker 2015).

3.4.2. Vulnerability functions

Vulnerability functions are probabilistic distributions that are employed for translating the physical damage of a structure into various parameters such as monetary loss, repair duration, and downtime given the level of the IM. The derivation of vulnerability functions involves two primary methods: direct empirical approaches and analytical methods. In the former, past event losses at specific locations with corresponding IM levels are considered, while the latter integrates fragility and consequence functions. Fragility functions describe the likelihood of reaching or exceeding a particular damage state based on the IM, and consequence functions represent probabilistic distributions of losses for given performance levels. The schematic depiction in Figure 8 outlines the analytical procedure for the estimation of vulnerability functions.

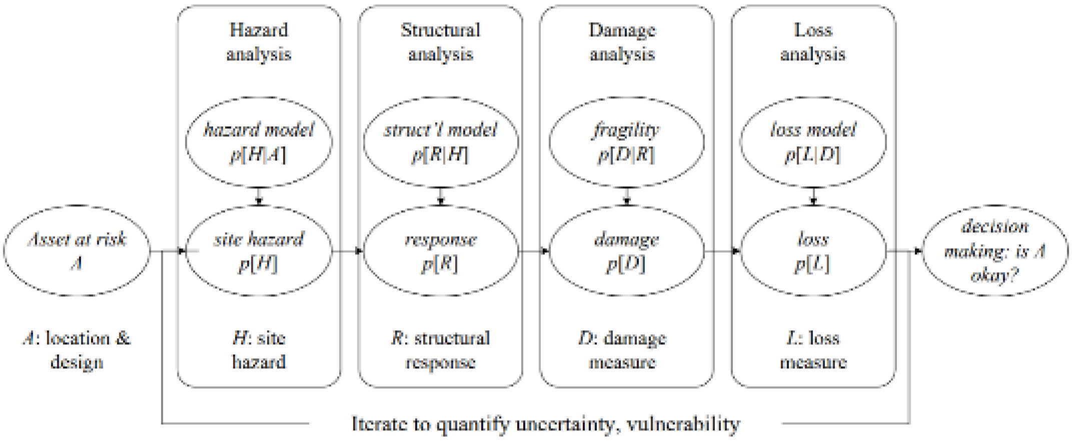


Figure 8: Framework for analytical estimation of vulnerability of a single asset (adopted from Porter 2019).

Within the PLOTO platform, two approaches are used to define IWW and interconnected non-IWW assets' vulnerability curves:

Component-based vulnerability assessment approach

The approach of FEMA P-58 (ATC 2009) is followed for obtaining the vulnerability functions. According to this approach vulnerability functions are derived after correlating asset EDPs directly to loss. It requires detailed information regarding the fragility and loss functions on all vulnerable components per asset. Then, the mean vulnerability function per component category, the behaviour of which is controlled by EDP_i, is computed as:

$$E(L_i \mid EDP) = N_{i,h} \sum_{i=0}^{N_{ds}} P\left(ds_i \mid EDP\right) \cdot m_{i,ds} \tag{5}$$

where i is an index to the component category, L is the loss, N_{ds} is the number component damage states, $N_{i,h}$ is the number of the components of category i in group h and $m_{i,ds}$ is the mean loss per unit of component category i in damage state ds.

System-only vulnerability assessment approach

In this approach system-level fragility curves are convolved with the cumulative consequence of an asset's damage state to assess the corresponding vulnerability functions. Thus, the mean vulnerability curve is calculated as:

$$E(L \mid IM) = \sum_{i=0}^{N_{DS}} E(L \mid DS_i) \cdot P\left(DS_i \mid IM\right) \tag{6}$$

where N_{DS} is the number of damage states, $P(DS_i \mid IM)$ is the probability of being in damage state i given the IM, $E(L \mid DS_i)$ is the expected loss (e.g. cost/downtime) given DS_i and $E(L \mid IM)$ is the expected loss given the IM. Figure 9 presents an example for vulnerability curve estimation. The variance, $var(L \mid IM)$, of the vulnerability curve is computed as:

$$\text{var}(L \mid IM) = \sum_{i=0}^{N_{DS}} \left[\text{var}(L \mid DS_i) + E^2(L \mid DS_i)\right] \cdot P\left(DS_i \mid IM\right) - E^2(L \mid IM) \tag{7}$$

Vulnerability curves can be obtained by using Eq. (6) and Eq. (7) into a repetitive process for a range of IMs. Figure 10 illustrates some indicative results including the median (50%), 16% and 84% quantiles of the vulnerability function.

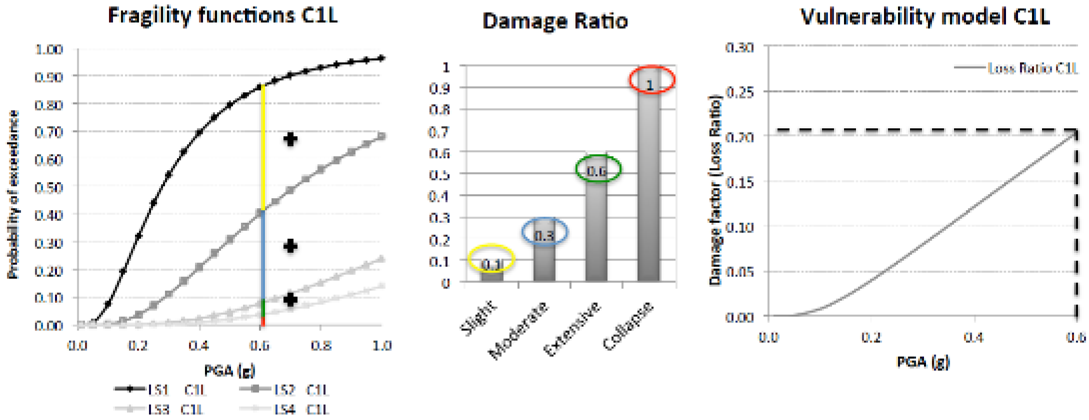


Figure 9: Example of vulnerability assessment given fragility and deterministic consequence data (adopted from D'Ayala et al. 2015).

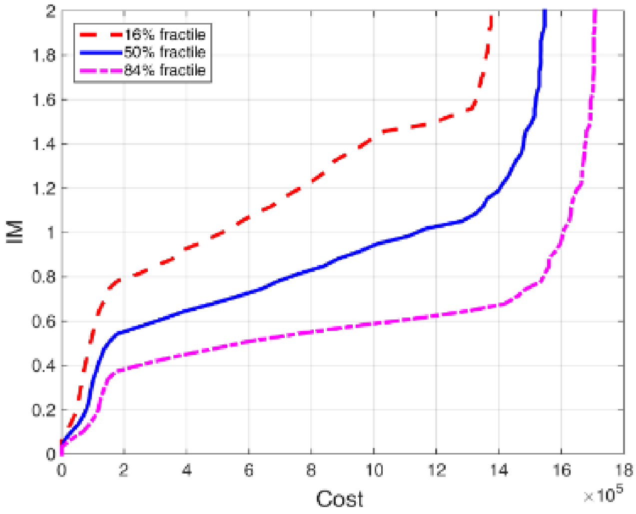


Figure 10: Example of the 16/50/84% fractiles of vulnerability curves in terms of cost computed using probabilistic cost distributions.

The two approaches for estimating vulnerability function differ significantly. In the first one (FEMA P-58 approach), the asset is examined on a component basis regarding the damages and the consequences. To this end, taking for example an IWW asset sustaining DS_2 in its foundation is distinguished from one sustaining DS_2 in its roof. The first one can be seen as a severe damage, while the second one may be considered as a minor one that is easy to be repaired. On the other hand, in the second approach (system-only vulnerability), the entire system, namely the entire IWW or non-IWW asset, is characterized by a single DS leading to a coarse resolution regarding the determination of consequences.

4. Applicable IWW and non-IWW assets

One of the main goals of PLOTO is to assess the vulnerability and to improve the resilience of IWW and hinterland infrastructure under weather, flood, and seismic hazards. To do so accurately and robustly, a proper way to provide highly-detailed data for the assets is needed. In PLOTO the assets per demonstration case are classified in two main categories; namely the *critical assets* (e.g., dikes, cranes, etc.) and the *less important yet non-negligible ones* (e.g., some warehouses, administration buildings). For the critical assets at risk, *asset-specific* numerical structural models are developed and the results are analysed to produce fragility, vulnerability, and consequence functions. All potential hazards of importance to each asset are considered and the entire potential range of stressors is applied to the structural models to predict their response, as well as the relevant damage at the detailed level of individual elements. Further to that, for the numerous lower importance assets, reduced-order *class-specific* models are employed in order to assess their performance in a robust way at a lower resolution with an adequate accuracy at the ensemble level. In other words, regarding vulnerability assessment, approach is followed with the assets being treated on a component-basis, whereas a system-only approach is followed for the latter. All these assets jointly form the exposure model of PLOTO. Furthermore, information gathered from traditional sensors positioned along the Inland Waterway (IWW) and the surrounding infrastructure, combined with recorded climate-related data such as snow height, wind speed, and temperature variations are utilized to compare and calibrate simulation results.

The procedure of FEMA P-58, is followed to assess the performance of all assets. The flowchart of this procedure is shown in Figure 11. Multiple potential scenarios that may occur on each asset are generated. For instance, regarding the assets treated via a component-based approach, for each IM scenario the component's EDPs are calculated based on the MSA results (results stored in the *name*.msa.mat/json file). By convolving the fragility functions of each individual component with the associated consequence functions (stored in *name*.mtdata.mat/json file), multiple IM-DV (or intensity-to-consequences) scenarios are generated. Note that for each alternative IM scenario, if the asset has not collapsed (total failure), the consequences are calculated based on the cumulative damage and associated consequences sustained by each component. If the asset has collapsed, the consequences for replacing the asset are considered using global fragility and consequence functions. A similar methodology is followed for the performance assessment of the assets of lower importance that receive a system-only treatment, by employing system-only global fragilities (typically via tools like HAZUS) and consequence functions instead of component-based ones.

The data stored in MSA and metadata files per asset are processed and multiple potential damage/consequence scenarios are generated given all potential hazards that threat the asset. By combining this information with the IM fields, which offer the spatial distribution of the selected IM, "all" potential scenarios that may happen on the portfolio of IWW and non-IWW assets are generated. This procedure enables a large-scale assessment of vulnerability of IWW, whereby loss, functionality and downtime with a relatively low computational effort. Numerous "what-is" and "what-if" scenarios can be performed for the improvement of IWW resilience.

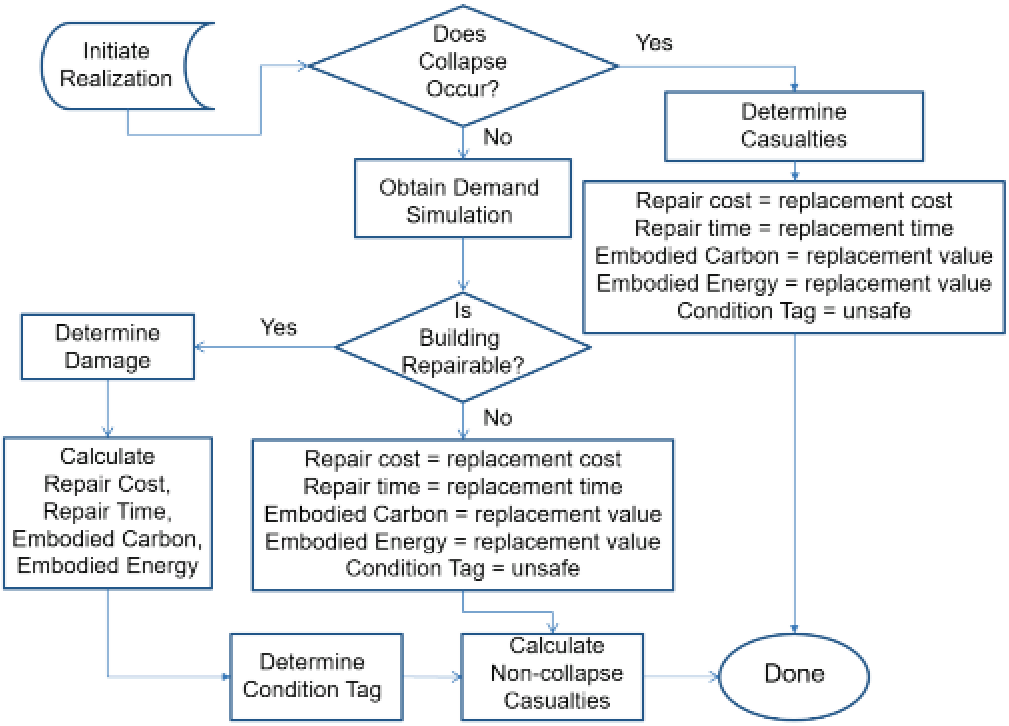


Figure 11: Flowchart for performance calculation (adopted from FEMA P-58).

Per use case of PLOTO various IWW and non-IWW assets consist the portfolio of PLOTO’s exposure model. In the following sections, the characteristic assets per Use Case are presented.

4.1 Use Case A

A brief description of the assets that refer to the Use Case A (Danube Area, Romania) and includes the exposure model of PLOTO for this Use Case is presented. These assets mainly refer to cranes or floating cranes that are installed at the ports and warehouses that are used for storage and logistic operations. Figure 12 present characteristic cranes that are installed at the port of Galati. These steel structures are mobile gantry cranes moving on rail tracks along quay wall.

Figure 12: Cranes installed at the port of Galati.

Figure 13 presents a self-propelled floating crane installed at the port of Galati. Again, it is a steel structure that is a key part of the port facilities.

Figure 13: Self-propelled crane installed at the port of Galati.

Warehouses are also assets related to the IWW port facilities. Figure 14 presents different types of warehouses that were constructed at the port of Galati. Figure 14a illustrates a warehouse that refers to a ground floor construction inside a port area (free zone) used to store raw materials. Figure 14b presents an open space warehouse used to store raw materials and big bags. These two warehouses are old structures. Figure 14c presents a newer warehouse that refers to a ground floor construction inside the port of Docuri area, which is used for logistic operation. It refers to a steel frame structure with steel panel closures.

(a)

(b)

(c)

Figure 14: Characteristic warehouses at the Use Case A.

4.2 Use case B

Figure 15 presents the map view of the Port of Budapest. As illustrated a lot of assets consist the port facilities that are included into the PLOTO's exposure model.

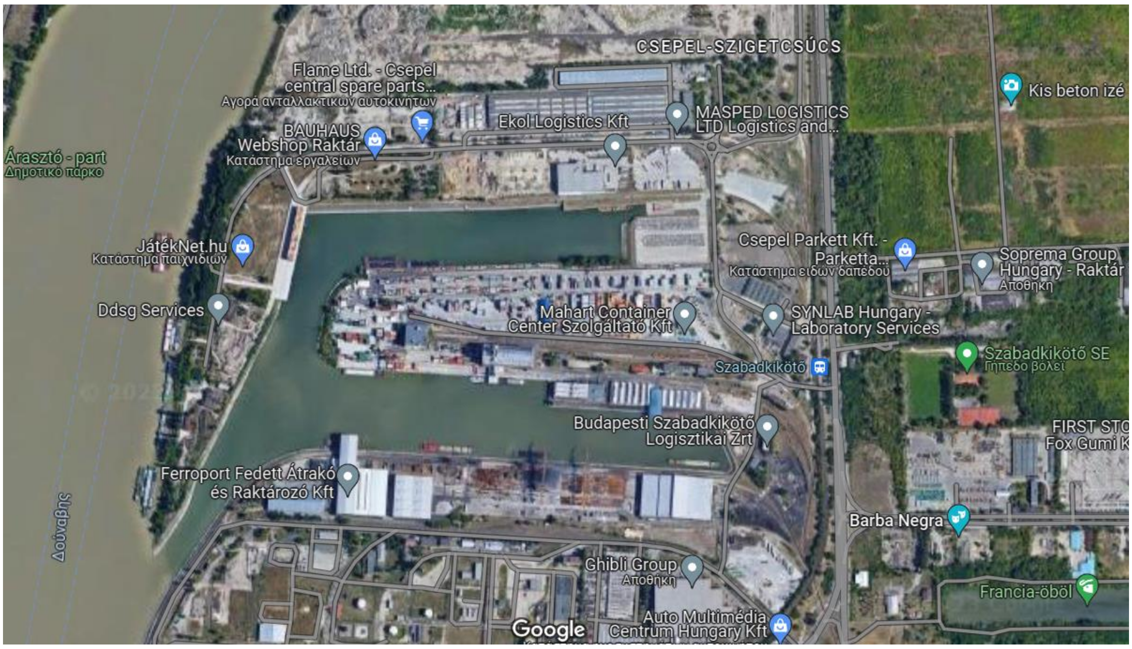


Figure 15: Map view of the Port of Budapest. (Source Google maps).

Figure 16 presents the buildings that compose the port facilities followed by a coding system with a specific ID code assigned to each building. As shown, when compared to the map of Figure 15, some of the buildings shown in Figure 16 have not yet being constructed; still they have been planned as future structures (e.g., F1, F2, F3 that refer to planned warehouses and H2, H3 that refer to planned office buildings) or they are under construction (C5, D2). Moreover, building B5 has been demolished. The existing buildings shown in Figure 16 serve for various usages of the port. The majority of them refer to warehouses. There are very old warehouses (e.g., K2, B7, B8) as well as newer ones (e.g., C1, C2). Most of them refer to ground floor structures with total height ranging within 3.00-15.00m while two of the older ones (B7, B8) refer to tall buildings with multiple floors (Figure 17). Furthermore, the older warehouses are built with concrete or masonry. The newer ones refer to mixed concrete-steel structures. Figure 17 offers a general view of the port with some of the warehouses encoded in Figure 16 being denoted. There are also office buildings located within the Port (e.g., A10, A11, E3, E7, Fer. 4) or are planned to be constructed (H2, H3). The majority of the existing office buildings refer to old or very old masonry buildings having 1 to 3 floors above the ground, some of them also have underground floors. Moreover, there are buildings for special uses like the medical laboratory (B9) and the data center (D4.2)

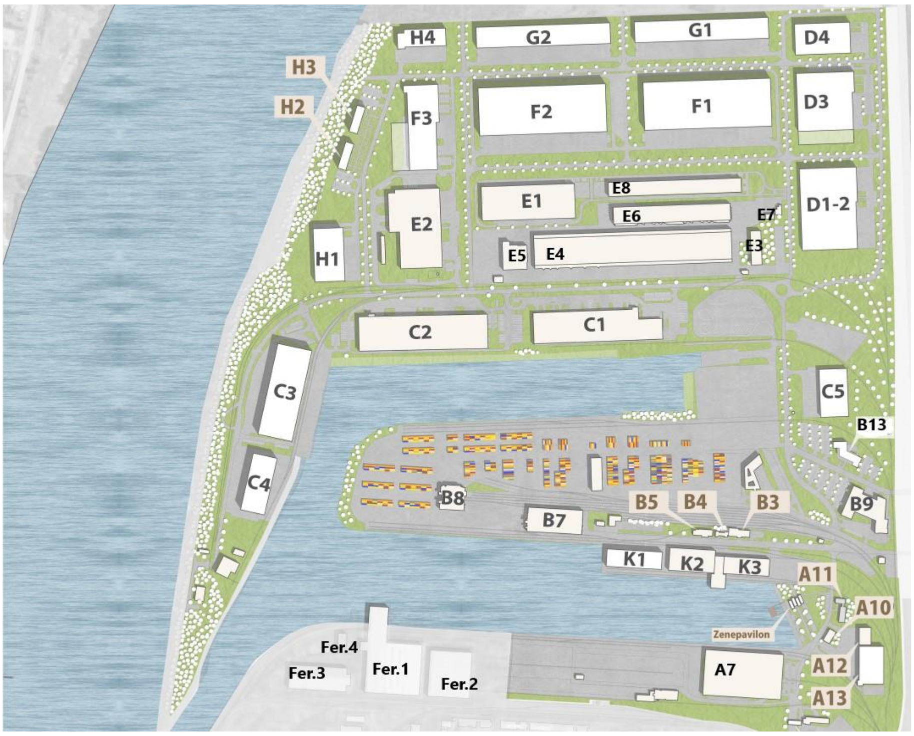


Figure 16: Map view of the Port of Budapest with the ID codes assigned to the buildings (existing buildings, planned for construction buildings, demolished building B5).

Figure 17: General view of the Port of Budapest with some indicative building denoted.

Except for the buildings, cranes are also structures related to the Port. Figure 18 presents the location on map of existed cranes (No. 1–5). Cranes are made of steel. There are overhead cranes (e.g. No 1, 3), container cranes (No. 4) and portal cranes (No. 5).

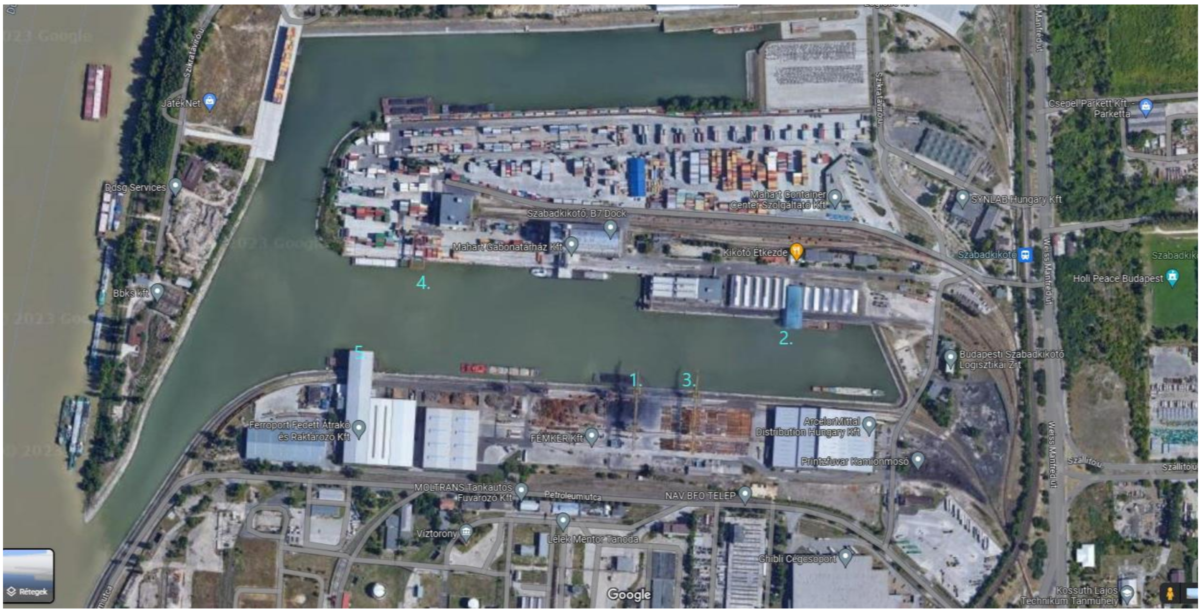
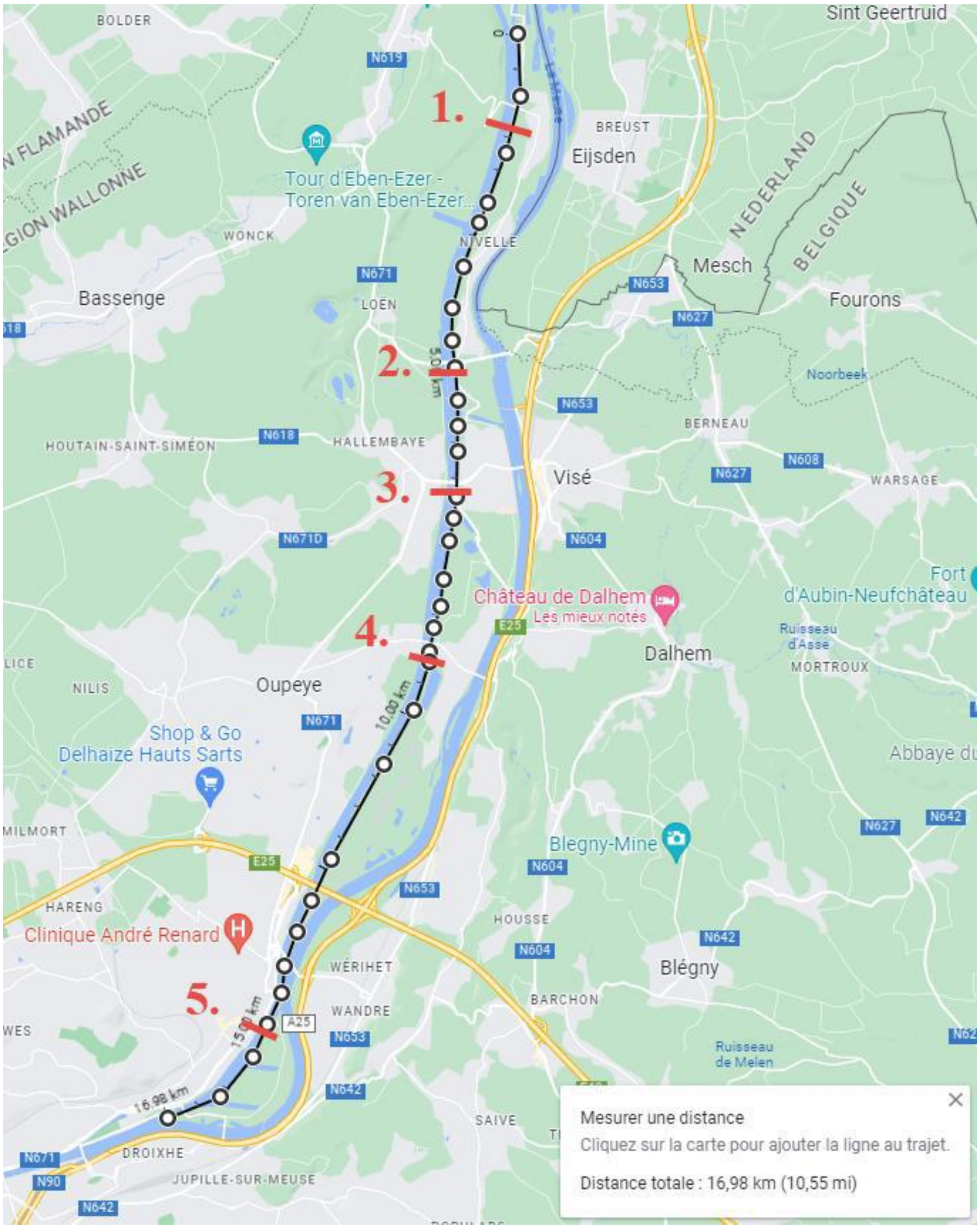


Figure 18: Location of cranes within the Port of Budapest (denoted with No. 1-5). (Source Google maps).

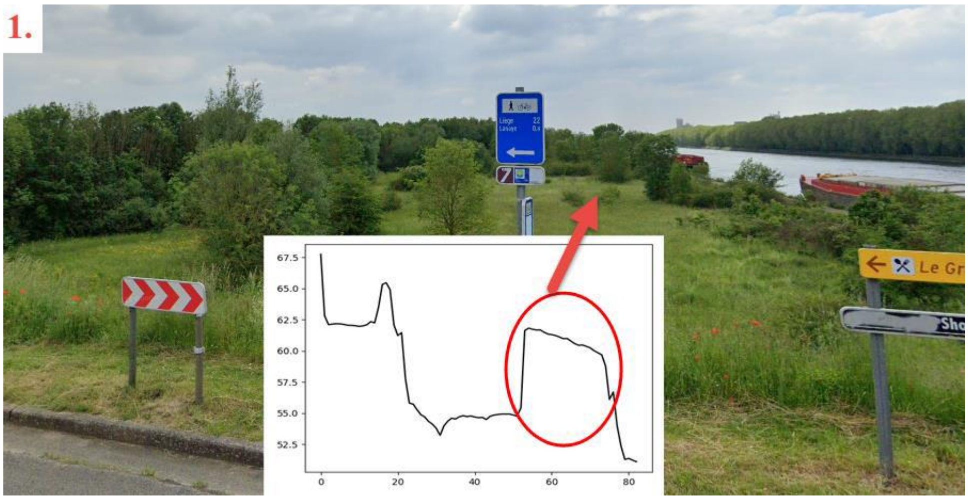
4.3 Use case C

For the Wallonia Use Case of PLOTO, dikes located in Albert canal are the main type of assets that are considered in the exposure model. Figure 19 presents a map view of the Albert canal with the position of each different dike type being denoted. Dikes are usually made of earth field, whereas also other materials may be used such as concrete. Different cases of dikes along the canal are then presented in Figure 20 to Figure 24. As shown in Figures from the topography graphs, for the East-dike of the Canal they have height around 6m, while their thickness varies from 4m to 20m.



Mesurer une distance
Cliquez sur la carte pour ajouter la ligne au trajet.
Distance totale : 16,98 km (10,55 mi)

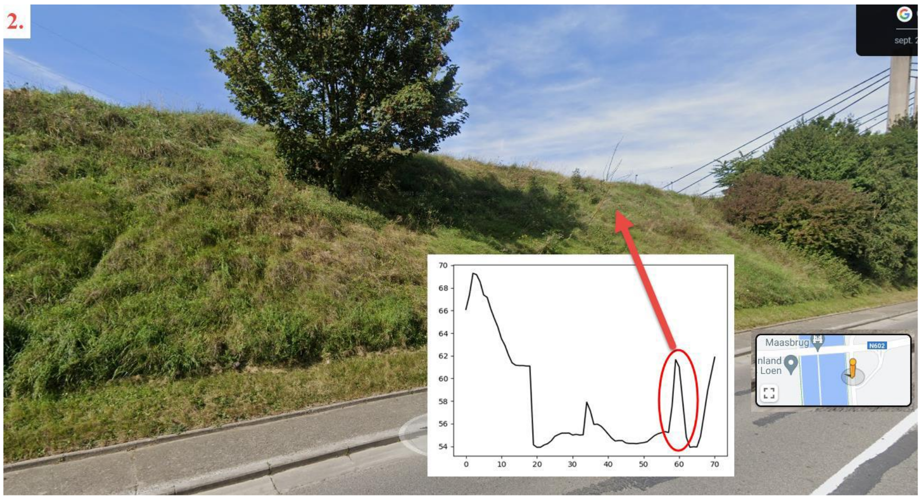
Figure 19: Map view of the Albert canal form Lanaye to Coronmeuse. Red lines with the ID numbers number denote different types of dikes. (Source Google maps).



(a) East dike

(b) West dike

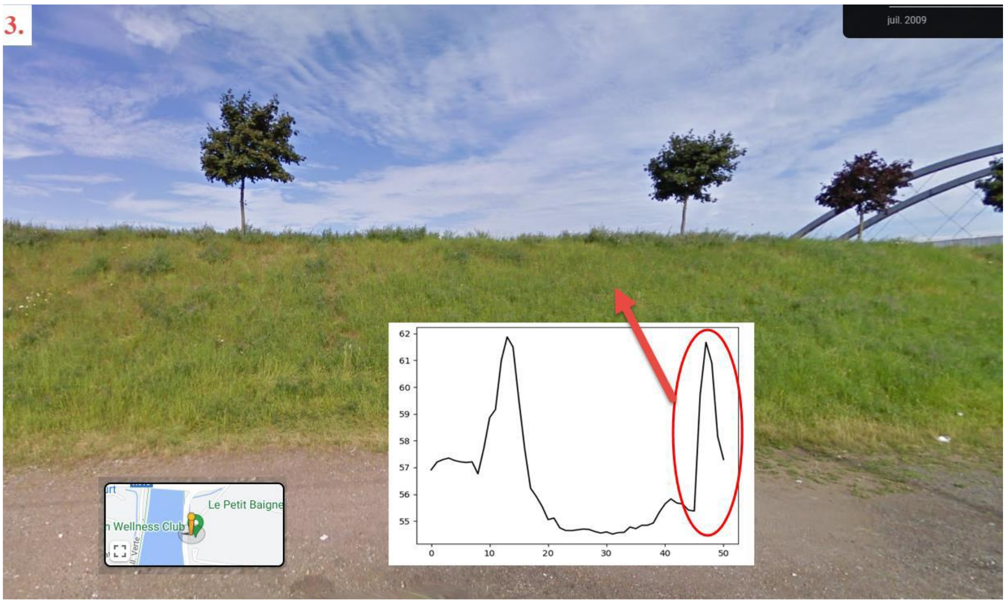
Figure 20: Dike at proximity of Lanaye bridge. The observable dike is highlighted in the topography graph. (Source Google maps).



(a) East dike

(b) West dike

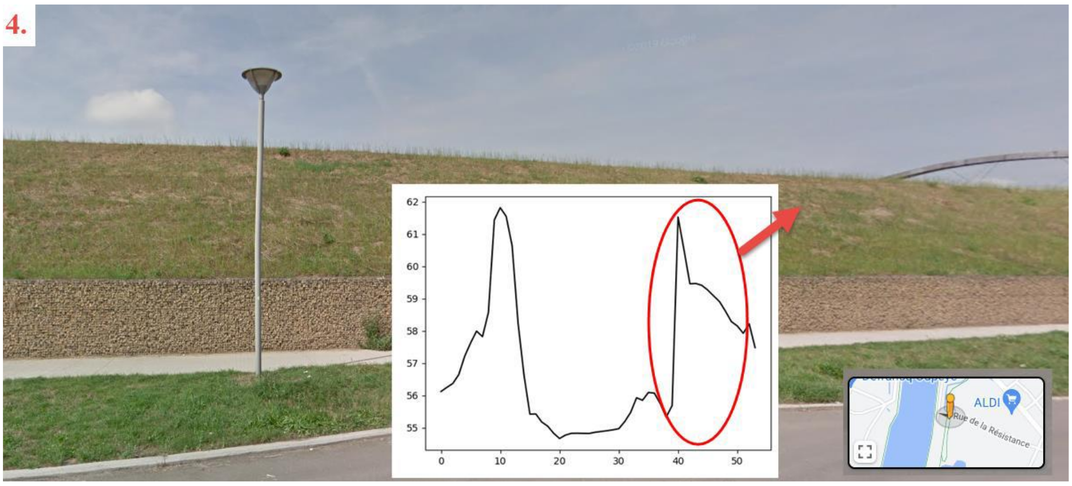
Figure 21: Dike at proximity of Lixhe bridge. The observable dike is highlighted in the topography graph. (Source Google maps).



(a) East dike

(b) West dike

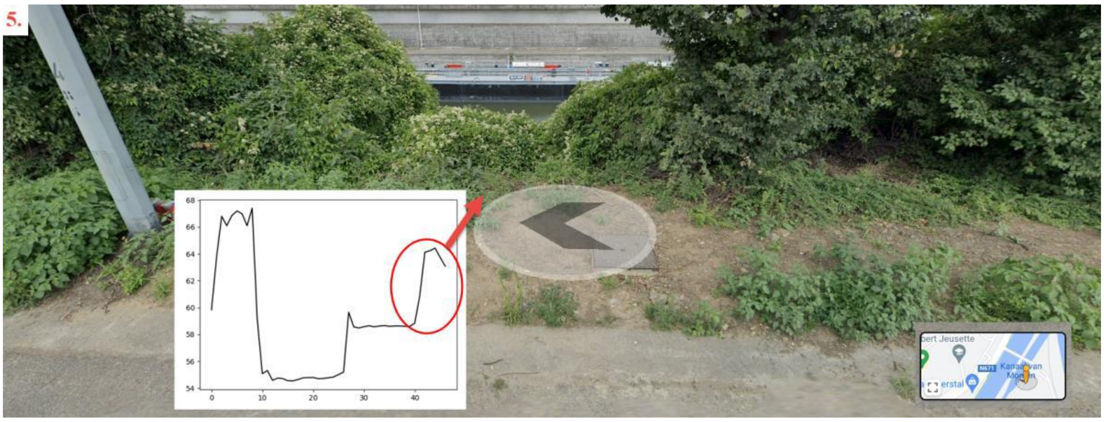
Figure 22: Dike at proximity of Haccourt bridge. The observable dike is highlighted in the topography graph. (Source Google maps).



(a) East dike

(c) West dike

Figure 23: Dike at proximity of Hermalle-sous-Argenteau bridge. The observable dike is highlighted in the topography graph. (Source Google maps).



(a) East dike

(b) West dike

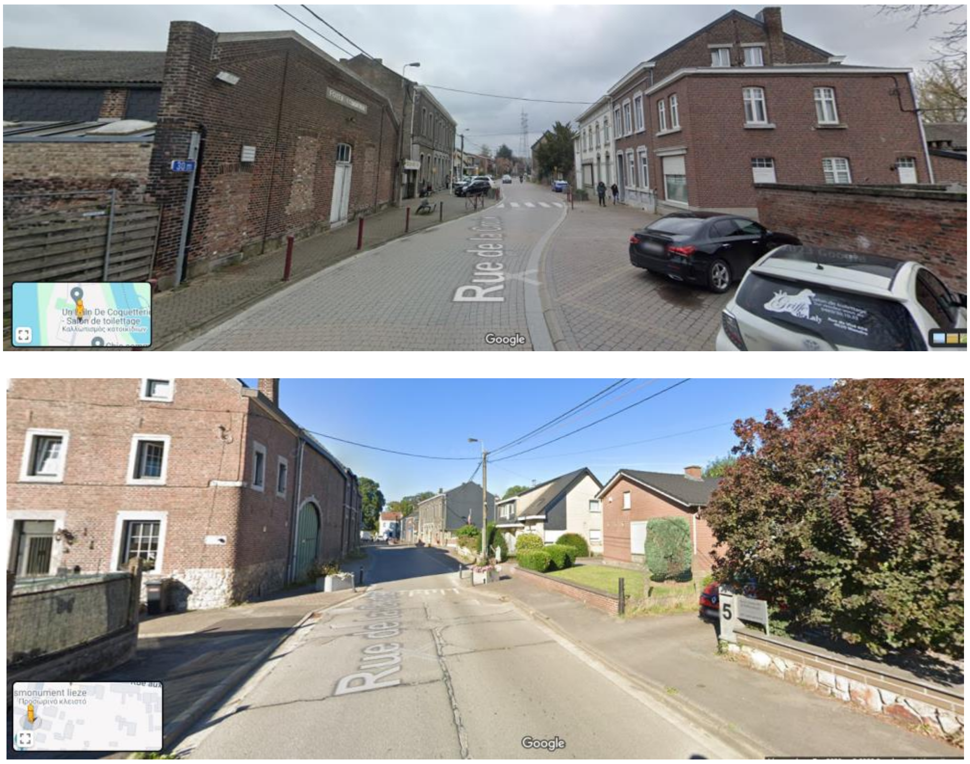
Figure 24: Dike at proximity of Herstal bridge. The observable dike is highlighted in the topography graph. (Source Google maps).

Except for the dikes, the nearby cities are part of the PLOTO's exposure model. Typical buildings of the nearby cities are presented in Figure 25. More specifically, indicative buildings at Lanaye, Nivelle, Lixhe, Vise, and Haccourt are illustrated. As presented, in most of the cases, buildings at the sites of interest are low-rise, meaning that they consist of one to three stories above the ground, whereas some also have basements (underground floors).

(a) buildings at Lanaye

Figure 25: Typical building cases from the nearby cities of the dikes of Wallonia Use Case. (Source Google maps). Continued.

(b) buildings at Nivelle



(c) buildings at Lixhe

Figure 25: Typical building cases from the nearby cities of the dikes of Wallonia Use Case. (Source Google maps). Continued.

(d) buildings at Vise

Figure 25: Typical building cases from the nearby cities of the dikes of Wallonia Use Case. (Source Google maps). Continued.

(e) buildings at Haccourt

Figure 25: Typical building cases from the nearby cities of the dikes of Wallonia Use Case. (Source Google maps).

4.4 Analysis of assets

After selecting the assets for PLOTO’s exposure model, the analysis for the assets follows in order to assess their performance against the potential hazard(s) per case. For each asset, the IM(s) and EDP(s) are defined, while the consequences are quantified in terms of e.g., monetary losses, downtime, business disruption. Analysis is being made either via asset-specific models for the case of the critical assets or via class-specific models for the assets with lower importance. MSA or with standardize tools for assessing structural fragility (e.g., HAZUS) are employed. For the assets of interest, each source of hazard (seismic, weather, flooding) is analysed separately based on the location of the asset and the natural hazards associated with the site of interest.

5. Description of the structure of MHVM

The typical structure of Multi-Hazard Vulnerability Module is described in this section. The MHVM consists of two files per asset or class of assets:

- The first one is entitled "*asset_name*.msa.mat/json", where "*asset_name*" is the name of the asset at hand. It includes the MSA results.
- The second one is entitled "*asset_name.*mtdata.mat/json", which includes the metadata for each asset.

Data from both files are combined to assess the pre-event vulnerability per asset in order to generate multiple damage/consequences scenarios. These scenarios per asset are then later combined with the IM fields to generate multiple alternative scenarios that may occur in the entire site (region) of interest per Use Case in the pre-event operation phase of PLOTO's platform. This procedure is depicted indicatively in Figure 26. For cases where fragility is calculated via tools like HAZUS, the scenarios of damage/consequences are generated via the decomposition of the corresponding fragility functions. At this stage, risk assessment of the entire Use Case site of interest is performed by considering all the "potential" scenarios that are calculated with their corresponding consequences in terms of damage and recovery being assessed by convolving the hazard results of all individual assets. This ensemble and detailed view of "all" events that can occur with the corresponding damage and loss that is predicted leads to a growing large "tree" of possible events, which can later be "pruned" in the trans-event operation phase. This pruning procedure aims to facilitate the goal of sensor-driven near-real-time assessment of PLOTO. Specifically, during the trans-event phase, which is the phase during which an event has just happened or happens at "real-time", the limited information that is available from the sensors is employed to prune the full set of potential scenarios. Hence, a smaller and easier manageable size of most probable outcomes is structured, which can lead the operators to better estimations of what is going to happen after that event in comparison with the full-fledged assessment of what could have happened (without sensor information).

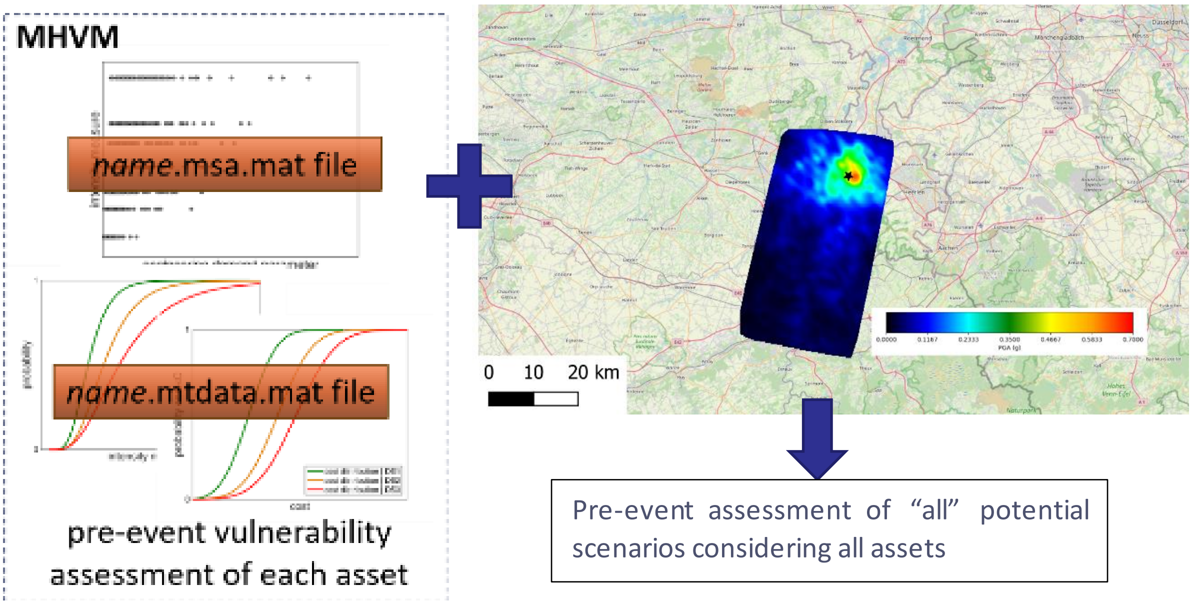


Figure 26: Pre-event assessment of "all" potential scenarios of the Wallonia Use Case by combining the MHVM with the IM fields.

5.1 Metadata file

Per-asset, the metadata file includes information regarding the fragility curves and the consequence functions for each damage state. For the assets that are treated via system-vulnerability approach, the corresponding fragility curves are probability-values functions of the IM of choice (e.g., the peak ground acceleration regarding the seismic hazard). In this case, the fragility functions provide information regarding the damage stage of the entire structure (asset) but they do not provide any specific information about its individual component. On the other hand, for the assets that are treated via component-based approach, component-fragilities are offered in the metadata file that are constructed conditioned on the individual component's EDP. In both cases, these fragilities are used in risk estimation.

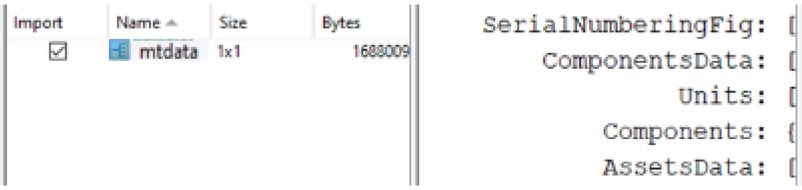
The general format of the metadata file is the same for both assets treated via system-only or component-based approach with only some details being different between them. The metadata file is named by the name or the ID of the asset (*asset_name*) followed by a predefined extension as "*asset_name*.mtdata.mat/json". Except for the MATLAB mat file, a json format file is also created with the metadata per asset. This format is more suitable for the assessing the risk of the entire network performed via Python software. Mat files are used to generate individual scenarios for the assets treated via a component-based approach. In this way, the metadata file of each individual asset can be stored either in "mat" or "json" file format and converted from one format to the other through available software.

5.1.1. Metadata file for the assets treated via a component-based approach

The typical structure of a metadata "mat" and "json" file is presented for the case of assets that are treated via a component-based approach. The files and the Figures that are presented herein do not consider specific cases from assets of PLOTO. They refer to indicative examples with dummy data that aim to describe the typical structure of the files necessary for the operation of the MHVM.

5.1.1.1. mtdata.mat file

Figure 27 presents a typical mtdata.mat file, generated through MATLAB. The metadata file consists of 5 fields. A description is provided for their structure and their contents for each one of these fields.



Import	Name ▲	Size	Bytes
☑	mtdata	1x1	1688009

```
SerialNumberingFig: [
    ComponentsData: [
             Units: [
        Components: {
        AssetsData: [
```

Figure 27: Example of a typical metadata file for assets treated via a component-based approach.

- ".SerialNumberingFig"
  A serial number per individual component is needed plus a figure with the serial numbers of the components studied across the asset. As an example, Figure 28 presents a bridge assumed to be an asset of interest. In this case, the bearings and the piers are the critical components of the asset. Hence a figure is stored in the field ".SerialNumberingFig" of the metadata file with the numbering of the components. It should be stressed out that the numbering should be aligned with the results of the multi-stripe analysis. For instance, regarding the piers, the MSA results for pier 1 (in terms of EDP) are found in the first entry of the MSA results file, the results for pier 2 in the second e ntry etc.

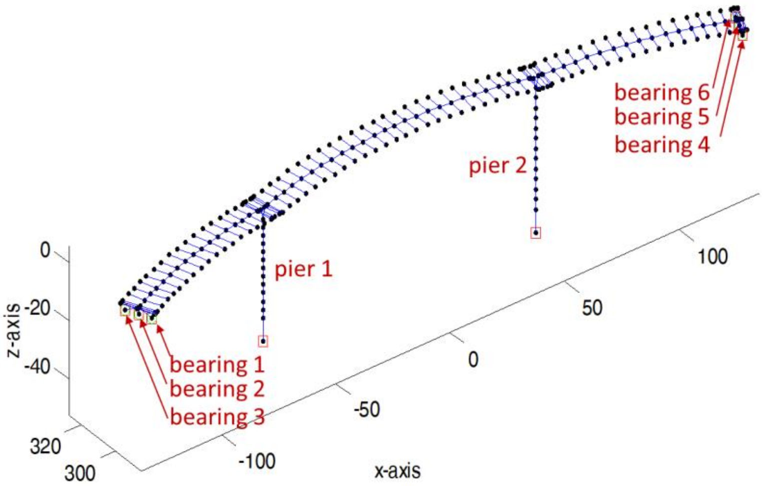


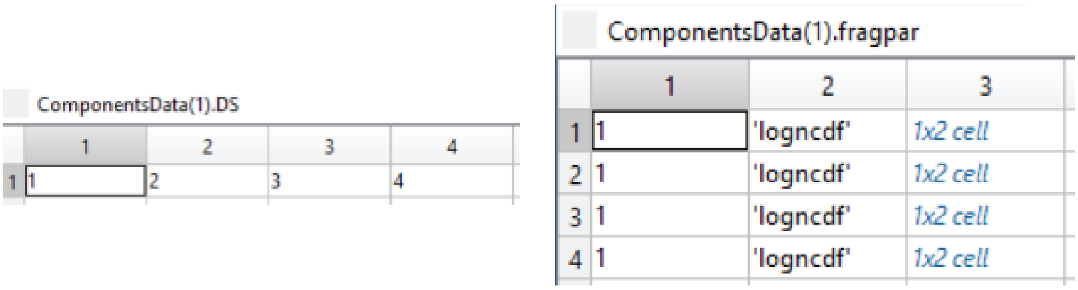
Figure 28: Example of a typical figure of serial numbering and description of components for a bridge (stored in the .SerialNumberingFig field of the asset_name.mtdata.mat file).

- ".ComponentsData"
  This field includes the data per individual component. In this field, generic categories of components are defined along with their associated engineering demand parameters (EDPs), fragility and consequence functions. Note that the engineering demand parameter should be the same as the corresponding EDPlabel of the MSA results. An example of ".ComponentsData" field is shown in Figure 29, where the generic categories of the components "Bearing.001", "Bearing.002" and

"Pier.001" are defined, along with the EDP that is selected per component (dummy data) and the associated Damage States (*DS*) fragility curves, (*fragpar*), cost (*costpar*) traffic reduction (*trafredpar*) and downtime, (*downpar*) functions. By moving a step forward in Figure 30, the structure of the *DS* and *fragpar* fields for a dummy component are presented. As shown, for this random component there are four (1–4) DSs defined, while in the *fragpar* field per *DS* (row) the corresponding fragility curve is assumed to follow the lognormal distribution (2nd column "longcdf") with the parameters of the 3rd column of the field.

Fields	name	EDP	DS	fragpar	costpar	trafredpar	downtimepar
1	'Bearing.001'	'maxbdr_srss'	1x4 cell	4x3 cell	4x2 cell	4x2 cell	4x2 cell
2	'Bearing.002'	'maxbdrx'	1x4 cell	4x3 cell	4x2 cell	4x2 cell	4x2 cell
5	'Pier.001'	'maxidr_srss'	1x4 cell	4x3 cell	4x2 cell	4x2 cell	4x2 cell

Figure 29: Example of definition of component's data for a bridge (asset_name.mtdata.mat, .ComponentsData field).



ComponentsData(1).DS

	1	2	3	4
1	1	2	3	4

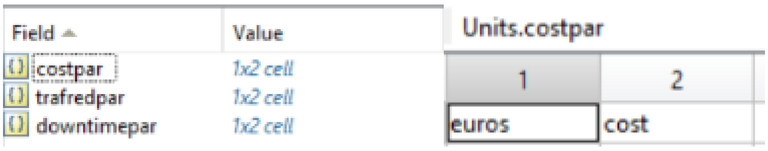
ComponentsData(1).fragpar

	1	2	3
1	1	'logncdf'	1x2 cell
2	1	'logncdf'	1x2 cell
3	1	'logncdf'	1x2 cell
4	1	'logncdf'	1x2 cell

(a) (b)

Figure 30: Example of (a) damage states (DS) and (b) fragility curve definition for a component (fragpar) (asset_name.mtdata.mat, .ComponentsData.DS and .ComponentsData.fragpar field).

- ".Units"
  The units of each consequence function are defined in the ".Units". Figure 31 presents an example of the typical structure of this field. As it is shown except for the units, a short description of each consequence function is also provided.



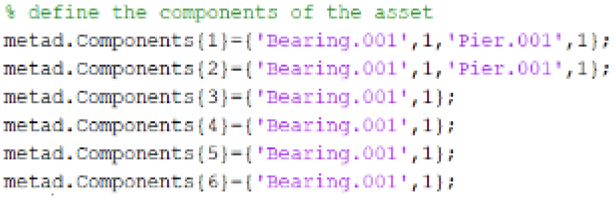
Field	Value
costpar	1x2 cell
trafredpar	1x2 cell
downtimepar	1x2 cell

Units.costpar

1	2
euros	cost

Figure 31: Example of consequence functions units definition (asset_name.mtdata.mat, .Units field).

- ".Components"
  The ".Components" field contains information about the components of the specific asset that are considered for risk estimation. It is structured as a cell array in MATLAB whose $i = 1 \ldots . N$ (or $\{1, N\}$ contents in MATLAB terminology) entries correspond to the components with serial number $i = 1 \ldots . N$ (Figure 28). Two entries are provided per component, which are (a) the name of the category of the component that has to be consistent with naming of fragility and consequence functions (Figure 29) and (b) the number of such components. For instance, in the typical structure of the field illustrated in Figure 32, it is assumed that all bearings are of the same generic bearing type of 'Bearing.001' and the piers of type 'Pier.001'.



```
% define the components of the asset
metad.Components{1}={'Bearing.001',1,'Pier.001',1};
metad.Components{2}={'Bearing.001',1,'Pier.001',1};
metad.Components{3}={'Bearing.001',1};
metad.Components{4}={'Bearing.001',1};
metad.Components{5}={'Bearing.001',1};
metad.Components{6}={'Bearing.001',1};
```

Figure 32: Example of component definition for a bridge (asset_name.mtdata.mat, .Components field).

- ".AssetsData"
  In this field of the metadata mat file some generic information about the asset are stored. These information can be generic collapse fragility and consequence functions of the asset that can be employed to define if the asset has collapsed. Also, in this field, data about the potential demolition of the asset and the consequences for replacing it can be stored.

5.1.1.2. mtdata.json file

A typical structure of a "json" file with the metadata of an asset treated via component-based approach is presented in Figure 33. The same information with the mat file is stored in json files of an asset; only the format differs. Data shown in this Figure are dummy and do not refer to an IWW or non-IWW asset of PLOTO's exposure model. Still, Figure 33 aims to present the basic structure of a "json" metadata file. As presented, the "units" and the "consequences_by_taxonomy" are initially set. For instance "cost" and "euros" can be used to calculate economic consequences in monetary terms. The taxonomy is used to link each individual component with the fragility and consequence functions. Then, for the entire asset as well as for the components that are defined for the asset at hand, the "damage_types" are defined inside the "json" file. Specifically, the name of each "component" is set with the "id" and the "description" of its "damage_states". Then the "consequences_per_edp" are set where the "vuln_params" per component are defined.

```
{ "mtdata" : {  "units" : {     "speed_limit" : "km/h",
                                "cost" : "euros",
                                "time": "days" }},
 "consequences_by_taxonomy": [{ "asset_taxonomy" : "taxonomy1",
                                "hazard_type" : "weather",
                                "mt_data" : { "max_speed_limit" :  120.0  ,
                                             "N_lanes": 2},
                                "damage_types": [{"damage_type": "ultimate",
                                                  "component_damage_state_description": [{   "component" : "comp1",
                                                                                             "damage states": [  { "id" : "DS0", "description" : "no damage" },
                                                                                                                 { "id" : "DS1", "description" : "demand exceeds capacity" }] },
                                                                                        {    "component" : "comp2",
                                                                                             "damage_states": [  { "id" : "DS0", "description" : "no damage" },
                                                                                                                 { "id" : "DS1", "description" : "demand exceeds capacity" }] },
                                                                                        {    "component" : "comp3",
                                                                                             "damage_states": [  { "id" : "DS0", "description" : "no damage" },
                                                                                                                 { "id" : "DS1", "description" : "demand exceeds capacity" }] }] ,
                                                 "consequences_per_edp": [{  "component" : "comp1",
                                                                             "vuln_params": [{"damage_state": 1,
                                                                                              "fragility": {"dist": "logncdf", "params": [1.0, 0.0]}}]},
                                                                          { "component" : "comp2",
                                                                             "vuln_params": [{"damage_state": 1,
                                                                                              "fragility": {"dist": "logncdf", "params": [1.0, 0.0]}}]},
                                                                         { "component" : "comp3",
                                                                             "vuln_params": [{"damage_state": 1,
                                                                                              "fragility": {"dist": "logncdf", "params": [1.0, 0.0]}}]},

                                                                         { "component" : "global",
                                                                             "vuln_params": [{"damage_state": 1,
                                                                                              "cost":        {"dist": "tnorminv2", "params": [25000.0, 0.00, 0, 900000000000000000000000.0]
                                                                                              "downtime":        [{"lane": 1,
                                                                                                                    "dist": "tnorminv2",
                                                                                                                    "params": [0.5, 0.05, 0.0, 900000000000000000000000.0]},
                                                                                                                  {"lane": 2,
                                                                                                                    "dist": "tnorminv2",
                                                                                                                    "params": [0.5, 0.05, 0.0, 900000000000000000000000.0]}],
                                                                                              "max_speed_limit": [{"lane":  1,
                                                                                                                       "dist": "tnorminv2",
                                                                                                                       "params": [0.0, 0.00, -0.001, 130.0]},
                                                                                                                    {"lane": 2,
                                                                                                                    "dist": "tnorminv2",
                                                                                                                    "params": [0.0, 0.00, -0.001, 130.0]}]}]}],

                                                 "msa_fname": "Fname_msa.json"}]}]}
```

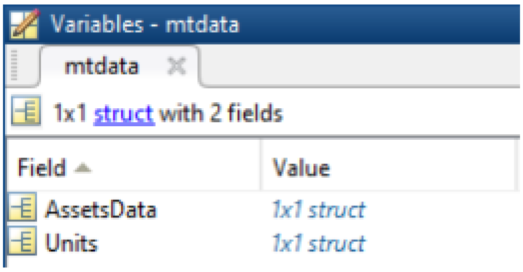
Figure 33: Example of the mtdata.json file for a dummy asset treated via component-based approach.

5.1.2. Metadata file for the assets treated via a system-only approach

The typical structure of a metadata “mat” and “json” file is presented for the case of assets that are treated via a system-only approach. The files and the Figures that are presented herein does not consider specific cases from assets of PLOTO but they refer to some indicative examples with dummy data that aim to describe the typical structure of the files that consist the MHVM.

5.1.2.1. mtdata.mat file

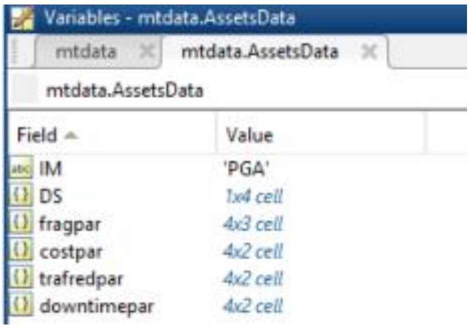
Figure 34 presents the structure of a typical metadata “mat” file for the case where an asset is treated via a system-only approach. As shown, two main fields are included into the “mtdata.mat” file. The “AssetsData” and the “Units”. In the first field (MATLAB structure), the name of the IM and the data regarding the fragility and the consequence functions for the entire system (Figure 35) are stored in the field “IM”. In the second field, the units are stored similarly to the previous section (Figure 36).



1x1 struct with 2 fields

Field	Value
AssetsData	1x1 struct
Units	1x1 struct

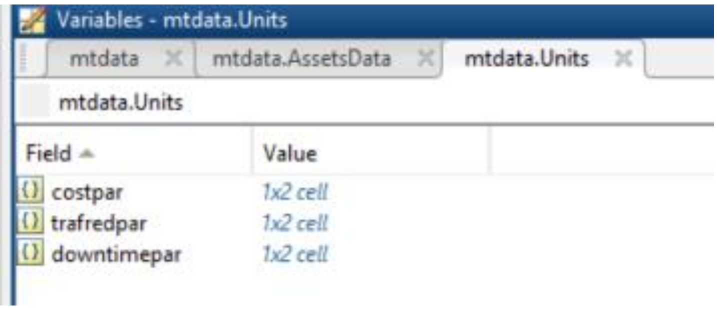
Figure 34: Typical structure of a mtdata.mat file for assets treated via a system-only approach.



mtdata.AssetsData

Field	Value
IM	'PGA'
DS	1x4 cell
fragpar	4x3 cell
costpar	4x2 cell
trafredpar	4x2 cell
downtimepar	4x2 cell

Figure 35: Typical example of the structure of the .AssetsData field for asset treated via a system-only approach.



mtdata.Units

Field	Value
costpar	1x2 cell
trafredpar	1x2 cell
downtimepar	1x2 cell

Figure 36: Typical example of the structure of the .Units field for asset treated via a system-only approach.

5.1.2.2. mtdata.json file

The structure of a “json” file with the metadata for a dummy asset with system-only treatment is presented in Figure 37. As shown, the typical structure of the “json” metadata file in this case is similar with this of the assets with the component-based treatment as above. The main difference is that instead of the data per individual component, the “global” data for the entire system are provided.

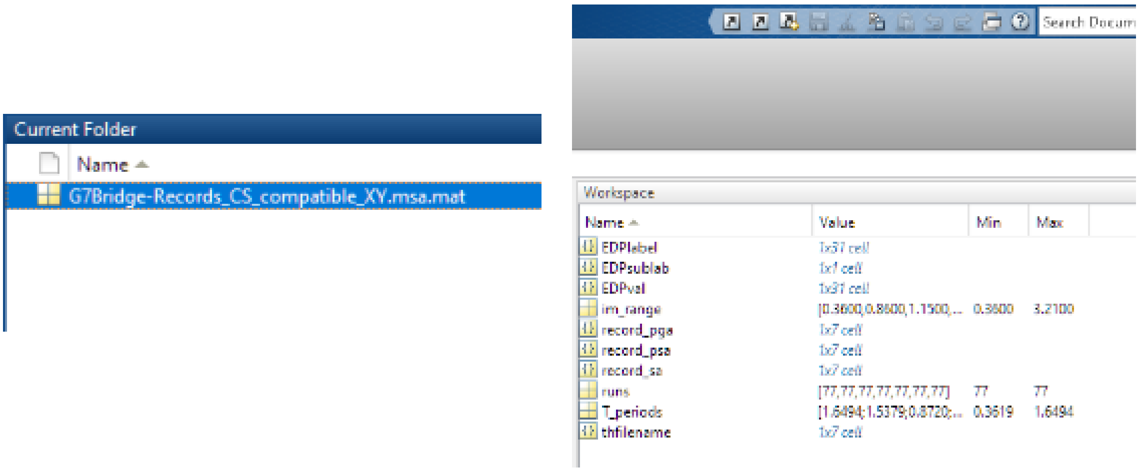
```
{ "mtdata" : {  "units" : {     "speed_limit" : "km/h",
                                "cost" : "euros/km",
                                "time": "days" }},
 "consequences_by_taxonomy": [{ "asset_taxonomy" : "pavement",
                                "hazard_type" : "weather",
                                "mt_data" : { "max_speed_limit" :  120.0  ,
                                              "N_lanes": 2},
                                "im_types" : [{"im_type": ["IM1"],
                                "damage_types": [{"damage_type": "ultimate",
--------------------------------------------------------------------------------

                                    {"im_type": ["u10"],
                                    "damage_types": [{"damage_type": "ultimate",
                                            "component_damage_state_description": [{    "component" : "global",
                                                                                  "IM": "u10",
                                                                                  "damage_states": [  { "id" : "DS0", "description" : "no damage" },
                                                                                                      { "id" : "DS1", "description" : "slight wind" },
                                                                                                      { "id" : "DS2", "description" : "moderate wind" },
                                                                                                      { "id" : "DS3", "description" : "severe wind" }]}],
                                       "consequences_per_edp": [{  "component" : "global",
                                                                   "vuln_params": [{"damage_state": 1,
                                                                                   "fragility": {"dist": "logncdf", "params": [8.3, 0.05]},
                                                                                   "cost":      {"dist": "tnorminv2", "params": [0.0, 0.0, -0.01, 9000000000000000000000000.0]},
                                                                                   "downtime":       [{"lane": 1,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.00, 0.0, 9000000000000000000000000.0]},
                                                                                                    {"lane": 2,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.0, 0.0, 9000000000000000000000000.0]}],
                                                                                   "max_speed_limit": [{"lane": 1,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [90.0, 0.00, 0.0, 130.0]},
                                                                                                      {"lane": 2,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [90.0, 0.00, -0.01, 130.0]}]},
                                                                                  {"damage_state": 2,
                                                                                   "fragility": {"dist": "logncdf", "params": [14.0, 0.05]},
                                                                                   "cost":      {"dist": "tnorminv2", "params": [0.0, 0.10, -0.01, 9000000000000000000000000.0]},
                                                                                   "downtime":       [{"lane": 1,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.00, 0.0, 9000000000000000000000000.0]},
                                                                                                    {"lane": 2,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.00, 0.0, 9000000000000000000000000.0]}],
                                                                                   "max_speed_limit": [{"lane": 1,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [60.0, 0.00, -0.01, 130.0]},
                                                                                                      {"lane": 2,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [60.0, 0.00, -0.01, 130.0]}]},
                                                                                  {"damage_state": 3,
                                                                                   "fragility": {"dist": "logncdf", "params": [22.0, 0.20]},
                                                                                   "cost":      {"dist": "tnorminv2", "params": [0.0, 0.10, -0.01, 9000000000000000000000000.0]},
                                                                                   "downtime":       [{"lane": 1,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.00, 0.0, 9000000000000000000000000.0]},
                                                                                                    {"lane": 2,
                                                                                                     "dist": "tnorminv2",
                                                                                                     "params": [0.04, 0.00, 0.0, 9000000000000000000000000.0]}],
                                                                                   "max_speed_limit": [{"lane": 1,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [0.0, 0.00, -0.01, 130.0]},
                                                                                                      {"lane": 2,
                                                                                                      "dist": "tnorminv2",
                                                                                                      "params": [0.0, 0.00, -0.01, 130.0]}]}]}]}]}]},
                                   {"im_type": ["temperature"],
```

Figure 37: Example of the mtdata.json file for a dummy asset treated via system-only approach.

5.2 MSA file

The scenario MSA file consists of the MSA results for the IWW and non-IWW assets. Figure 38 presents the typical structure of the MSA file for a dummy asset.



G7Bridge-Records_CS_compatible_XY.msa.mat

Name	Value	Min	Max
EDPlabel	1x37 cell		
EDPsublab	1x1 cell		
EDPval	1x31 cell		
im_range	[0.3600,0.8600,1.1500,...	0.3600	3.2100
record_pga	1x7 cell		
record_psa	1x7 cell		
record_sa	1x7 cell		
runs	[77,77,77,77,77,77,77]	77	77
T_periods	[1.6494;1.5379;0.8720;...	0.3619	1.6494
thfilename	1x7 cell		

(a) (b)

Figure 38: (a) Typical example of a scenario MSA file and (b) variables stored in a scenario MSA file.

5.2.1. Levels of the IM

Per hazard (stressor) considered for each asset of interest the following IMs are identified:

- **earthquake**: the array of IM levels includes the levels of the 5%-damped spectral acceleration, $S_a(T)$ or the peak ground acceleration, PGA. The values are stored in the variable "im_range" shown in Figure 38b.
- **wind**: two vectors are needed in this case. The first includes the wind speed (e.g., in m/s) and the second the direction of the wind (e.g, in degrees). Via the "meshgrid" function of MATLAB, the grid can be generated automatically.
- **temperature**: the temperature is typically provided in °C
- **precipitation**: typically, the water in mm over a given period is provided.
- **flooding**: typically, the water level in mm is provided.

5.2.2. EDP response levels

The EDP response per IM level is stored in the MSA response file as shown in Figure 38b. Specifically, the variables that are typically stored per component or per asset in the MSA response file are listed below:

- ***EDPlabel***: strings containing the name of each of the *EDPs* recorded
- ***EDPsublab***: strings containing a short description for each of the examined *EDP* variables
- ***EDPval***: recorded *EDP* values.
- ***im_range***: range of *IM* values (i.e., stripe *IM* levels)
- ***runs***: number of analysis runs per *IM* level
- ***T_periods***: the first N vibration periods of the structure (where *N* is defined by the user in the structural analysis software).
- ***thfilename***: the names of loading history file employed for asset analysis

For the specific case of the seismic response analysis, the following variables are also stored:

- ***record_pga***: each record's (and component's) PGA
- ***record_psa***: each record's (and each component's) pseudo-$S_a(T)$ values for each of the periods found in *T_periods*
- ***record_sa***: each record's (and each component's) $S_a(T)$ values for each of the periods found in *T_periods*

6. Conclusions

This report is one of the two Deliverables of WP4 related to Task 4.2 "Development of vulnerability modules". In this report, the methodology behind the development of the multi-hazard vulnerability modules (MHVMs) was presented. The definition of basic quantities such as system's fragility, vulnerability and consequences were provided. Different approaches for assessing the risk/vulnerability/damage/loss were presented. Moreover, the characteristic assets that consist the exposure model of PLOTO were presented per Use Case site (Romania, Hungary, Belgium). Finally, the typical structure of MHVMs as it is developed by using software libraries were described with indicative examples of the specific file's structure being given. In the second version of this report (D4.4 Multi-Hazard Vulnerability Modules for IWW and connected hinterland infrastructures final version, M24), additional details will be included regarding the assets, the stressors that are related to them and their treatment in the MHVM modules.

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