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A model for restoration time of a linearly dependent system after earthquake and its implementation on a winery

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1. Introduction

Natural disasters always involve economic losses. According to "The Annual Global Climate and Catastrophe Report" [2], in 2013 natural disasters caused a global economic loss of $192 billion, generated by 296 separate events. The most deadly disaster was Super Typhoon Haiyan, which left nearly 8,000 people dead or missing in the Philippines while the costliest single event was the May/June flood in Central Europe with approximately $22 billion of economic losses. Considering the time from 1950 to 2013, the costliest disaster was the earthquake and consequent tsunami occurred in 2011 in Japan for an amount of actualized $218 billion. It is interesting to note that the reported economic impact amounts of all these recent events cannot be considered conclusive until a long-term recovery has occurred. This involves not only the restoration of structures and businesses, but also long-term community dynamics. Wright et all. [15] state how disasters have few discernible effects beyond the disruption they cause during the immediate post-impact and short-term recovery periods. Unluckily, long-term disaster impact effects are often difficult to identify and hard to interpret. Moreover, is also true that long-term effects are not necessary negatives, because they depend on the efficiency of disaster recovery management.

Date(s)	Event	Location	Deaths	Structures/ Claims	Economic Loss (USD)	Insured Loss (USD)
May/June	Flooding	Central Europe	25	150,000	22 billion	5.3 billion
April 20	Earthquake	China	196	620,000	14 billion	250 million
November 7-10	STY Haiyan	Philippines, Vietnam	8,000	1,300,000	13 billion	1.5 billion
October 5-8	TY Fitow	China, Japan	8	97,000	10 billion	1.0 billion
Jan/Sept	Drought	China	N/A	N/A	10 billion	350 million
Jan/May	Drought	Brazil	N/A	N/A	8.0 billion	350 million
June	Flooding	Canada	4	25,000	5.2 billion	1.7 billion
Aug/Sept	Flooding	China	118	215,000	5.0 billion	405 million
July	Flooding	China	125	375,000	4.5 billion	150 million
September 13-20	HU Manuel	Mexico	169	35,000	4.2 billion	685 million
				All Other Events	95 billion	34 billion
				Totals	**192 billion[1]**	**45 billion[1,2]**

Fig 1.1: *Top 10 global economic loss events in 2013. [2]*

Considering an average annual global economic loss connected to natural events of $200 billion, several questions rise on human society vulnerability and the goodness of disaster management programs, but the most important question is on how to reduce disaster effects without involving heavy resources and changes in community dynamics.

An important answer is the improvement of risk mitigation and recovery planning. This permits to contain the damages of usually unpredictable and inevitable catastrophic events. In this context, simulating programs and software for disaster damages and recovery assessment can produce a wide support for the development of disaster management strategies and for the identification and fixation of major vulnerable components.

Date(s)	Event	Location	Economic Loss[1] Actual (USD)	Economic Loss[2] (2013 USD)
March 11, 2011	EQ/Tsunami	Japan	210,000,000,000	218,400,000,000
January 17, 1995	Earthquake	Japan	102,500,000,000	158,500,000,000
August 2005	Hurricane Katrina	United States	125,000,000,000	147,900,000,000
May 12, 2008	Earthquake	China	85,000,000,000	91,200,000,000
Summer 1988	Drought	United States	40,000,000,000	80,300,000,000
October 2012	Hurricane Sandy	U.S., Caribbean, Bahamas, Canada	72,000,000,000	72,300,000,000
January 17, 1994	Earthquake	United States	44,000,000,000	69,900,000,000
Summer 1980	Drought	United States	20,000,000,000	59,700,000,000
November 23, 1980	Earthquake	Italy	18,500,000,000	50,300,000,000
July - December 2011	Flooding	Thailand	45,000,000,000	46,300,000,000

[1] Economic loss include those sustained from direct damages, plus additional directly attributable event costs
[2] Adjusted using U.S. Consumer Price Index (CPI)

Fig 1.2*: Top 10 global economic loss events in the period 1950-2013.[2]*

Focusing on seismic risk, it’s meaningful to note as half of the ten costliest story events are earthquakes. This fact is due to many reasons, especially:

- Difficulty of earthquake forecast;
- Inappropriateness of mitigation solutions;
- Generation of collateral hazards;
- Localization of densely inhabited and industrialized societies in high seismic risk zone.

First of all, although in the last 30 years research around earthquake sources and connected signals progressed highly, earthquakes basically are still unpredictable and their modelling tools presents many uncertainties, due to the lack of a full knowledge about earthquake causes. In fact, considering for example the quakes connected to tectonic plates movements, even if it is possible estimate the likely impact zone and intensity of future earthquake, it is quite impossible to assess the time of earthquake impact, since it is hard to monitor and calculate the tectonic plates movements in a reliable way. Hence, in order to reduce seismic risk, it is useful the development of risk mitigation solutions. Basically this definition involves the use of two different strategies:

- Seismic risk prevention, according to financial, structural, educational, political, insurance, aspects.
- Earthquake management planning, from the beginning of the emergency situation to the end of the short-term recovery process and the strategies for long-term disaster effects.

However, mitigation strategies can be expensive and politically weak hence they request the availability of financial resources and the sharing of common purposes. For these reasons mitigation strategies often result unsuitable to avoid wide economic losses.

Another problematic aspect of the seismic risk is the combination of an earthquake with the possible consequent natural and artificial disasters. The 1906 San Francisco earthquake was an emblematic case. Reports state that the 90% of the total damages on the buildings, corresponding to 25,000 destroyed buildings, was the result of the multiple fires subsequent to the magnitude 7.8 earthquake. Recently, a terrible example was the 2011 Japan earthquake and the subsequent tsunami that caused a nuclear accident with a huge increase of total economic losses. Finally, earthquakes have a big economic impact also because 62% of the world's population lives in countries with a significant seismic hazard. Concerning the areas of the "ring of fire" and adjacent zones, where 81% of world's largest earthquake occur, it is possible spot there some of the world's largest population areas as well as some of the world's biggest economies.

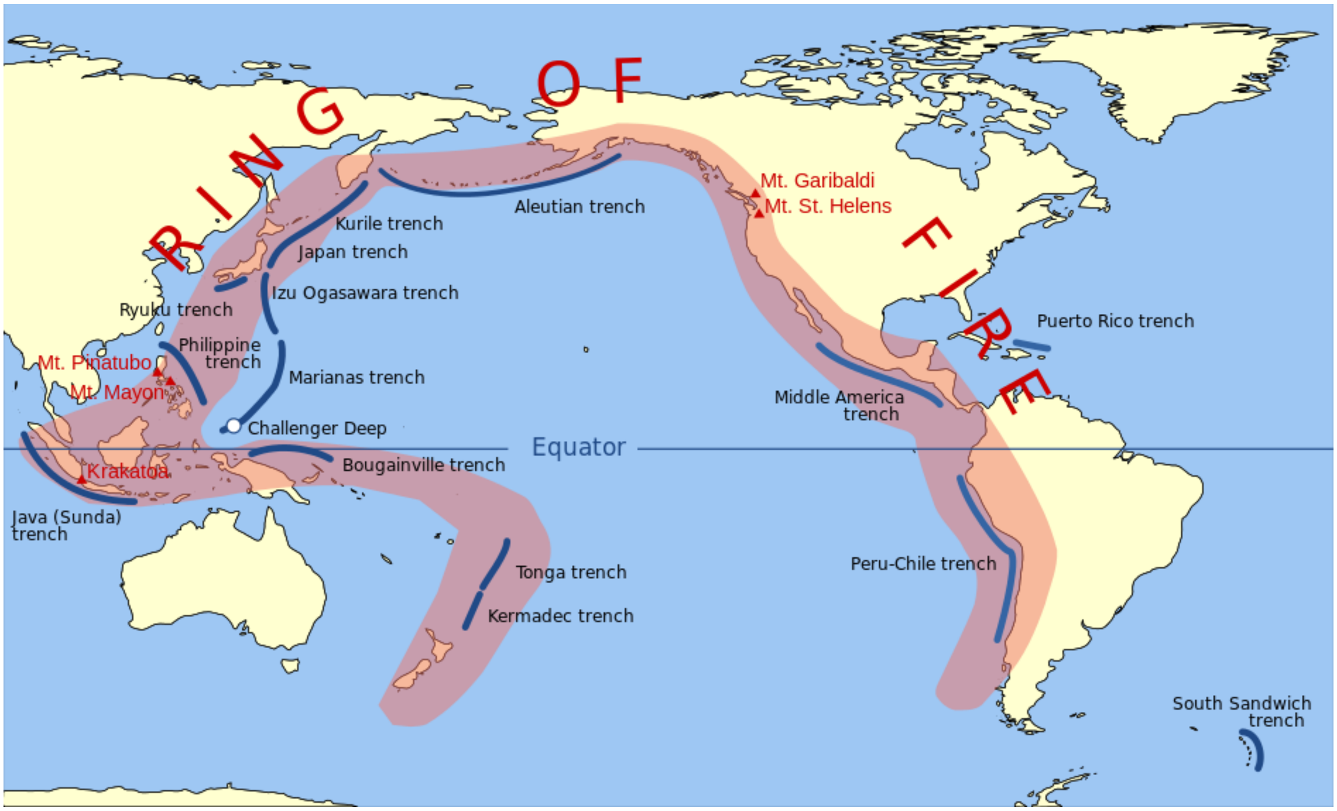


***Fig 1.3**: Ring of fire area.*

For the previous reasons, more than for other disaster typologies, earthquake the economic impact estimates of earthquake assume a relevant importance for the reduction of the risk and for the acceleration of the recovery process of pre-earthquake conditions. In particular, an immediate businesses recovery is fundamental, since it generates economic resources for damaged people and prevents businesses from being possibly relocated.

1.1. The 2014 South Napa Earthquake

One of the last seismic event with relevant economic losses was the south Napa earthquake which occurred the 24th August 2014. The earthquake epicenter, close to the city of Napa in Central California, measured an intensity of 6.0 on the moment magnitude scale and probably was dependent on the West Napa Fault activity. The South Napa Earthquake has been the largest seismic event in the Bay area since the 1989 Loma Prieta Earthquake. The quake, luckily located in a low demographic density zone, killed one person and injured 200. Early estimates by Californian officials indicated that the earthquake caused over $400 million in damage even if, according to a later estimate by the USGS, in the future the economic costs to Napa County probably will reach $1 billion. Although earthquakes with the same magnitude have caused much larger economic losses, as the 6.1 magnitude Emilia Earthquake in 2012 which produced $12,8 billion of economic losses, South Napa Earthquake has caused business losses especially in wine industry, the business study case of the present research. . Napa valley wine industry started in the first half of 1800's and, except the prohibition period, has always been a renowned and appreciated agricultural district insomuch as in 1968 was the first agricultural preserve declared in United States. At present Napa Valley houses over 400 wineries with 40,000 people employed directly or in connected businesses for a total profit over $10 billion per year. Napa earthquake , according to 18th September 2014 Napa City Council, caused direct damages to wineries and connected infrastructures for $80.3 million, but the assessment has not been completed yet. The 60% of Napa County wineries sustained some degree of damage. The most common damages noticed in wineries were barrel support failure, steel tank damages and storage structure failure.

Fig 1.4*: Support barrels failure in a Napa winery.*

***Fig 1.5**: Steel tanks collapse in a Napa winery.*

Considering the high seismicity and the occurrence of similar previous catastrophic earthquakes in the area, it is possible to think of a lack of seismic mitigation for a well-known business like the Napa Valley wine industry. Basically, this can involve longer recovery time and an increase of the economic loss for wineries. About this, Webb et all. [14] in an interesting paper suggest that small businesses like Napa wineries which count on few resources, are more vulnerable to earthquakes. Hence, in a long-term recovery perspective, these individual businesses impacted by disasters are clearly linked to economic trends, decisions affecting communities and also community-level recovery strategies. If recovery politics are not well-done, small businesses can suffer economic losses even long after the earthquake occurrence. Concerning South Napa quake, two different organizations, FEMA and SBA, are running short-term recovery programs but currently they lack a long-term recovery plan. However, as Webb illustrates, both niche businesses and well-known businesses appear to have a faster recovery process. Surely the revenues coming from brand Napa will allow an additional relief for business recovery. About this, Napa City Council reports a relief fund of $10 million was created as a gift from Napa Valley Vintners in order to provide additional short term assistance.

1.2. The goal of this thesis

The present research shows a possible method to evaluate and analyzes restoration scenarios for a linearly dependent process vulnerable to seismic risk. The restoration scenario considered is defined by the time in which businesses can return to their pre-disaster functionality level, hence the long-term recovery effects and financial flow restoration are not taken into account. Since the recovery time is necessarily correlated to the damage extent, the method implements also a model to calculate damage states, given a certain ground motion. The purposes of the study are:

- Considering how the internal components influence in damages and restoration process assessment;
- Characterizing the restoration process behavior;
- Assessing an average restoration scenario for the system.

The most part of well-known and reliable software for damage loss estimates, calculate damages and restoration assessment for single components categories, considering damages of a business typology only respect the sum of facility and non-structural damages. On the contrary, in the proposed model, system damages (and consequent recovery) take into account the propagation of damages between components within the system. This is possible through the disaggregation of the system in single components and the development of a flow simulation defining the real process. Resulting effects on restoration process effect the amount of recovery time but mostly the modalities of recovery achievement. Finally the model allows to reduce uncertainties and to improve reliability of simulated restoration processes through a probabilistic sampling with definition of an average recovery scenario.

This first model implementation has been subjected to several simplifying assumptions according to the study purposes. An important assumption is the consideration of only direct damages, without considering economic and social indirect damages. In this study the model has been implemented on wineries for basically three different reasons:

1. Firstly, wine production is a **well-defined linear process**. In fact, winemaking process in general presents some necessary and basic production steps which are common to all different winery typologies. Hence, starting from a basic winery model it is easy to implement the method on more detailed or also real cases. Moreover, winemaking, as the most part of food processing processes, is defined from a relatively simple framework which can be considered linear, so easier to implement respect to circular or a tree system.

2. The second reason is the **high seismic risk**. Food processing processes, especially if the product is liquid, are highly vulnerable to seismic threats. In fact, in these kinds of processes, seismic damages to the components could mean the total loss of the product. For example in a winery, the rupture of the bottom of a full steel tanks involves a loss of thousands of wine gallons and so of thousands of dollars. In addition, wine is a seasonal product, hence it is barely replaceable.

3. The last reason is the **data resource availability**. California is the ideal place for this kind of study. Indeed, to the one side the Golden State produces the 90% of U.S. wine and houses several well-known wine districts with well-established production processes. To the other side, the high risk seismic zone involved the development of several seismic monitoring, mitigation and research organizations. The consequence of these two facts is the existence of several seismic codes and previous earthquake damages dataset for industry components, suitable also for wine industry components.

The proposed method presents a modular framework and its characterization for a certain industry process typology is obtained through the use of specific input parameters and the definition of the process flow model. Hence, potentially it can be applied to any kind of industrial process and also correspondent supply chains.

1.3. Thesis structure

The study is divide into the following six chapters:

- Chapter 1: **Introduction**. The problem of disaster economic losses mitigation is described, remarking the necessity of a good recovery management. Focusing on seismic risk in winery business, damages and politics adopted in the recent South Napa earthquake are described. Finally the goals of the thesis are exposed.

- Chapter 2: **Literature Overview**. In the chapter some literature references to the analyzed problem are described, in particular considering the seismic damages and recovery process assessment.

- Chapter 3: **Methodology**. In this chapter, the framework of the proposed model is described. First of all the conceptual process is analyzed in a general overview. Then, a detailed analysis on assumptions, reasons and methodologies used in the model is accomplished for each step .

- Chapter 4: **Model Implementation**. All the aspects and characteristic assumptions relative to winery case study modelling are described. Moreover, a used method for statistical validation of the model.

- Chapter 5: **Results**. Resulting restoration scenarios for the winery case are shown and commented. In the second part of the chapter, particular results trend and effect given by model assumption are deeper analyzed.

- Chapter 6: **Conclusions**. The chapter contains a summary of the model described in thesis and conclusions gathered from results. Finally some possible future development for this study are suggested.

2. Literature overview

Post disaster assessment of damages is as important as difficult. It is important since it enables governments, associations and economic subjects to plan and carry out disaster recovery. It is difficult because it requests resources and good networks of information. Concerning the business restoration, Lindell [8] describes three different time phases in disaster recovery. The first phase is disaster assessment, involving emergency operations and a preliminary damages assessment. Then the short-term recovery starts, consisting in securing impact zone and in establishing conditions to begin recovery process of structures and business. Finally the long-term reconstruction defines the time of entire recovery process considering the whole impact area and all possible aspects (e.g. psychological, demographic, economic and political aspects).

The definition of loss and recovery estimates allows to define and improve the recovery management, necessary in order to monitor the performance of the three recovery phases and to ensure coordination between them and the sources for their accomplishment. Moreover these estimates are useful to plan disaster risk mitigation. Focusing the attention on business recovery, in scientific literature two different study approaches to the economic impacts of environmental disasters and to the ways in which businesses are disrupted and manage recovery from these events can be outlined:

- Economic approach, based on analysis of individual companies process and financial flow or supply chains subjected to disruptions, usually has the aim of defining and assessing business strategies in order to mitigate financial and process management aspects of company or supply chain disaster risk.

- Engineering approach, focused on analysis of correlations between disaster characteristics and its impact on business, usually has the aim of estimating economic losses, recovery cost and indirect damages of business system in order to mitigate technologic aspect of company or system disaster risk.

In the proposed model, the recovery time assessment is obtained following an engineering approach, even if with an economic tool. In fact, despite the research goal does not consist in business strategy definition or benefit-cost analysis, the identification of the company process flow and its characteristics provides additional information for the recovery estimate respect to a simple evaluation of structural damages and consequent economic losses and recovery time.

2.1. Statement of the problem

The two main aspects of disaster recovery estimate are the definition of damages extent and consequent restoration process behavior. They could be obtained considering the disaster risk for a system. Jelinek and Kraussman [6] propose a general definition of risk corresponding to the product between hazard, vulnerability and exposure.

$$R = H \times V \times E \qquad (2.1)$$

where:

R is the Risk,

H represents Hazard,

V is Vulnerability due to the hazard level, in general terms V(H),

E is the economic value of exposed goods, namely Exposure, in general terms E(V,H).

It is possible to note as the only independent variable to define the risk is the hazard, described in this context as the probability that a disaster happen in a specified area for a given return time. Hence, considering a system with specific characteristic is possible to evaluate its vulnerability and consequently the exposed value. Damage assessment and recovery process are based on vulnerability of system components.

Concretely, considering a damaged component, from a certain starting intensity measure of the earthquake, according to hazard probability, it is possible to assess the likely damage extent through the definition of different damage states. Each damage state defines a correspondent loss of functionality. Each loss of functionality involves in:

- A correspondent repair cost. It depends from extent damage and component characteristics and allows to calculate the disaster economic impact for the system regarding only direct damages.
- A correspondent restoration time. It could be thought as a hiding cost and is characterized by multiple factors. It is the objective variable of the present work, in particular the definition of major influence factors on it.

The steps previous described can be implemented following a similar framework method to the one suggested by PEER's approach, a performance based approach to the problem of earthquake analysis, developed by Porter [12]. This method is develop as a decision maker regarding impact of a decision variable on the loss analysis. Porter considered four different steps for evaluating anti seismic convenience of structures design and location. As the figure 2.1 shows, starting from the hazard analysis, damage extent is obtained through structural response. Then, knowing structure damage states, is possible to assess the decision variable. Analytically the model can be exposed as:

$$g[DV|D] = \int\int\int p[DV|DM,D]p[DM|EDP,D]p[EDP|IM,D]dIMdEDPdDM \qquad (2.2)$$

Where:

g[X|Y] refers to the occurrence frequency of X given Y;

p[X|Y] refers to the probability density of X conditioned on knowledge of Y;

DV is Decision Variable;

DM is Damage Measure;

EDP is an Engineering Demand Parameter;

IM is the Intensity Measure of seismic action.

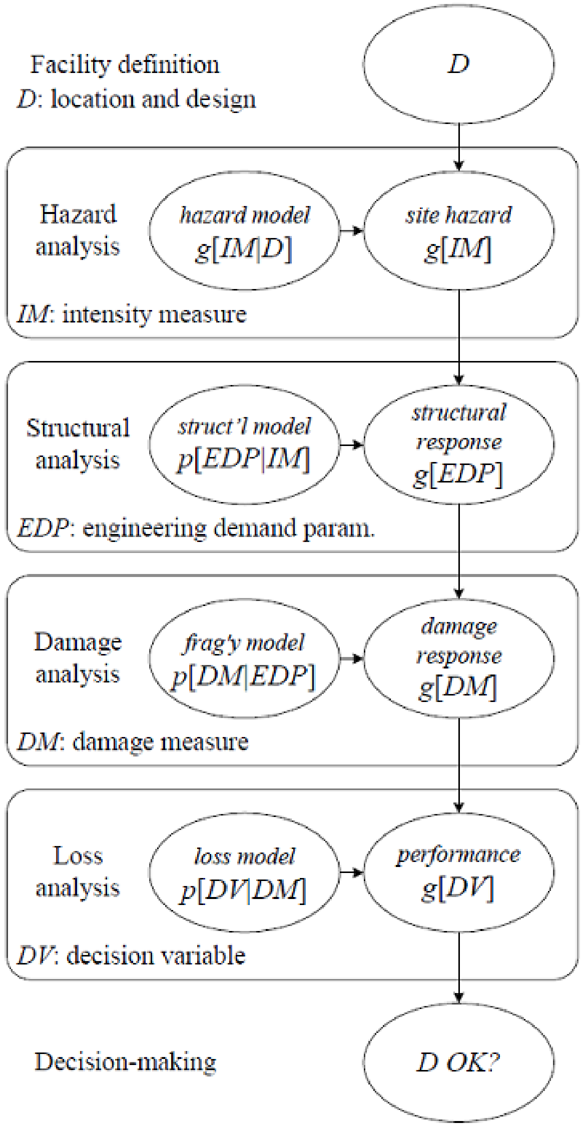


Fig 2.1*: Porter's maker decision framework.[12]*

Implementing a similar conceptual approach, it is possible to characterize each step using several assessment methods and existing tools in engineering literature. Concerning a business system seismic risk, among the most valuable methodologies to assess damages and recovery time, in the thesis model have been used some methods from ATC13 and HAZUS approaches.

2.2. ATC-13

ATC-13 methodology, edited by the Applied Technology Council (ATC) [17], was commissioned at the beginning of the 80s from the Federal Emergency Management Agency (FEMA) in order to develop earthquake damage evaluation data for facilities in California. Due to the lack of loss and inventory data in the literature, ATC established an advisory Project Engineering Panel (PEP) composed of earthquake engineering specialists to define necessary input for loss assessment. Besides methodology for earthquake damage and loss estimates and inventory information, the report contains also estimates of the recovery time for many facilities and structures classes.

The estimate method is a simulation model known as FEMA Earthquake Damage and Loss Estimation System (FEDLOSS). The model employs a modular structure to ensure a major flexibility using different kinds of data. Model inputs are facility earthquake damage and loss estimates and it is characterized by the cross matching between the economic sector facility data (facility types) and structure inventory data (structure types). FEDLOSS allows the calculation of:

- Expected physical damage caused by ground shaking;
- Expected losses from collateral earthquake hazard (i.e. ground failure, inundation and fire);
- Expected percentage of loss of function or usability and time required to restore the facility to its pre-damage usability;
- Expected percentage of population killed and injured.

Considering damage assessment, estimates of percent physical damage caused by ground shaking are expressed through an opportune questionnaire submitted to PEP in terms of damage factor versus Modified Mercalli Intensity scale and are developed for 78 Earthquake Engineering Facility Classes. Correspondent damage states are defined as showed in table 2.1. With this damages classification is possible defines damage probability matrices (DPM’s) and calculate expected dollar loss caused by ground shaking for each of 78 facility classes.

Damage state		Damage Factor Range (%)	Central Damage Factor (%)
1	None	0	0
2	Slight	0 - 1	0,5
3	Light	1 - 10	5
4	Moderate	10 - 30	20
5	Heavy	30 - 60	45
6	Major	60 - 100	80
7	Destroyed	100	100

***Tab 2.1**: ATC-13 damage states*

The other interesting point developed by FEDLOSS is the loss of function and restoration time estimates. These variables are directly related to direct damage to the individual facility and direct damage to lifelines on which the facility depends. Impact of lifeline failures on loss of function on particular facilities largely depends on damage extent of lifelines components. Also here, PEP provided input data, considering 35 Social Function Classes and 11 spatially lifeline systems connected to them. Moreover, for each social function, PEP estimated the time required to restore facilities to 30,60 and 100% of their pre-earthquake usability. An important assumption is the consideration of only on-site effects, such as damage to the structure, damage to the equipment necessary for the operation of the facility and loss of on-site utilities. Resulting weighted-mean restoration times for each facility class are computed for each damage-factor level and each restoration level considered. ATC-13 process used to obtain and calculate functionality of facility during restoration time can be schematized as in the figure below:

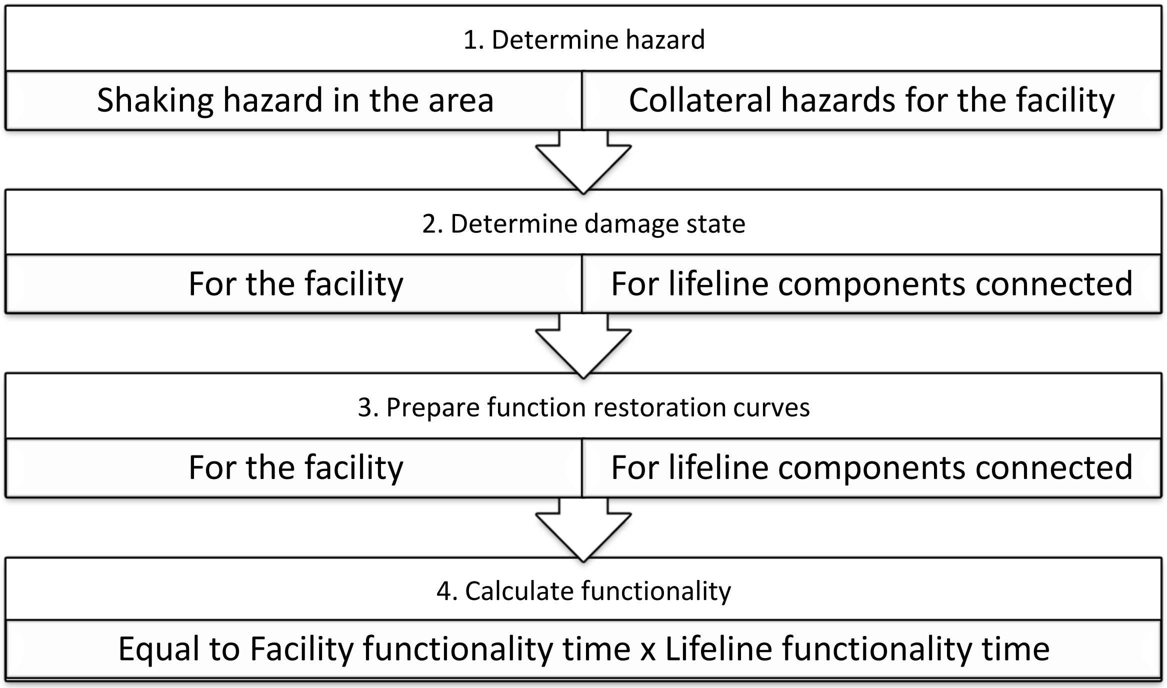


Fig 2.2: *ATC-13 methodology framework.*

2.3. HAZUS

HAZUS [5] software can be thought as ATC-13 method evolution. Developed from FEMA and built on Geographical Implementation System (GIS) technology, this commercial off-the-shelf loss and risk assessment software package, was released in 1997. Effected by an updating process, later versions of the software were released. Actually, HAZUS is define as a multi hazard (MH) modelling software, since it can model different types of hazard (i.e. flooding, hurricane, coastal surge and earthquake).

Considering the performing earthquake loss estimation, it's conceived for regional estimates to plan and simulate efforts to mitigate risk and to prepare emergency response and recovery. Earthquake loss estimation methodology presents a modular framework to facilitate model improvement adding or modifying individual modules. This approach permits a logical evolution of methodology as research progresses and the possibility for software users to limit their studies to selected losses. For example, it is interesting to remark as, although this methodology was implemented for North America territory, HAZUS toolset has been adopted by emergency management organization worldwide such as Singapore, Canada, Australia and Pakistan, thanks to its reliability and the possibility to modified input data and modules aspects depending on region study characteristics. HAZUS methodology framework is represented in the figure below:

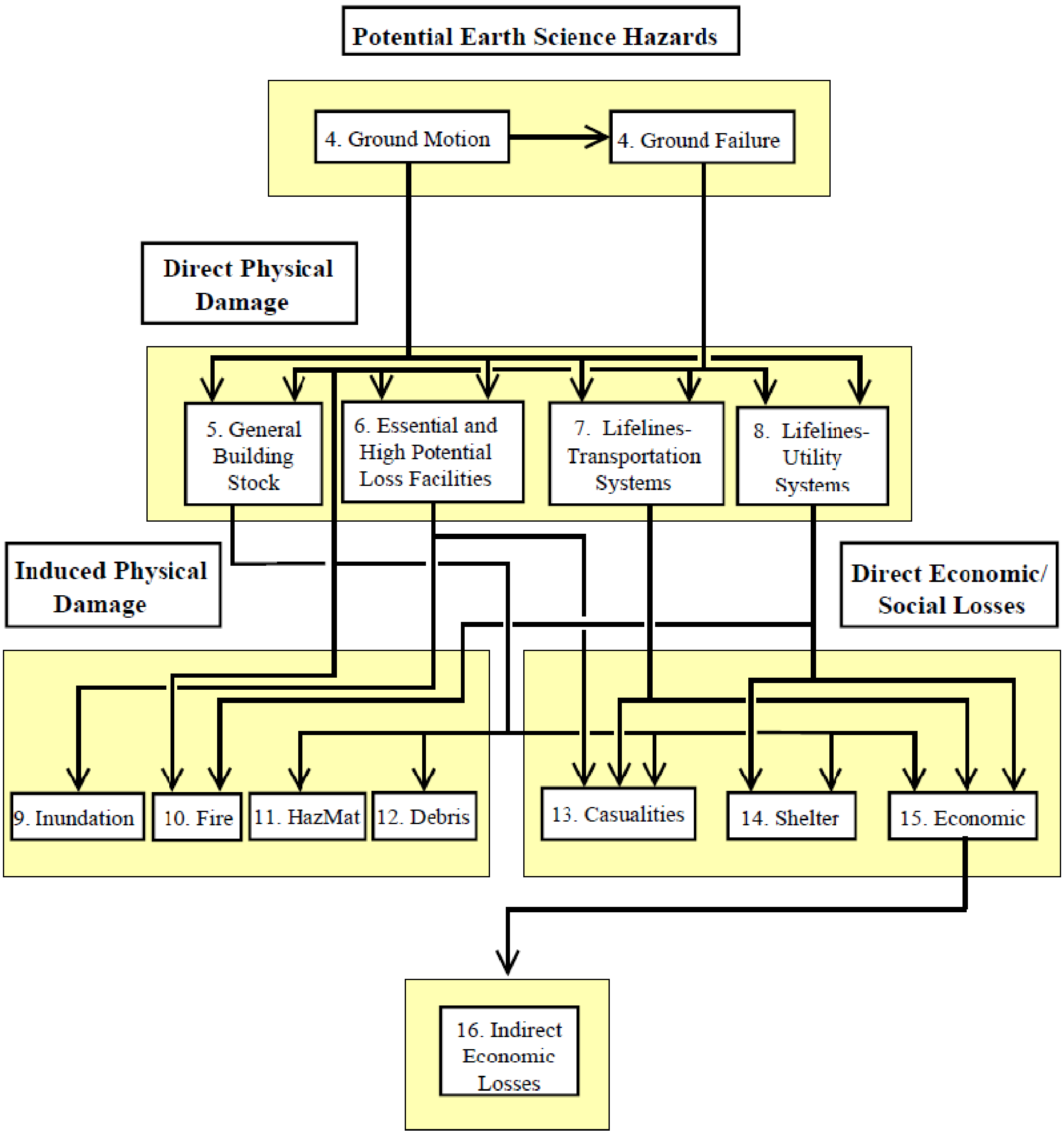


Fig 2.3*: HAZUS methodology framework.[5]*

This methodology permits many kind of analysis, among which:

- Describing damage states;
- Developing building damage functions;
- Grouping, ranking and analyzing lifeline systems.

Damage functions, defined according to a probabilistic approach, allow to assess structure damages extent, correlating the earthquake intensity to a correspondent structural damage state. HAZUS implement two types of damage functions, namely fragility curves and capacity curves. Those are characterized by the typology of structure or system and the intensity measure of the ground motion considered as input. The model, differently from ATC-13, considers only five damage states:

- None;
- Slight;
- Moderate;
- Extensive;
- Complete.

Moreover, facility damages are obtained as the sum of ground shaking damages and ground failure damages. This fact involves the use of two different types of damage functions for each structure analyzed. HAZUS provides damage functions for a great number buildings and lifeline systems, accurately classified. Basic model building types, based on FEMA-178 [4] are classified in 36 different building typologies, 4 seismic standard building designs and 33 different occupancy classes. Then, 6 lifelines utility systems with respective components and 7 transportation systems are examined. Finally, the model analyzes also nonstructural components for each building typology. Once the damage state has been obtained, is possible to evaluate direct and indirect losses using several analytical methods provided by the model.

The definition of restoration time isn't a primary goal of HAZUS software. To assess the recovery process, the model develop probabilistic functions, namely restoration curves, using ATC-13 methodology previous described. These functions are provided only for lifelines components and transportation systems in order to optimize building monetary losses estimate. In fact, this is calculated as the sum between:

- Monetary losses due to building damage: it considers cost of repairing or replacing damaged buildings and their contents;
- Monetary losses resulting from building damage and closure: it considers losses due to business interruption.

3. Methodology

As already said, the calculation of restoration scenarios for a system, starting from hazard earthquake variable, requests the definition of several steps and correspondent variables. Hence, in the model development, different methods and methodologies have been used, according to model purpose and analyzed system typology. However, since a concrete possibility to implement the model in several industry sectors exists, the model is illustrated with a general approach, remarking as the research goal is more focused on the model explanation and analysis than on the results interpretation of wineries restoration processes.

3.1. Method Framework

Basically, the proposed method is based on the correlation between an intensity value of the earthquake impacting on the system and the correspondent restoration time for the system. The correlation is obtained through some intermediate phases which can be handled as separated modules. During the model implementation the modules analysis is repeated several times, depending on the number of components of the system. In fact, the most interesting characteristic of the model is the disaggregation of the system analyzed in individual components in order to better characterize the recovery process. Hence, initially damages and restoration analysis are implemented for each system component. At a later stage components are assembled into the system process, matching the several restoration analysis and considering the mutual influence between components to determinate the system restoration scenario. The steps of the model are:

- Disaggregation of the system in components vulnerable to earthquake: this first step involves the definition of some "elementary" components which compose the process system;
- Assessment of components damages: for each component, the damages extent is calculated through the use of fragility functions;
- Assessment of components restoration process: for each component restoration process is calculated through the use of restoration functions;

- Assembly of the components into the system analyzed: components restoration functions are aggregated using a process diagram flow into the system;
- Definition of system restoration scenario: it is the output of the diagram flow and the final result.

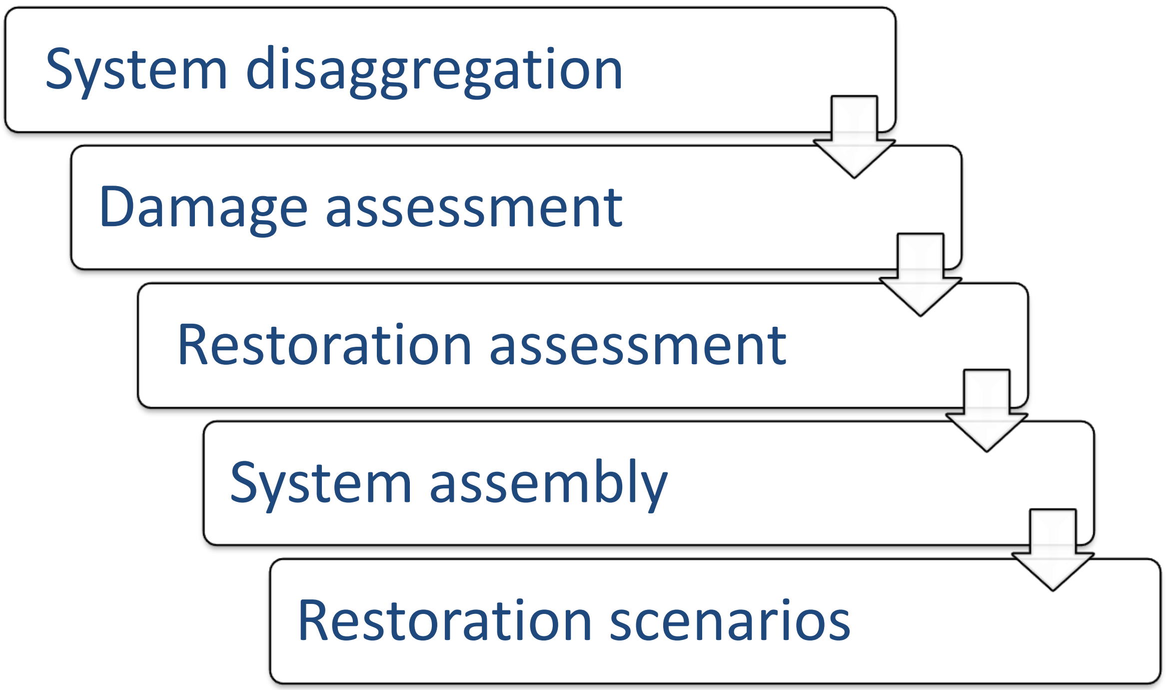


Fig 3.1. *Main steps of proposed methodology.*

Fragility and restoration functions are probabilistic functions specific for each component. Fragility curves, which relate the earthquake intensity measure in input with a correspondent damage state in output considering the structural fragility, are implemented as fragility functions. Restoration curves, which define restoration time, given as input the damage states (obtained from fragility curves) and additional recovery characteristics, are used as restoration functions. Hence, parameters of components restoration curves are used in a diagram system flow to simulate the productive process of a winery, and obtain the restoration scenario system. Finally, using a probabilistic sampling method, it is possible to define an average restoration scenario for the whole system.

For a single component (C), each framework step involves a different variable analysis. The starting seismic hazard variable, correspondent to an earthquake intensity measure (IM), is transformed progressively in equivalent damage state (DS), loss of functionality and restoration time (TR). The figure below shows a model conceptual scheme similar to the one developed from Porter for the PEER's project described in chapter 2. The reference suggest the possibility to use the present model also as a decision maker, since it is possible identify the most problematic components of the system restoration and to make the appropriate decisions.

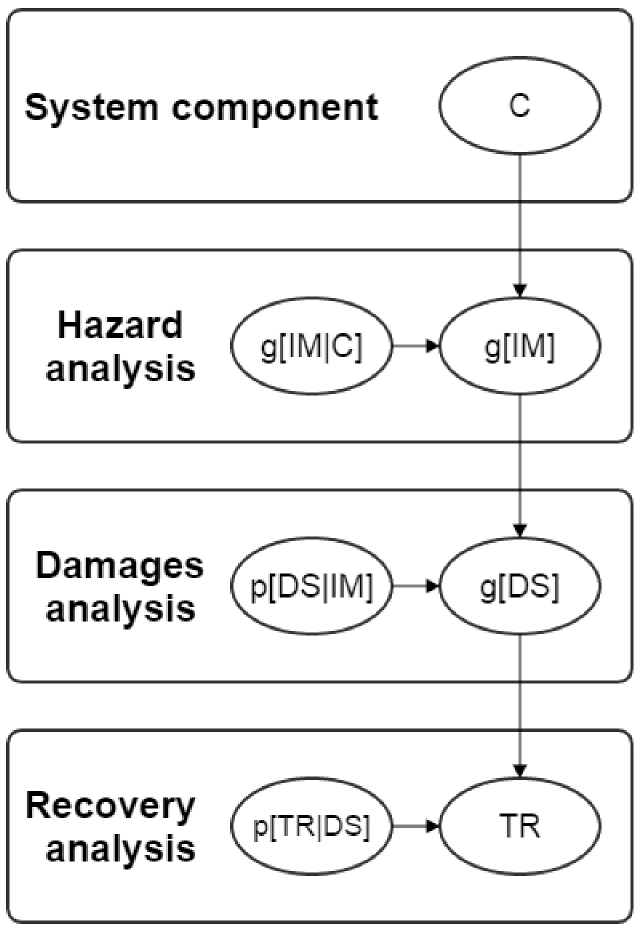


Fig 3.2. *Single components analysis.*

It is important to remind that, even if scientific literature presents several methods similar to the present model, they are usually oriented to evaluate specific study cases, without a general connotation and economic process losses, without a deeply restoration process assessment. In the sections below methods used for model steps are described and at the same time input components and parameters for a winery system are defined.

3.2. Disaggregation in vulnerable components

The first step of the analysis system model requests the definition of the system process steps and the identification of the vulnerable seismic components. While the characterizations of system processes strictly depend on business typology, the identification of vulnerable components for seismic analysis presents some general characteristics:

- **Component size**. Since it is unfeasible considered as vulnerable component each single machinery or specific elements into a system process, a vulnerable component can be intended as a single process elements or as a combination of several process elements, depending on available damage dataset.
- **Involvement level into the process.** In a simplified analysis, it makes sense considering only the main elements of the process which are not immediately replaceable.
- **Level of seismic vulnerability.** A component is vulnerable to the earthquake if it is subjected to seismic damages which can compromise its functionality.

It is important to remark as, in the present research, a process system corresponds to an industry manufacturing process which describes the transformation of basic components in a final product. In fact, potentially the model could be applicable also to whole supply chains, even if, in this case, the model analysis would require the definition of two different levels of vulnerable components, one referring to each process system and one referring to all supply chains business and connection structures between them.

3.2.1. Winery vulnerable components

Winemaking process is established from many different steps. Nardin et all. [10] describe the whole winery production chain, discerning four main phases: the vineyards management, the harvest, the winemaking cycle and external logistics and commercialization. For the purpose of this research, the system process is identified only with the winemaking cycle which corresponds to technological operations for converting the grapes arrived to the winery into the final packaged products. The consideration of the other phases, together with basic process elements suppliers and customers (i.e. bottles manufacturing company, marc buyer, etc.), involves a supply chain analysis.

The winemaking cycle defers depending on wine typology (i.e. red, white, rosè) and accessory making of particular winemaking entities. Nardin identify several main step which can be resumed in:

- **Grape harvest and pressing**. This step includes starting winemaking operations, from the harvest of grapes with woven-wires?? to the production of must with wine press.
- **Wine fermentation**. This process request a protected and refrigerated space.
- **Wine maturation**. It defines the time and processes for the wine maturation. Maturation time changes a lot depending wine characteristics.
- **Wine packaging**. It defines bottling and labelling operations.

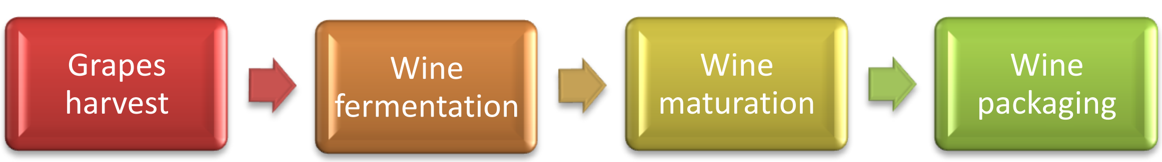


Fig 3.3 . *Winemaking steps evaluated in the research*.

Focusing on the engineering components which present a seismic risk and the consequent impact on the productive process, the table below illustrates some of the usual technological components used in the winemaking process.

Winemaking process			
Grapes collection and pressing	**Wine fermentation**	**Wine maturation**	**Wine packaging**
woven-wire grapes carrier grape grinder pumps wine press cellular explosion plant pipes	refrigeration plant maceration machinery maceration tanks cold static settling machinery cold static settling tanks pipes	filter-press machine plants for wine stabilization plants for wine betterments storage tanks storage barrels storage structures pipes	bottling machinery labelling machinery bottles carrier storage structures

Tab 3.1 . *Wine-making steps evaluated in the research*.

According to the assumption of the vulnerable component choice described in the previous section and compatible with the literature sources, in the present research three types of vulnerable components have been considered :

- **Steel tanks**. This category identify all the existing kind of steel tanks in winemaking process. In particular, wine storage tanks, plants tanks and fermentation tanks. Structures connected with tanks are also included. Steel tanks are considered seismic vulnerable for wineries since they are continuously involved into the system process their failure could mean the total loss of the product.
- **Machinery.** This wide category include every kind of machinery used in the wine processing and packaging, from the woven-wire for the grapes collection to the labelling machinery. Moreover it describes furniture and other structure for storage (e.g. supports for wooden barrels), different from steel tanks. Their failure could mean important productive process delays and also loss of the product.
- **Exposed pipes**. This particular category define the piping for wine transportation inside the winery plant and for the environment refrigeration. Their failure could mean delays and loss of product.

It is interesting to note that the winery building is not considered a vulnerable component. This is due to the impossibility to classify in a single component the multitude of building typologies used in winery constructions. Hence, in order to keep a general approach into the model implementation for wineries, winery facilities are assumed as anti-seismic. Anyway, to define damage dataset and damage functions for non-structural elements as machinery, effects of structural damages are taken into account, making the model implementation in the present work more realistic.

Fig 3.4 – 3.7. *Winery vulnerable components. Clockwise from the top left: plants of steel tanks and connected pipes; bottling machinery; storage structures with wood barrels; wine storage steel tanks.*

3.3. Components damage assessment

Components damage assessment gives an idea of earthquake power and its direct impact on the process. Literature provides innumerable methods to evaluate damages, knowing earthquake intensity. Considering the many uncertainties and approximations in seismic analysis, starting from the ground motion extrapolation, in the present research has been used a probabilistic approach to assess seismic damages, through the implementation of fragility functions. These functions, already touched on in section 3.1, describe the structure (or component) response to the earthquake, directly correlating the intensity measure of a given ground motion with the correspondent likely damage state of the structure. As fragility functions, fragility curves have been used.

3.3.1. Fragility curves

In order to describe fragility curves, firstly it is necessary to define damage states, output variables connected to them. Damage states care described using performance scale of damage level in ascending order of size, which defines the extent and severity of functionality losses. Following HAZUS approach, 5 discrete damage states are defined:

- None
- Slight
- Moderate
- Extensive
- Complete

Each of these levels describe the entity of physic earthquake damages on the structure, from the absence of injuries (None) to the collapse(Complete). Obviously, damage states descriptions changes depending on analyzed component characteristics.

To estimate the damage state reached by the components, fragility curves have been developed. Fragility curves describe the probability of reaching or exceeding different state of damage, given an earthquake intensity measure. In other words, these fragility functions define boundaries between damage states. Their implementation can be obtained in an empirical or in analytical way.

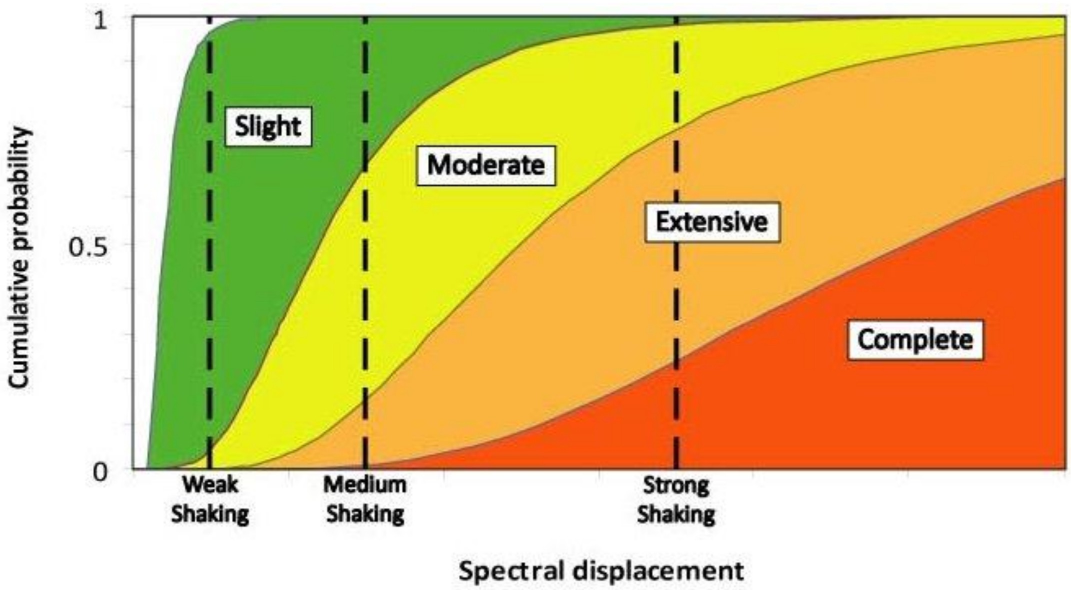


Fig 3.8. *Fragility curves representation.[5]*

Analytical fragility curves are developed by modeling, through F.E.M. programs, vulnerable elements of structure in order to find the intensity measure that would cause the system to reach each damage state, simulating numerically the seismic response. Different types of analysis are used about this, from spectrum elastic to structural dynamic. An analytical approach permits to obtain best results but at the same time it requests a high calculation resources and a perfect knowledge of the specific characteristics of structures and mechanical behavior of materials. On the other hand, there are empirical fragility curves, which are directly calculated using damages dataset of real earthquakes and controlling uncertainty spread. Moreover, their computation does not request great amounts of information and resources. Empirical curves can be evaluated in different ways, depending on size and characteristics of available database. Porter et all. [12], describe the most common procedures for creating fragility functions using various kinds of data, ascertaining the possibility to obtain them also from small or incomplete database. Shinozuka et all. [13] compare analytical and empirical approaches developing bridges fragility curves on the basis of statistical analysis and defining their issues and values inspect their differences. Certainly, the greatest weakness of the empirical approach is the characterization of fragility curves using particular database of specific earthquakes, invalidating their application to other environment, for instance with different soil conditions or different spectra response typology. Acknowledging the features of both approaches, for the purpose of this research empirical fragility curves have been obtained, because of the lack of real studio cases and the necessity of easy and quick calculation.

Probabilistic fragility curves can be fitted by log-normal cumulative distribution. In this case, they are represented by the formula:

$$\mathrm{P}\left[{}^{\mathrm{ds}}/_{\mathrm{IM}}\right] = \Phi\left[\frac{1}{\beta_{\mathrm{ds}}}\ln\left(\frac{\mathrm{IM}}{\overline{\mathrm{IM}}_{\mathrm{d,ds}}}\right)\right] \qquad (3.1)$$

Where:

Ds	damage state;
IM	intensity measure;
β_{ds}	is the standard deviation of lognormal distribution;
Φ	is the standard cumulative log-normal distribution function;
$\overline{\mathrm{IM}}_{\mathrm{d,ds}}$	is the IM that defines the mean value of each damage state;

Hence, each fragility curve correspond to a function of density probability related to its correspondent damage state threshold. Intensity Measure is identify by peak building response, usually Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV) for structures vulnerable to ground shacking. In the research, as intensity measure has been used the PGA.

3.3.2. Winery components fragility curves

Considering the winery system analysis, fragility functions have been calculated using two different empirical approaches, depending on the characteristics and database availability for the three components considered. To develop machinery and exposed pipes fragility functions, curves parameters (means and lognormal standard deviations) provided by HAZUS have been used fragility. Instead, steel tanks fragility curves have been calculated directly from damages databases.

Machinery fragility curves

As showed in table 3.2, considering non-structural components, HAZUS distinguish two different categories, drift-sensitive (identify by PGV as intensity measure) and acceleration-sensitive (PGA as IM) elements. Each of these two categories contains different nonstructural elements. However, due to lack of dataset and impossibility to define damage functions for each non-structural component, HAZUS defines only one set of fragility curves for both groups and these are assumed to be "typical" of it sub-components. Moreover, non-structural damages are considered to be independent of the structural model building types. Hence, non-structural statistical medians are the same for each building types, while β values are slightly different for each building type, since log-normal standard deviations is the sum of different standard deviations among which some related to building types response.

Type	Item	Drift-Sensitive*	Acceleration -Sensitive*
Architectural	Nonbearing Walls/Partitions	•	◦
	Cantilever Elements and Parapets		•
	Exterior Wall Panels	•	◦
	Veneer and Finishes	•	◦
	Penthouses	•	
	Racks and Cabinets		•
	Access Floors		•
	Appendages and Ornaments		•
Mechanical and Electrical	General Mechanical (boilers, etc.)		•
	Manufacturing and Process Machinery		•
	Piping Systems	◦	•
	Storage Tanks and Spheres		•
	HVAC Systems (chillers, ductwork, etc.)	◦	•
	Elevators	◦	•
	Trussed Towers		•
	General Electrical (switchgear, ducts, etc.)	◦	•
	Lighting Fixtures		•
Contents	File Cabinets, Bookcases, etc.		•
	Office Equipment and Furnishings		•
	Computer/Communication Equipment		•
	Nonpermanent Manufacturing Equipment		•
	Manufacturing/Storage Inventory		•
	Art and other Valuable Objects		•

Tab 3.2. *List of typical nonstructural components and contents of buildings*.

According to machinery component described in the section 3.2, two non-structural categories have been considered, both acceleration-sensitive:

- **Manufacturing and process machinery**, represent the whole of internal machineries;
- **Manufacturing/storage inventory,** represent the whole of storage structures;

Damage states description for machinery components is:

- **Slight nonstructural damage**: the most vulnerable equipment moves and damages attached piping or ducts or furniture.
- **Moderate nonstructural damage**: movements are larger and damage is more extensive; machines piping leaks at few locations, shelves and barrels may require realignment, some bottles package fall down.
- **Extensive nonstructural damage**: equipment on spring isolators topples and falls; unanchored equipment slides or falls; anchored equipment shows stretched bolts or strain at anchorages; many stocks are ruined.
- **Complete nonstructural damage**: equipment is damaged by sliding, overturning or failure of their supports and is not operable; some machinery supports have failed causing ruptures and tools to fall or hang down; the most part of storage is destroyed.

Below are showed fragility curves and correspondent parameters (tab 3.3).

Internal Machinery and Storage		
Type	*IM*	*Seismic Design*
Non Structural Acceleration-Sensitive - PC1	PGA	Moderate
Damage State	*μ*	*β*
Slight	0,25	0,68
Moderate	0,50	0,67
Extensive	1,00	0,66
Complete	2,00	0,66

Tab 3.3. *Fragility curves parameters for machinery.*

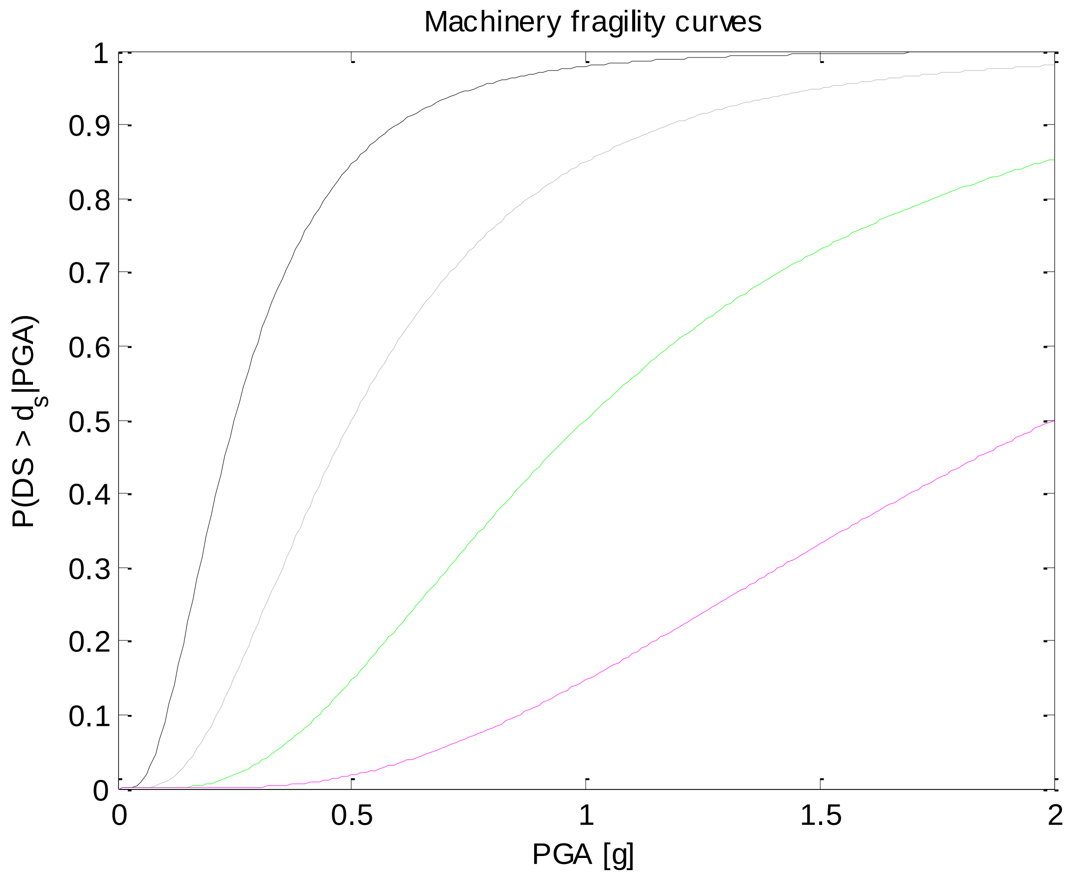


Fig 3.9. *Machinery fragility curves.*

Exposed pipes fragility curves

This component, unlike buried pipes, is usually excluded from fragility curves researches, since it hasn't such big diffusion in typical industrial plants analyzed and doesn't suffer excessive earthquake damages. Jhonson et all, in [7], assert that seismic injuries to exposed piping are sufficiently rare to consider them as damages of other components. However, in this winery research model piping are considered an important element into the system process. Hence, to obtain their damages functions, HAZUS parameters for **subcomponent exposed pipes for tanks farm** are used. The code extensive and completed damage states, since lower damages state do not bring a significant contribution to losses assessment.

Exposed Pipes		
Type	*IM*	*Seismic Design*
Subcomponent for Tanks Farm – Exposed Pipes	PGA	Moderate Code
Damage State	*μ*	*β*
Extensive	0,53	0,60
Complete	1,00	0,60

Tab 3.4. *Fragility curves parameters for exposed pipes.*

Fragility curves are showed in fig. 3.10. The correspondent damage states description is:

- **Extensive damage:** clear fractures on the iron with great lack of liquid
- **Complete damage:** rupture of piping portion with total lack of liquid.

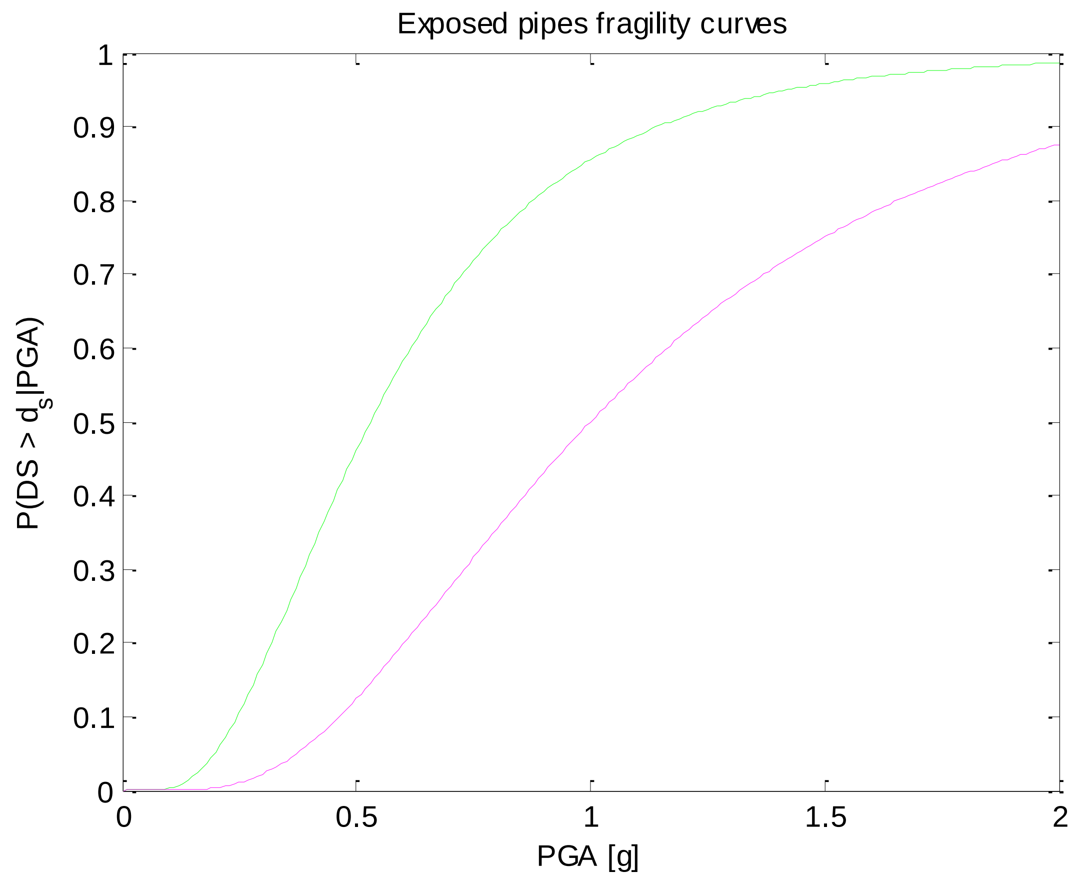


Fig 3.10. *Exposed pipes fragility curves.*

Steel tanks fragility curves

Considering winery steel tanks, probably the most meaningful component of the system, fragility curves has been calculated directly from available dataset. In fact, despite HAZUS provides steel tanks parameters for oil system and potable water system, their specificity make them unadapt to represent wine storage tanks. Moreover, there are not other publications which have implemented damage functions parameters for this kind of tanks. Hence, it is necessary "to build" fragility curves considering every step, from the definition of an initial database to the final implementation. In particular, after fitting samples with an opportune distribution, it is necessary to consider an optimization algorithm to optimize the distribution parameters obtained. Among the many approaches suggested by literature, **maximum likelihood estimation** has been chosen. This method, for a fixed set of data and corresponding statistical model, selects the set of values of the model parameters that maximizes the likelihood function. In other words, optimized parameters fit dataset in the best possible way, considering a certain statistical distribution. Moreover, for some statistical models, among which normal distribution, it gives a well-defined unified approach.

The first step to implement fragility curves is the definition of a significant statistical database, associating damage levels (parameter data) to damaged tanks observed in previous earthquake and correspondent PGA (measured data). Principal issues are sources reliability and database size. Damaged tanks samples have been brought from seismic reports realized by two well-known engineering associations, **ALA** [1]and **NIST** [11], both considering different types of storage tanks, without particular focusing on a specific typology. The whole resultant database size is formed by 598 tanks observed in more than 11 earthquake, subdivided in 8 PGA ranges, depending on sample intensity measure. (see annex A).

Once the database is defined, a first set of two-parameters log-normal distributions are obtained, fitting, for each damage state, realizations number in the PGA ranges. The resultant distributions need to be optimized because, being damage functions constructed independently, their log-standard deviations are different and fragility curves can intersect, even if it is not supposed to happen. For this reason, the maximum likelihood method is applied using an algorithm that permits a simultaneous estimation of means and of a common log-standard deviation for all damage states. This specific methodology, explained below, is taken from [13] and does not have an identifying name.

First of all, is assumed another mathematical relation, perfectly correspondent to 3.1, to define fragility curve for each E_j damage state,:

$$F_j(a_i; c_j, \zeta_j) = \Phi\left[\frac{\ln\left(a_i/c_j\right)}{\zeta_j}\right] \quad (3.2)$$

Where:

a_i is PGA recorded for the sample i with i=1,..,n total samples;

c_j, ζ_j are mean and log-standard deviations of each damage state;

Φ is the log-normal distribution.

Then, the method defines $P_{ik} = P(a_i, E_k)$ as the probability that a tank i, selected randomly from the sample, will be in the damage state j if subjected to an i ground motion. Expressing these functions with (3.2) and assuming a common log-standard deviation ζ, the five damage state probabilities can be re-write as:

$$P_{i1} = P(a_i, E_1) = 1 - F_1(a_i; c_1, \zeta) \quad (3.3)$$

$$P_{ik} = P(a_i, E_k) = F_{k-1}(a_i; c_{k-1}, \zeta) - F_k(a_i; c_k, \zeta) \quad (3.4)$$

$$P_{i5} = P(a_i, E_5) = F_4(a_i; c_4, \zeta) \quad (3.5)$$

With k=2,3,4 intermediate damage states.

Using (3.3), (3.4) and (3.5), all damage states probabilities are related each other and the common ζ guarantees that fragility curves don't intersect. Finally, is defined the likelihood function L:

$$L(c_1, c_2, c_3, c_4, \zeta) = \prod_{i=1}^{n} \prod_{k=1}^{5} P_k(a_i, E_k)^{x_{ik}} \qquad (3.6)$$

Where:

$x_{ik} = 1$ if the damage state E_k occurs for the i-th tank subjected to a = a_i, and

$x_{ik} = 0$ otherwise.

Point of maximum is obtained equalizing L function derivate relative to each variable to 0 simultaneously.

Shinozuka's methodology has been applied to our database through MATLAB software. Starting the optimization with means and log-standard deviation values obtained from the initial dataset, is necessary create for each of this variables a vector of length n with possible values having a small gap around the starting point. Hence, in order to find the combination between the parameters values which maximizes the likelihood function, all the possible combinations considering the five variable vectors are calculated. In this work, has been chosen a number of five different values for each parameters with a gap of +/- 0.1, +/-0.2 on the initial value. Vectors are combined into a matrix, created with combine function, having a number of 5^5=3125 possible parameters combinations. To evaluate the maximizing combination, each of them is implemented into L function script. The likelihood function L and its maximum L are develop using the following pseudo-code:

```
function
    for each  combination parameters
        for each  sample acceleration
            calculate  ample damage state
        end
    calculate  probabilities multiplication
    end
end function
```

Parameters of the maximizing combination are reporting in the table 3.5. Correspondent fragility curves are showed in figure 3.11

Steel Tanks	
Damage State	*μ*
Slight	0,56
Moderate	0,66
Extensive	0,79
Complete	0,97
Damage State	*β*
Common log-standard deviation	0,53

Tab 3.5. *Fragility curves parameters for steel tanks.*

Damage states for steel tanks refer to the following physic damages:

- **Slight damage:** is defined by the tank suffering minor damage without loss of its contents or functionality. Minor damage to the tank roof due to water sloshing, or localized wrinkles in steel tanks.
- **Moderate damage:** is defined by the tank being considerably damaged, but only minor loss of content. Elephant foot buckling without loss of content, or moderate inlet/outlet elements and roof damages.
- **Extensive damage:** is defined by the tank being severely damaged and going out of service. Elephant foot buckling with loss of content, extensive shell buckling on the top of the tank with roof collapse and leakage of liquid, bottom rupture.
- **Complete damage:** is defined by the tank collapsing and losing all of its content.

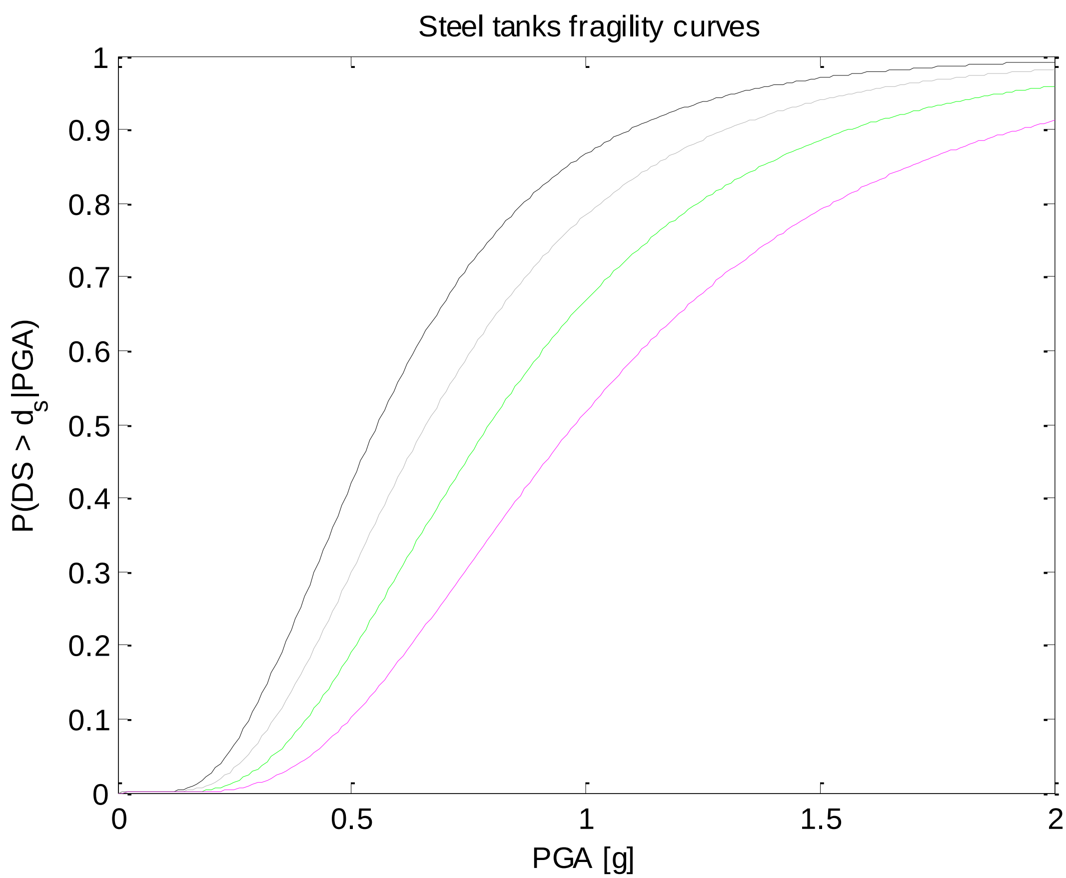


Fig 3.11. *Steel tanks fragility curves.*

3.4. Components restoration assessment

Once components damage states are defined, it is possible to assess the corresponding recovery time. Unlike damage assessment, literature provides few methodologies for restoration estimating, since generally this is considered as a secondary factor in earthquake economic impact estimates. The best approach consists on using probabilistic restoration functions. The achievement of restoration functions requests the knowledge of many data and aspects depending on specific earthquake and impact zone characteristics, as used methods of structures fixation, general post-earthquake operations management but also social and political dynamics. In particular for a single component, restoration function is dependent on:

- Degree of damage;
- Importance of the component in post-earthquake recovery;
- The availability of manpower and resources for restoration or reconstruction;
- The availability of supplies, replacement parts, and services.

Because of the general lack and high peculiarity of these information, restoration functions evaluation is difficult and full of approximations. Similarly to fragility functions development, recovery functions can be evaluated in an analytical or an empirical way.

3.4.1. Restoration curves

In this model analysis, as restoration functions of winery components, recovery curves which relate the component residual functionality to a correspondent recovery time function, have been implemented . The component residual functionality depending on the component damage state, obtained with fragility curves. Basically, a restoration curve expresses the time required for restoring function at a given component to the pre-earthquake level. It is defined by restoration day number and percentage of component functionality. Restoration curves developed on winery analysis follow the ATC 13 approach.

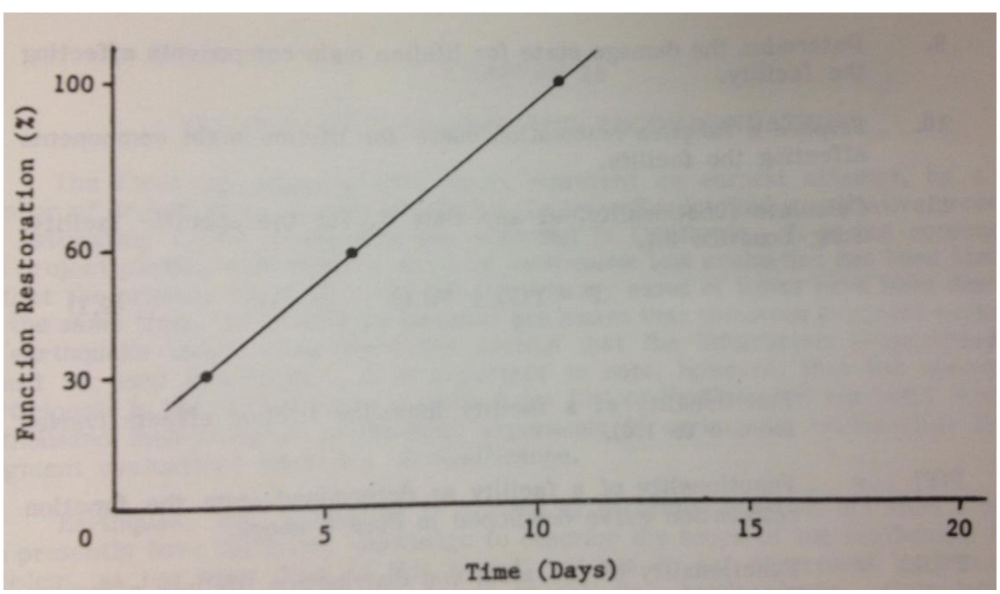


Fig 3.12. *Example of a linear restoration curve.*

As already said in the chapter 2, ATC 13 presents a method to create empirical restoration functions and it provides probabilistic parameters to develop restoration curves for different social classes facility functions. This methodology provides means and standard deviations expressed as restoration day number, obtained through weighted opinions of a board of seismic engineering experts. ATC 13 restoration curves contain some assumptions which are:

- Component damage state describes the state of direct damage and service lifeline damage to the facility;
- Unlimited resources are available for reconstruction;
- The time to restore function at a component includes restoration of all factors critical to that component;
- Restoration curves are developed with linear functions.

3.4.2. Winery components restoration curves

Definition of components fragility curves has been obtained using ATC-13 parameters for opportune social classes. However, in order to improve the reliability of ATC-13 approach, restoration functions have been optimized for system processes, defining additional assumptions on components restoration curves:

- Definition of fixed starting residual functionalities related to damage states (DS). Clearly, residual functionality (RF) percentage is inversely proportional to the damage state extent. Relationship scale between DS and RS, identical for the three components, is:
    - DS 1 - 100% RF
    - DS 2 - 80% RF
    - DS 3 - 50% RF
    - DS 4 - 20% RF
    - DS 5 - 0% RF

- Correction of restoration curves slopes. Definition of residual facilities request the correction of curves slope. Considering linear functions, the function slope, defining as the inverse of restoration curve mean, describes the restoration process velocity. The slope correction is obtained dividing the starting loss of functionality (complementary percentage of RS) for the mean of the correspondent restoration curve:
  - DS 1- no slope
  - DS 2 - 0,2/ μ slope
  - DS 3 - 0,5/ μ slope
  - DS 4 - 0.8/ μ slope
  - DS 5 - 1,0/ μ slope
- Definition of probabilistic starting delays on restoration process related to damage states. They permits to keep into account random issues in the starting of restoration process. Starting delays parameters have been calculated defining, for each damage state, three percentiles of delay days and fitting them through a log-normal distribution. Starting delay values are identical for machinery and exposed pipes.

	Pipes and machinery					**Steel tanks**				
	Lognormal distr.		*Percentiles (days)*			*Lognormal distr.*		*Percentiles (days)*		
DS	*μ*	*β*	*16%*	*50%*	*84%*	*μ*	*β*	*16%*	*50%*	*84%*
2	1,099	0,852	1,3	3,0	7,0	1,946	0,697	3,5	7,0	14,0
3	1,946	0,697	3,5	7,0	14,0	1,946	0,697	3,5	7,0	14,0
4	2,303	0,697	5,0	10,0	20,0	2,639	0,697	7,0	14,0	28,0
5	2,639	0,697	7,0	14,0	28,0	2,639	0,697	7,0	14,0	28,0

Tab. 3.6. *Statistic parameters for defining starting delays in the model*

The full explenantion of the causes at the base of restoration curves additional assumption are exposed into the section 5.4, where their impact on the restoration scenarios is also analyzed.

The resulting components restoration curves and correspondent ATC-13 parameters are illustrated below. It is important to point out that, in order to clarify functions shapes and the differences between damage states in figures below standard deviations equal to zero both for the curve distributions and for the starting delays have been considered. Moreover the starting delay involves a shift of the final restoration time with consequent right shift of the full recovery achievement respect ATC-13 parameters.

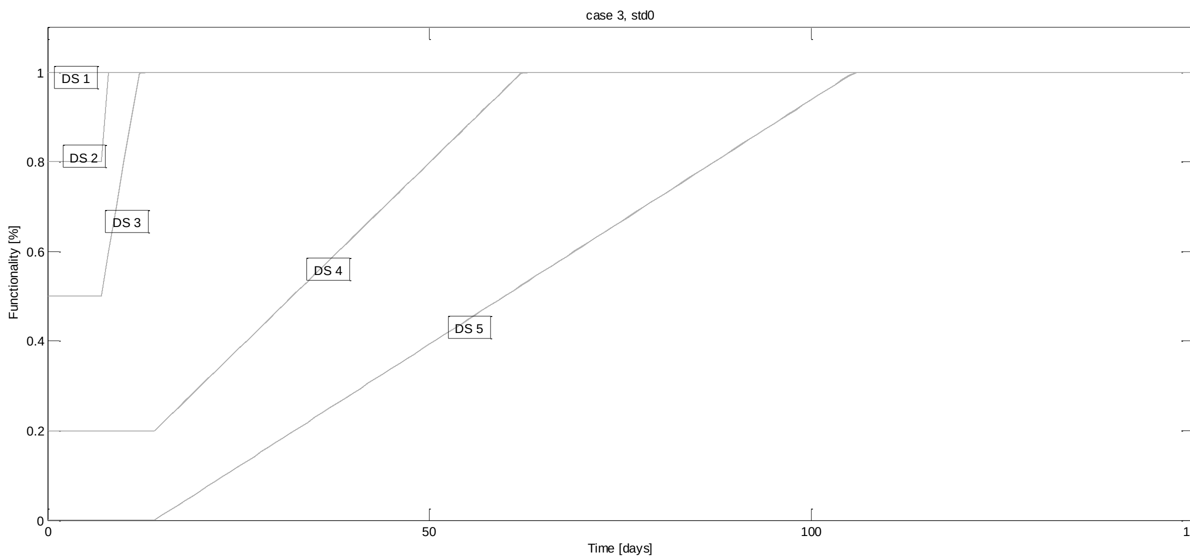


Fig. 3.13. *Definition of fragility curves and relative damage states for a generic component.*

Machinery

Internal Machinery and Storage		
Social class	Food and drug processing	
Damage State	*μ (days)*	*β*
Slight - DS2	4,40	5,30
Moderate - DS3	16,10	14,40
Extensive - DS4	72,70	63,90
Complete - DS5	235,60	115,20

Tab.3.7. *Restoration curves parameters for machinery.*

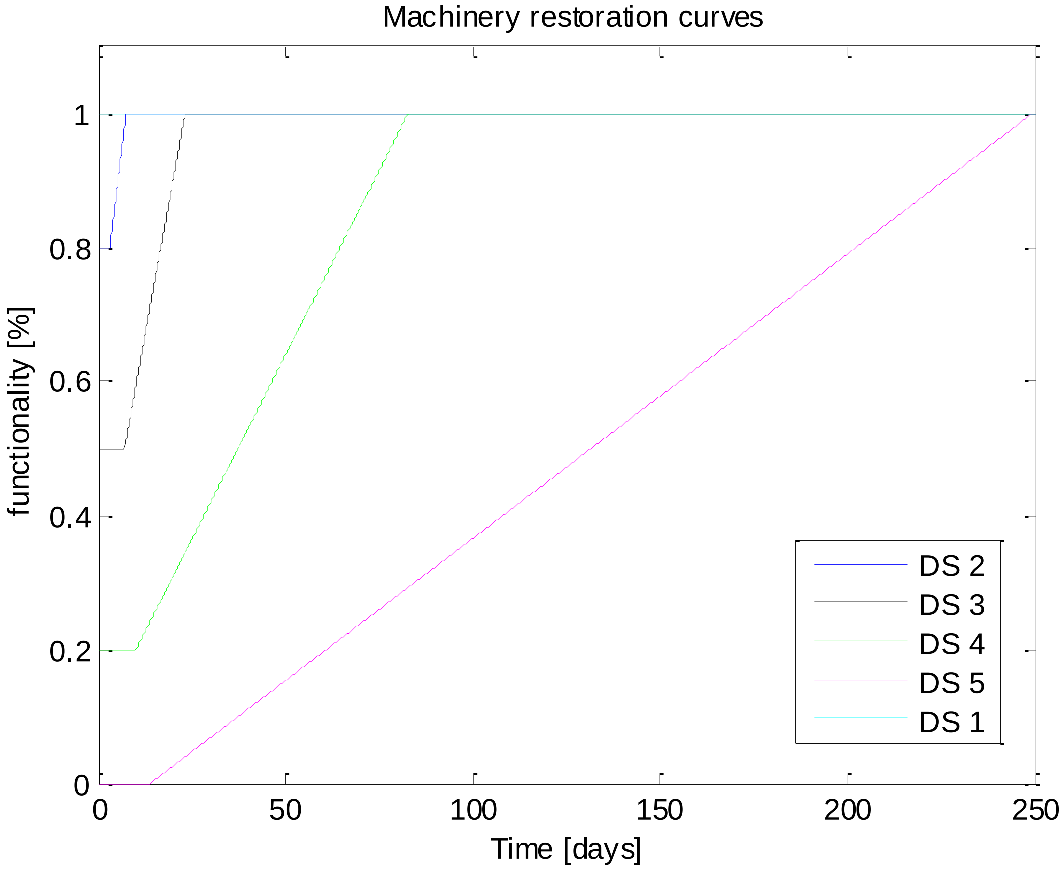


Fig.3.14 *Restoration curves for machinery.*

Exposed pipes

Exposed pipes		
Social class	Water supply - Trunk lines	
Damage State	*μ (days)*	*β*
Slight - DS2	1,60	1,30
Moderate - DS3	3,40	3,60
Extensive - DS4	9,50	7,40
Complete - DS5	24,60	21,10

Tab.3.8 *Restoration curves parameters for exposed pipes.*

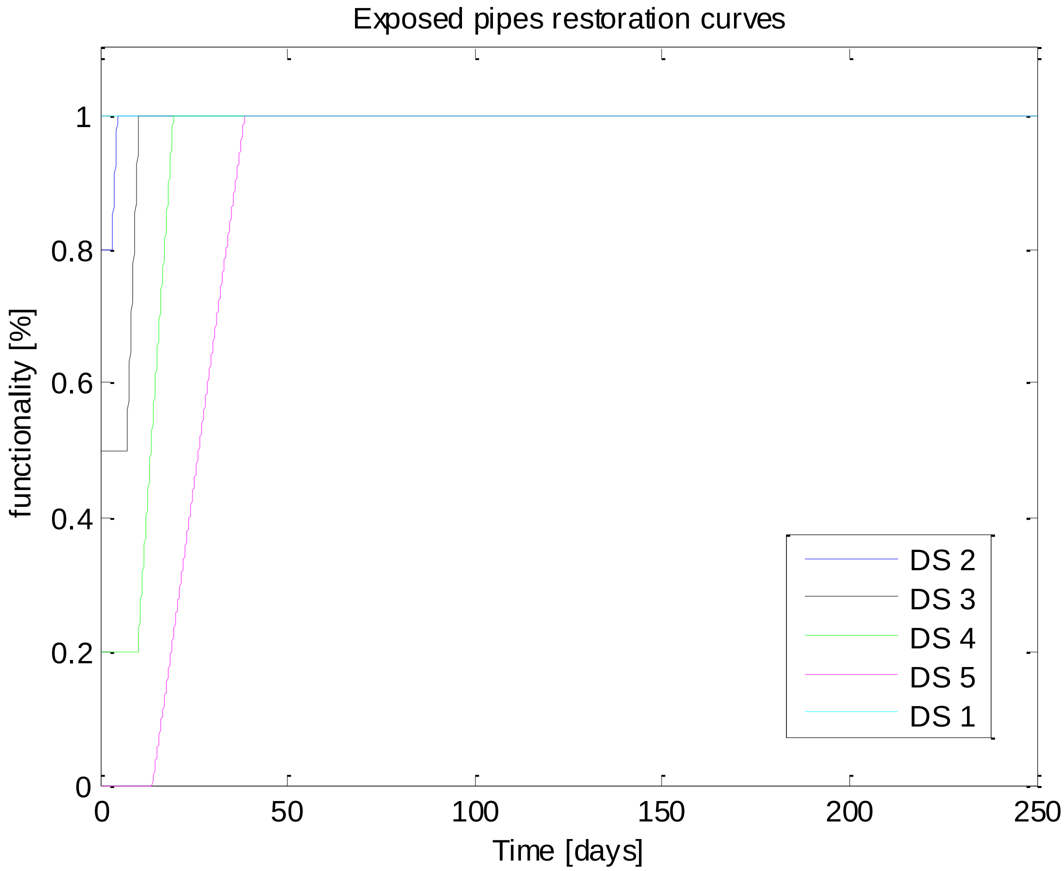


Fig.3.15 *Restoration curves for exposed pipes.*

Steel tanks

Steel tanks		
Social class	Water supply - Terminal Reservoir	
Damage State	*μ (days)*	*β*
Slight - DS2	0,70	1,10
Moderate - DS3	5,00	5,10
Extensive - DS4	48,10	38,50
Complete - DS5	91,60	51,20

Tab. 3.9 *Restoration curves parameters for steel tanks.*

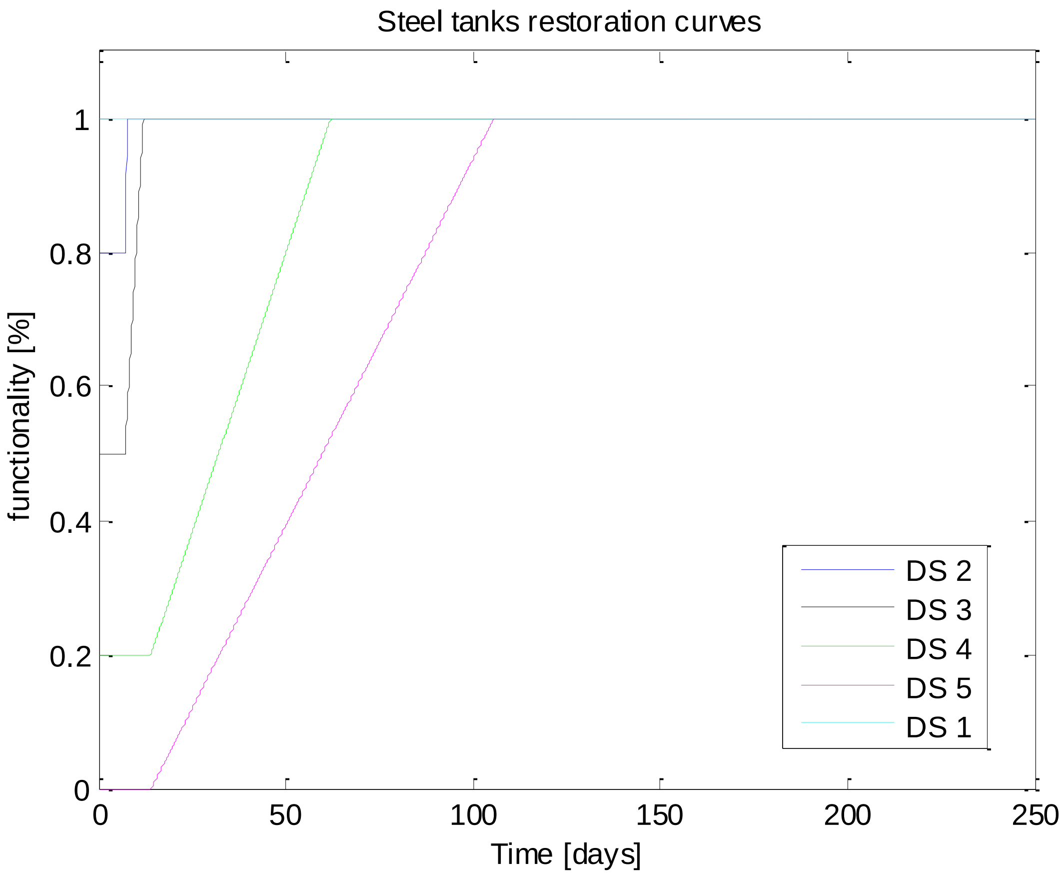


Fig. 3.16. *Restoration curves for steel tanks.*

3.5. System assembly

System assembly is the model most important step. In fact, it allows to “sum” restoration time of each component, obtaining the system restoration scenario. Unlike the previous modules, it deeply depends on the system structure and characteristics. In fact, the assembling occurs simulating the productive process, which can be developed through a process flow diagram. Flow diagram allows to consider, into restoration process, effects given by the components position inside the process and the connection typology between components.

3.5.1. Process flow diagram

Generally, a process flow diagram is a diagram commonly used in process engineering to indicate the general flow of plant processes and equipment. The diagram displays only the relationship between major equipment of a plant facility and does not show minor system details. The use of process flow diagram in the model allows to simulate the business process and to quantify the loss of functionality along the system. For restoration assessment, process flow diagram is repeated with a temporal step of 1 day, implementing in each component changing parameters given by restoration curves. The resulting restoration scenario depends from the whole components behavior. In particular, concerning possible connection typology between components, is possible define two categories:

- **In series components**. In this case the loss of functionality of the former components affects directly the functionality of the other components. If only one component collapse, whole the process stops. Hence the restoration process is strictly affected by the most vulnerable component and its fixation allows a quadratic growth of restored functionality;
- **Parallel components**. Loss of functionality of components in parallel does not affect the other components which results uncorrelated. This involves a faster restoration scenario since it is possible to reallocate flow of damaged components in other.

Mutual influence between components affects also the shape of output restoration scenario, which, unlike components linear restoration curves, could assume also a curve or a mixed behavior. The causes connected to this are illustrated into the chapter of analysis results.

3.5.2. Winery Flow Diagram

Winery process flow diagram is built defining for each winemaking step the vulnerable components involved. Hence, depending on components number considered and complexity of system framework, it is possible to define different levels of recovery analysis. Implementing an hypothetical winemaking process and considering as primary goal of the research the analysis of the model characteristics, an elementary winery has been considered. Moreover, using an easy process framework, it is possible to better clarify components effects in restoration scenarios. According to Nardin's winemaking cycle categories, a general winery framework for the model analysis has been designed as showed in the figure 3.17. Beyond the steps identification, for each step, the most recurring vulnerable components are reported. The predominance of a vulnerable component typology is also identify by using different colors.

Defined the process framework, a correspondent flow diagram has been generated. In order to create an easy winery diagram flow from the previous framework, any step and the correspondent components have been collected in a unique flow component. Moreover, to test the effects of different components connections, both in series and parallel components have been considered.

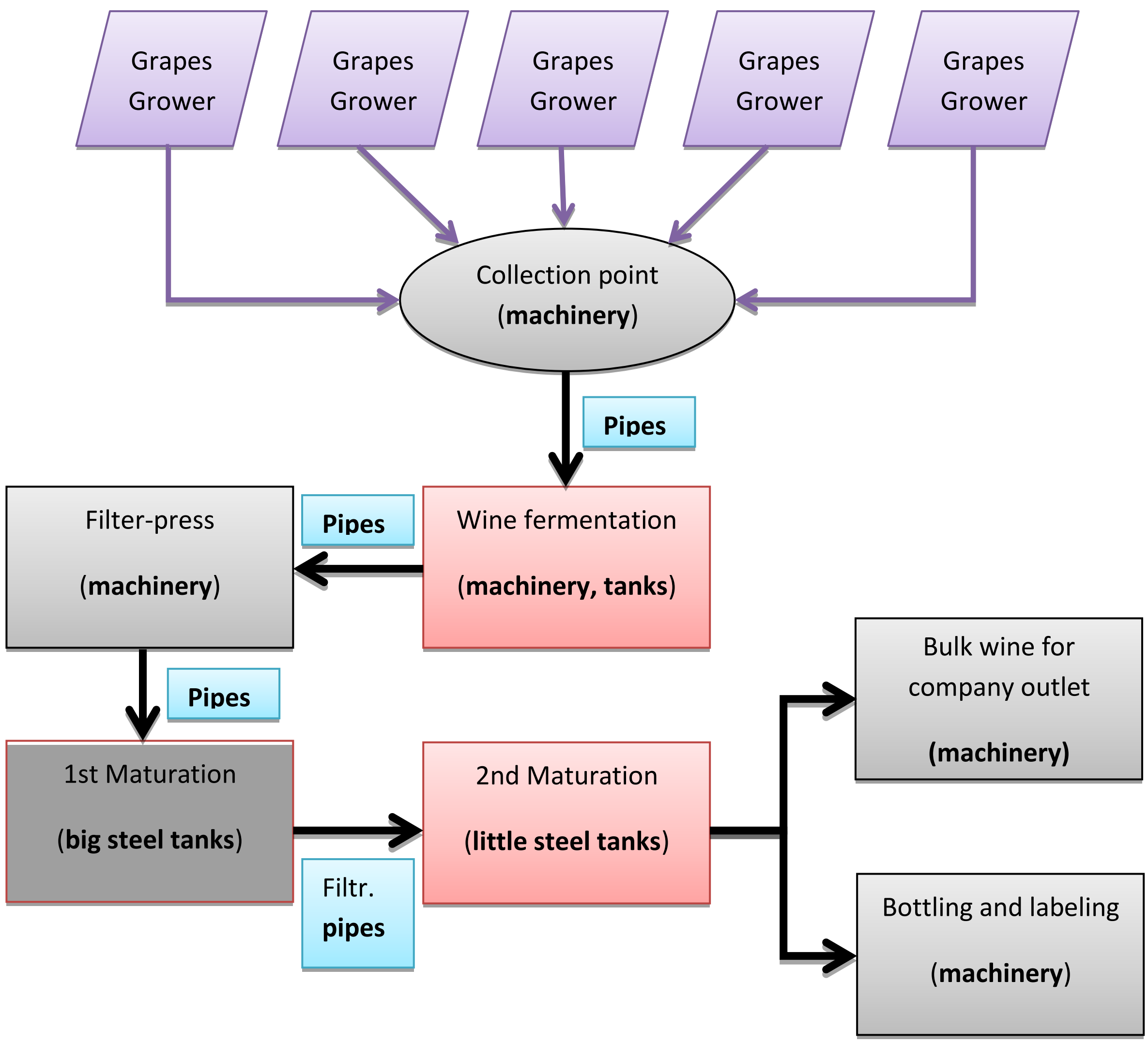
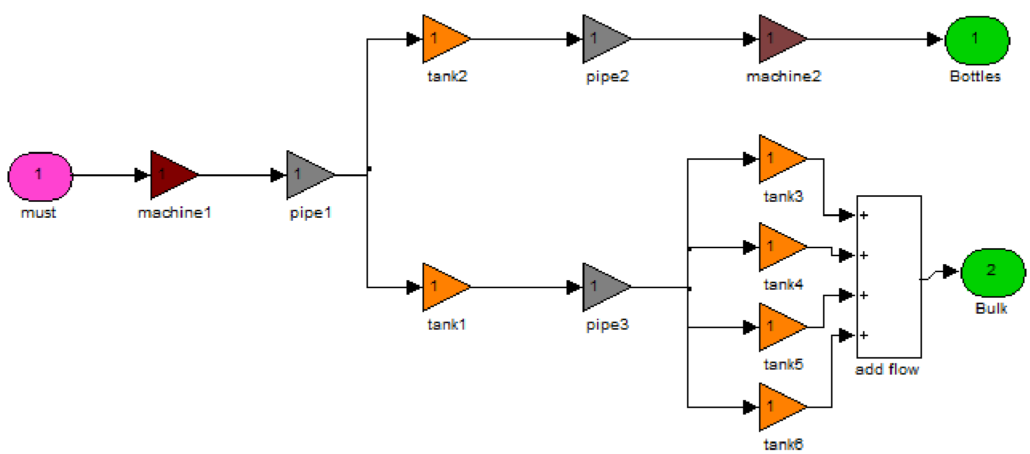


Fig 3.17. *While grapes growers are showed only for goodness of representation, other colors identify components considered in wine making steps (grey =machinery, white=pipes, red=steel tanks).*

In particular, the former three winemaking steps (grapes harvest, wine fermentation and wine filtration) have been identified as a single machinery component. At the later stage, maturation step has been considered after the subdivision of the process depending on the final product (bulk wine or bottle wine). Considering the bulk wine line of work, both maturation steps have been implemented using steel tanks components, considered in parallel in the second maturation. Instead, the wine bottle line of work has been represented with a tank component for wine stabilization and later a machinery component for bottling and labeling. All the operational components described have been connected through exposed pipes components.

The described diagram flow, shown in a representative way in the figure below, is the most complex implemented in the research, and despite its basic diagram framework, allows a reliable assessment of the restoration process.



Scheme 3.18. *Winery diagram flow, implementing through Simulink software. It is composed from eleven components of three different typologies and with two different connection ways.*

4. Model implementation

From a computational point of view, model implementation is defined as a structure relating to the main three steps: components damage assessment, components recovery assessment and system assembly. Each of these three modules contains substructures for data input and processing which return output values of correspondent objective variables on the main structure. For each vulnerable component, considering as input variable the earthquake PGA, the model assesses a probabilistic damage state. Each damage state in order involves a fixed loss of functionality, a probabilistic starting delay in the recovery process and a probabilistic restoration time. At this point, to obtain the resulting average restoration scenario, a sampling method has been used .

4.1. Earthquake scenarios

It is important to illustrate some aspects of the earthquake scenarios related to model input quake intensity measure. As already said, the peak ground acceleration (PGA), used as the model input intensity measure, is also used to assess fragility curves parameters. The method used to evaluate fragility curves through PGA is called "the equivalent PGA" and it is composed of the following steps:

- Assessment of response to the earthquake for the component through the generation of capacity curves (seismic structural displacement for each damage state considered);
- Definition of fragility functions equivalent PGA matching component capacity curves with damages states spectrum shape.

Hence, despite the most direct way to measure earthquake impact is the structural displacement, PGA has been used in this research because it is the most appropriate measure of damage for lifeline facilities. Considering nonstructural components, it is not necessary calculate the capacity curves since PGA is given directly from ground motion analysis.

However, besides ground motion intensity, the spectrum shape is also a function of earthquake source, earthquake magnitude, distance from earthquake sources to site, site condition and effective damping. This involves the particularizations of each fragility curve for a given earthquake scenario.

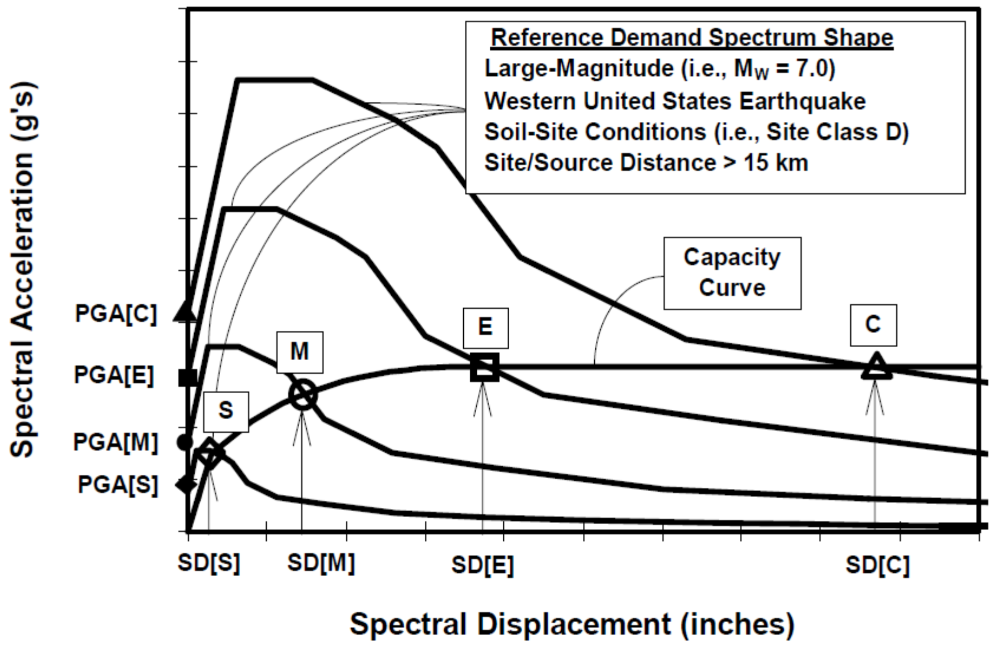


Fig 4.1. *Graphic representation of equivalent PGA method. In the test box are reported characteristics used from HAZUS to implement shape spectra. [5]*

Considering the fragility curves of the components implemented in winery analysis, the curves have been obtained using parameters provided by HAZUS (machinery and exposed pipes) and Californian damages database (steel tanks). Since HAZUS parameters are developed using spectrum shape with characteristics of West United States earthquakes scenarios, there is congruence into the definition of fragility curves PGA between all system components considered. However this aspect represents also a limit for the model cause is not optimized to implement system placed in other areas and subjected a different earthquake scenarios.

Finally, in model implementation have been considered two additional assumption concerning earthquake scenarios characteristics:

- All winemaking steps have been considered localized in a tight area to allow the use of the same input PGA values for every component.

- Into the damage analysis are considered only damages due to ground shaking, without considering eventual ground failures.

4.2. Monte Carlo method

Effecting damage analysis on a system, is necessary to adopt a probabilistic sampling approach in order to assess the behavior of the model. This means, considering initial variables described by density distributions, to define a set of probabilities which characterizes the results, given certain surrounding conditions. Probabilistic sampling could be made using an analytical approach, but on a practical basis this is unfeasible. A possible solution can be the use of Monte Carlo method.

Monte Carlo methods are a broad class of computational algorithms that rely on random sampling to obtain numerical results. It was invented by two physicists in 1946, John von Neumann and Stanislaw Ulam, while they were investigating in radiation shielding at Los Alamos scientific laboratory to solve a problem of lack of data. The name was given by Nicholas Metropolis in honor of the Monte Carlo Casino. The concept of this simulation is to provide for a chosen variable, a large number of random values, in order to estimate accurately its mean and dispersion in a complex system.

The most common Monte Carlo procedure is the "inverse transform" method. Melchers [9] , talking about structures analysis, illustrates theoretical basis of the method. Considering a basic variable Xi, its cumulative distribution function $FX(xi)$ assumes a value between 0 and 1. The inverse transform method consists in generating a uniformly distributed random number ri included in the interval (0,1) and equating this to $FX(xi)$.

$$FX(xi) = ri \qquad (4.1)$$

In this way, if the inverse function $FX^{-1}(xi)$ exists, the sample value xi can be found.

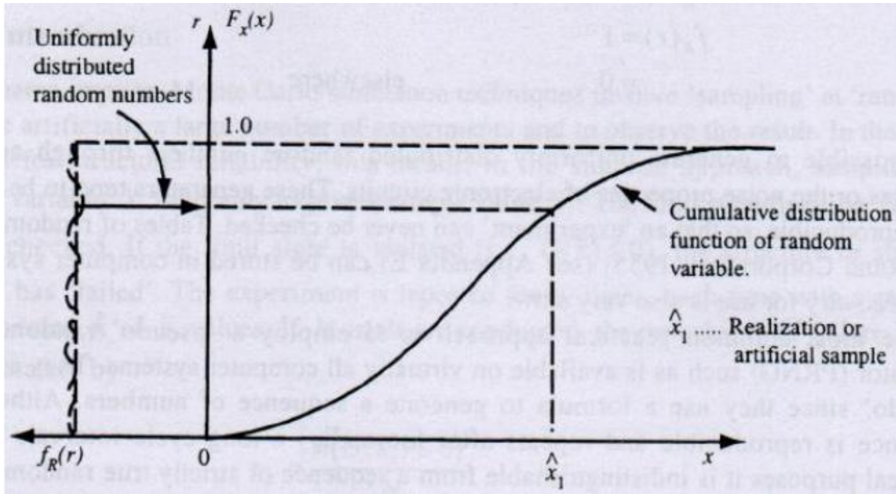
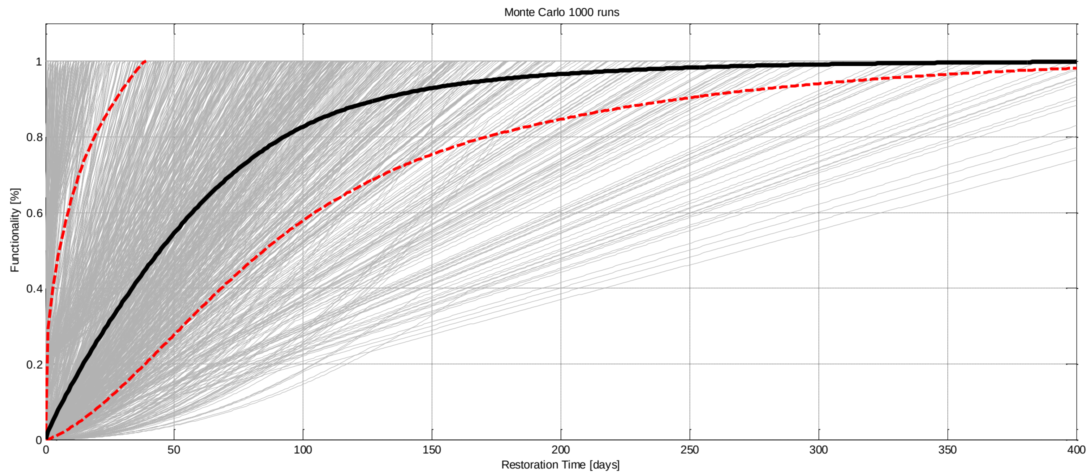


Fig.4.2. *Graphic representation of inverse transform method.*

Monte Carlo method is used in the presented model to sampling probabilistic variables, in order to assess the impact of statistical uncertainties in restoration scenarios. In fact, depending on event probabilities for variable and standard deviation of density function fitting the variable, output samples present different values which take in account random statistical uncertainties. In recovery analysis, Monte Carlo method is applied to probabilistic variables given by fragility and restoration curves. It allows the definition of damage states samples from fragility functions and restoration times samples from restoration functions. Moreover, Monte Carlo method is also applied to sample starting recovery delay into restoration curves. At the end of the model implementations, given a Monte Carlo simulations number, are obtained likewise restoration scenarios number. Hence, it is necessary to use the same number of Monte Carlo for each sampled variable.

To obtain a valid statistical sampling, 1000 Monte Carlo simulations have been run for each of the three probabilistic variables. Simulations have been repeated for each component, allowing the independence between components samples. The choice to run 1000 Monte Carlo has been retained sufficient for sampling goodness since this simulation number guarantee the event of all likely combinations between system components, given a certain input variable value. In order to verify this fact, one elementary system (two equal components in series) has been implemented considering two different Monte Carlo simulations number: 1000 runs for the first case and 10000 runs for the second case. Resulting restoration scenarios are showed in figures 4.3 and 4.4. It is possible to note as adopting a ten times greater number of Monte Carlo (10000 runs), the resulting average restoration scenarios and variance boundaries times do not present meaningful differences cause all the possible combinations between components restoration curves are already hit using 1000 Monte Carlo simulations.



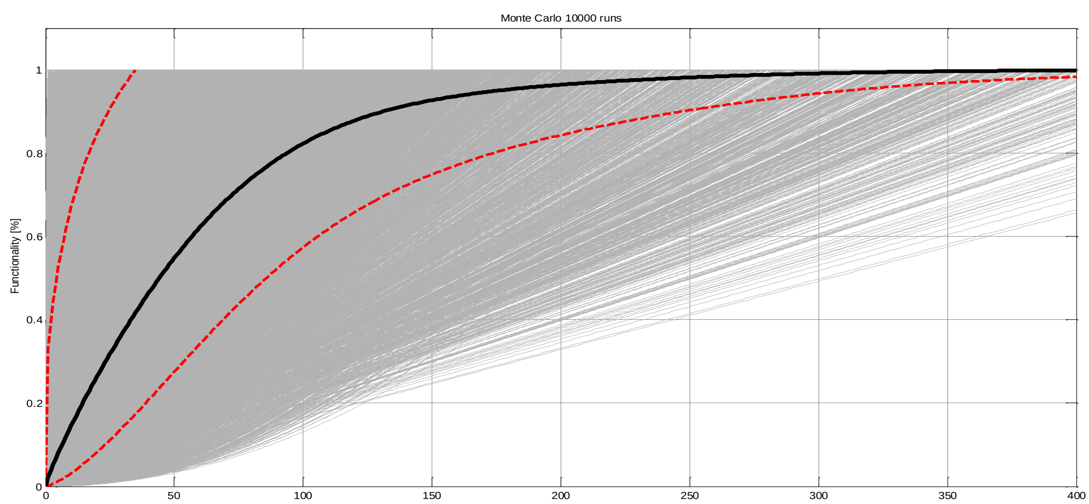


Fig. 4.3-4.4. *System restoration scenarios considering 1000 (top figure) and 10000 (bottom figure) Monte Carlo runs.*

4.3. Winery implementation characteristics

Two different software have been used to implement the winery case:

- **Matlab**: software for generic numerical computation. It has been used to implement the main framework of the model and the substructures of damage and restoration assessment;
- **Simulink**: data flow graphical programming language tool for modeling, simulating and analyzing multidomain dynamic system. It has been used to implement the process flow diagram of the system. It works as a substructures of Matlab model framework.

For each component, the following computational parameters have been considered :

- Three input probabilistic variable types: fragility parameters, restoration parameters and restoration starting delay parameters;
- Three different input PGA: 0,4 g

  0,8 g

  1,2 g
- 1000 Monte Carlo runs.

The process flow diagram used to simulate the winery process is showed in figure []. Recovery process has been obtained providing to the Simulink model for each component restoration slope, restoration starting delay and residual functionality. An important assumption consists in considering all the components at their maximum operative level. In this way, considering damaged parallel components, the reallocation of the product is not allowed. Output graphs show the restoration scenarios starting from the first day after the earthquake to 400 days later.

In order to calibrate the model and to define the correlations between components, several cases have been implemented, starting from the most basic model, one component with two damage states, to the complete winery system. In the table below are showed the characteristics of the twelve main cases implemented, useful for understanding the model behavior given increasing variables and components number.

Cases implemented				
# Cases	**# Components**	**# Fragility curves**	**Components typology**	**Connections typology**
1	1	1	Steel tanks	no connections
2	1	2	Steel tanks	no connections
3	1	5	Steel tanks	no connections
4	2	1	Steel tanks	in series
5	2	2	Steel tanks	in series
6a	2	5	Steel tanks	in series
6b	2	5	Steel tanks, Machinery	in series
7a	2	5	Steel tanks	in parallel
7b	2	5	Steel tanks, Machinery	in parallel
8	3	5	Steel tanks, Machinery, Exposed pipes	in series
9	8	5	Steel tanks, Machinery, Exposed pipes	in series
10	11	5	Steel tanks, Machinery, Exposed pipes	in series and in parallel

Tab 4.1. *Characteristics of implemented cases*

In particular, to implement the basic cases 1,2,3,4 and 5, only one input PGA equal to 1g has been considered since these cases are helpful to show the output model structure but at the same time not valuable to describe a system restoration scenario.

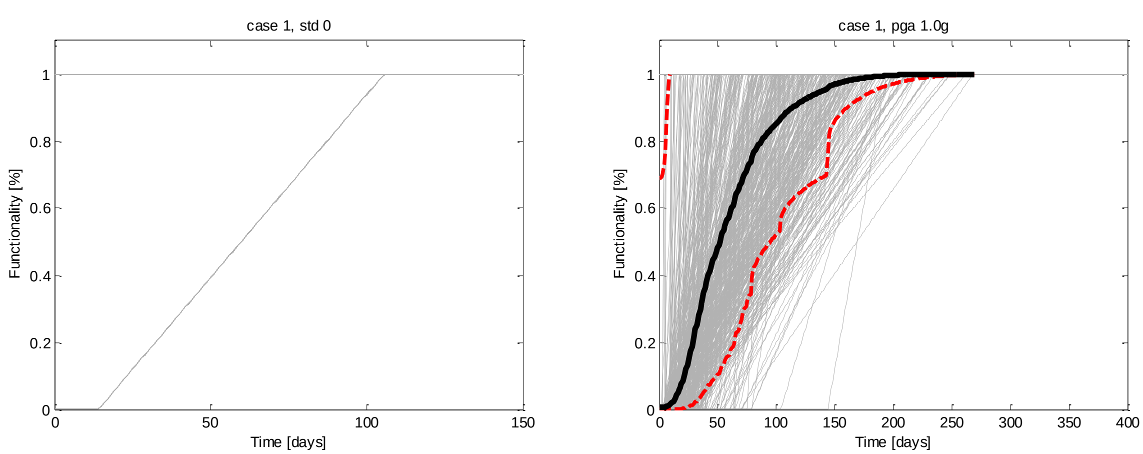
5. Results

In the first part of this chapter resulting scenarios of ten cases are showed in ascending order of complexity. Illustrated cases are the most interesting in order to show the shape and characteristics of restoration scenarios. For each case analyzed, two different kinds of graphs are illustrated. The first type, show restoration scenarios with standard deviations and starting delay equal to zero in order to point out the recovery model behavior. The second graph shows the resulting restoration scenarios set with average scenario and σ percentiles marked. In the second part of chapter, according to trends and characteristic observed to results, are showed the influence of some restoration aspect on the total restoration scenarios.

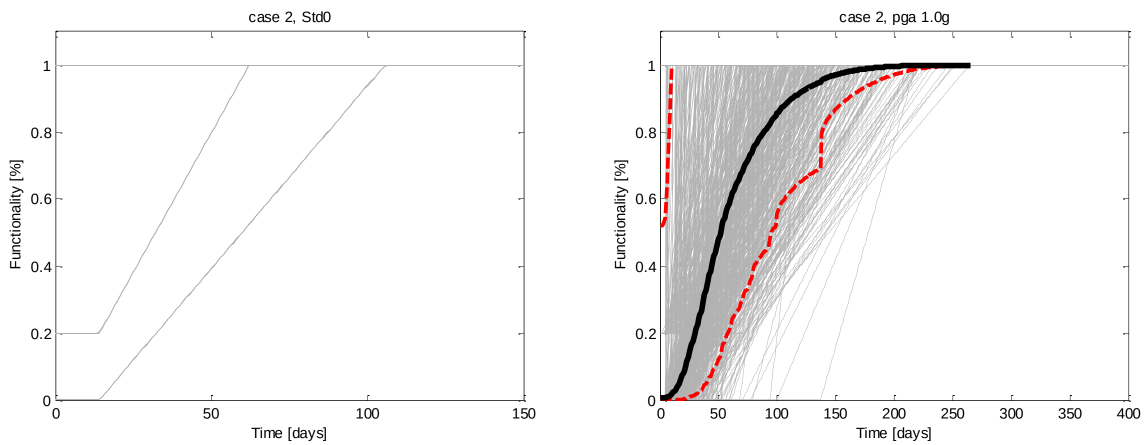
5.1. Cases 1,2,3,4 and 5

The former cases cannot be considered a system, but they are useful to describe the restoration scenarios framework change, increasing the number of damage states and components considered. For convenience of comparison among cases results, components analyzed are steel tanks for all the cases. Results analysis can be split up in two groups. In the first group (cases 1,2,3) , restoration scenarios of a single component increasing fragility curves number are described. While in the second group (cases 4, 5), restoration scenarios of a connected couple of components are illustrated, considering different fragility curves levels number.

Case 1 – one component and two damage states



Case 2 – one component and three damage states



Case 3 – one component and five damage states

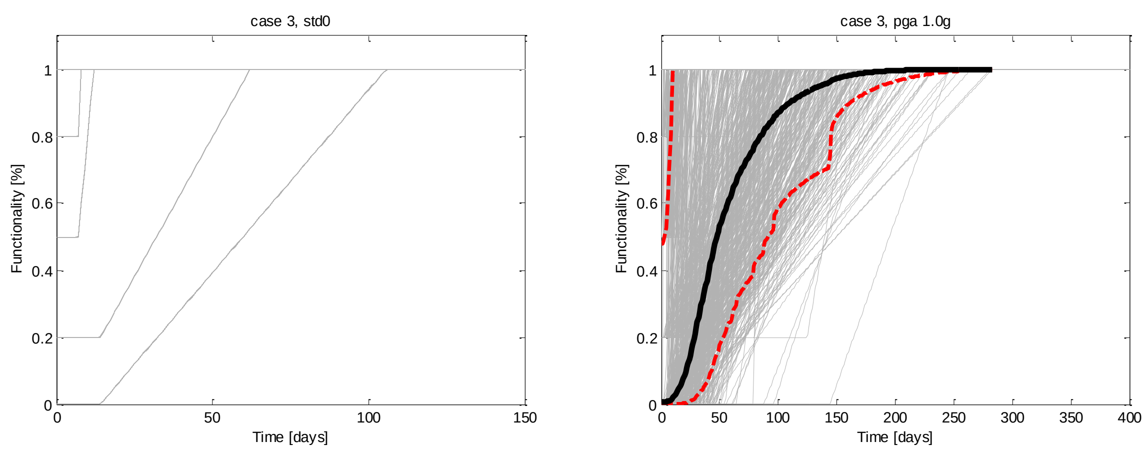
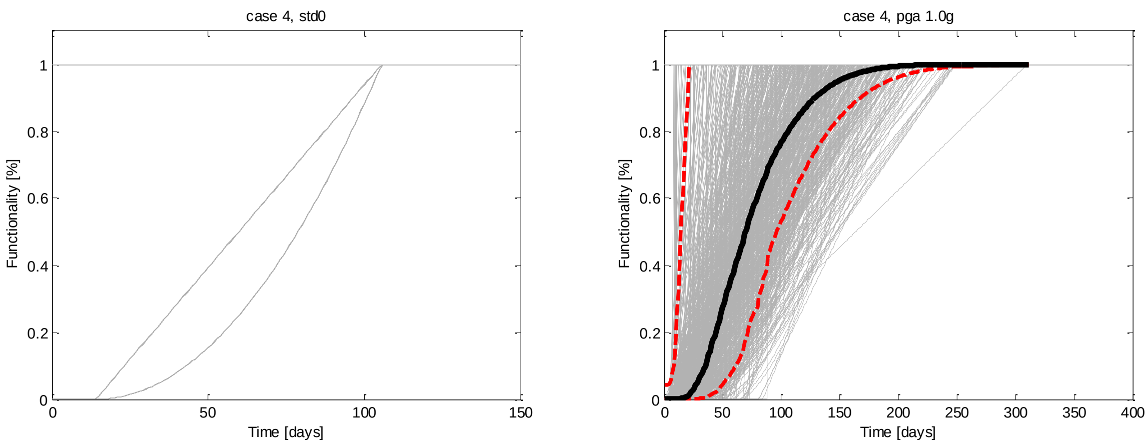


Fig.5.1-5.6. *Restoration scenarios graphs of cases 1,2 and 3.*

Zero standard deviations graphs allow to check the correct model implementation. In fact, it is possible to observe the restoration curves shape for steel tanks, already showed in section 3.4.2. Accuracy of the model setting is proved also from the correspondence between parameters of restoration day means, starting residual functionalities, average starting delays and their graphs outline. Moreover is also possible to ascertain that the full recovery achievement correspond to the sum of the average restoration time plus the average starting delay.

Concerning system restoration scenarios graphs, it is possible to note as the model accuracy improves increasing the number of damage states, since more damages combination are considered. This is confirmed also observing the interesting trend showing as the increase of damage states considered do not influence considerably the mean restoration time, but reduces standard deviations from it. On the right σ boundary are evident some dimples probably given by the difference of starting time between damage states restoration time, that is a consequence of starting delays.

Case 4 – two components and two damage states



Case 5 – two components and three damage states

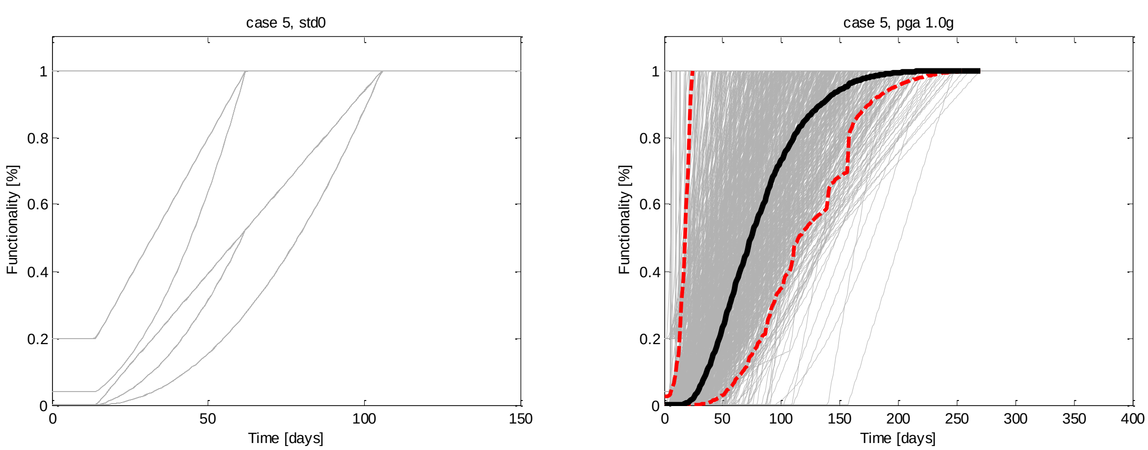


Fig 5.7 – 5.10. *Restoration scenarios graphs of cases 4 and 5.*

Cases 4 and 5 describe the interaction between two components of the same types supposed in series and considering a reduced number of damage states. Here restoration scenarios is the combination between restoration curves of each component. Analyzing graphs with standard deviations equal to zero, is possible to note that, when both components are in a damage state different from DS1, resulting scenario is curved, otherwise the restoration process appears linear. This recovery characterization is due to the fact that DS1 restoration curves, describing a situation of no damage, do not have a correction slope, since their match with greater damage states corresponds to restoration curves of these. Finally, even if it is intuitive, it is also interesting to remark as, concerning the same type of component, restoration scenarios with damage states upset (i.e. scenario A:tank1 DS4 – tank2 DS5 and scenario B: tank1 DS5 – tank2 DS4) are coincident.

System restoration scenarios graphs show a right shift of restoration scenarios if compared with cases 1 and 2. This is due to effect of influence between components that involves a delay in the restoration process. Moreover, it is also possible to note as matching more components together, dimples on σ boundary tend to disappear, probably because a major number of possible restoration scenarios combinations evenly distribute starting delay effect.

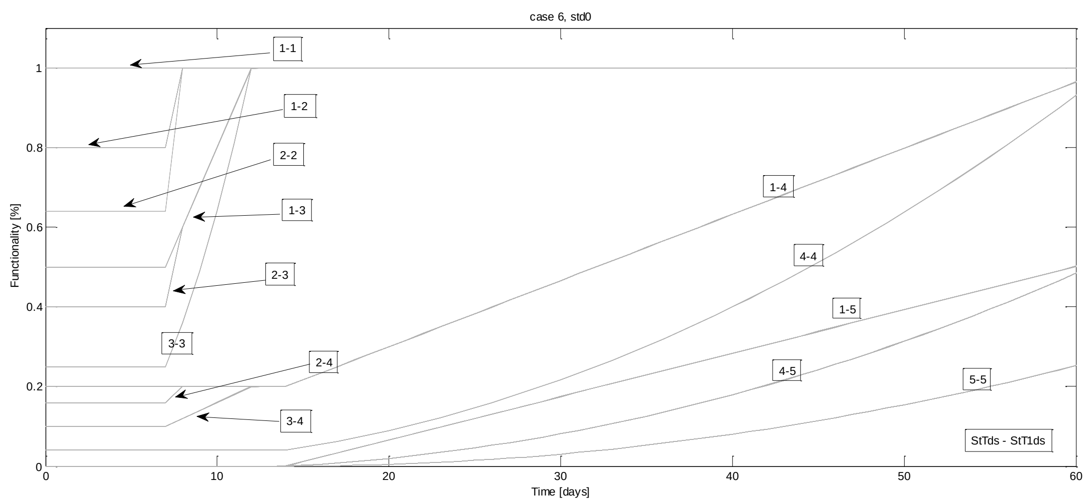
5.2. Cases 6 and 7

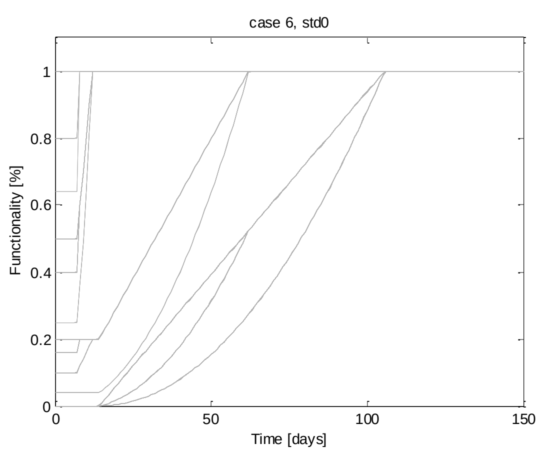
Although also these cases cannot be considered a system, representing a system with two components and five damage states, they are extremely interesting in order to define model characteristics relative to the possible different typology of influence between components. In fact, considering two generic components, 25 different restoration scenarios combinations are possible. In order to implement these cases, different connection and components typology have been matched obtaining four cases:

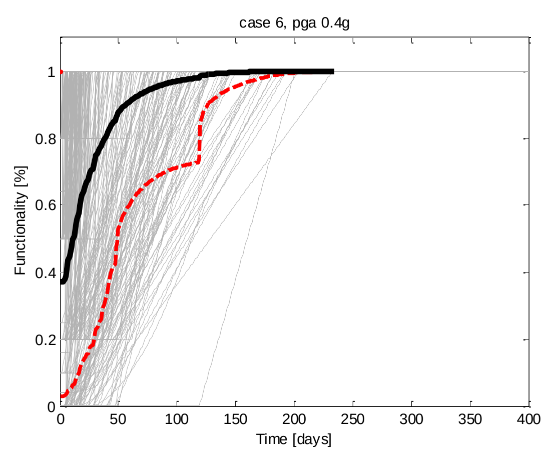
- Case 6a: two identical components (steel tanks) connected in series;
- Case 6b: two identical components (steel tanks) connected in series;
- Case 7a: two different components (steel tank and machinery) connected in parallel;

- Case 7b: two different components (steel tank and machinery) connected in parallel;

Case 6a – two identical components and five damage states







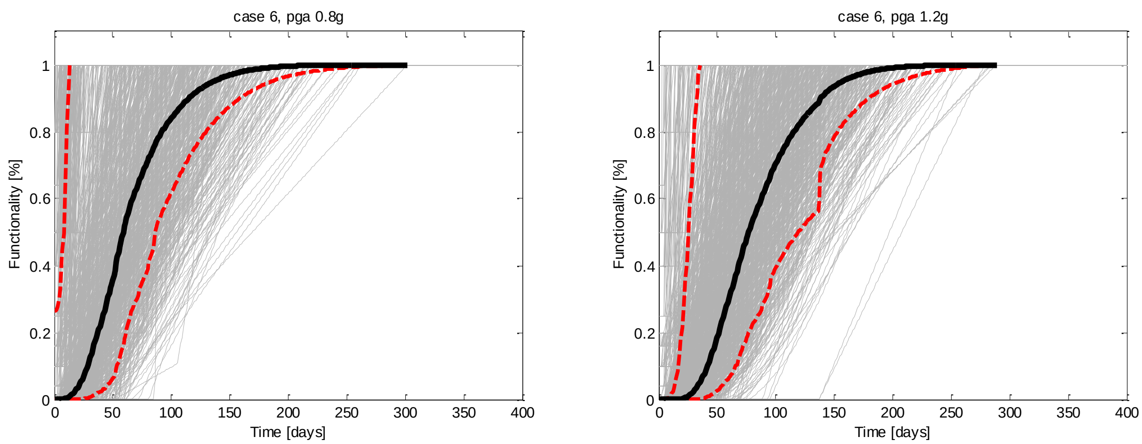


Fig 5.11 – 5.15. *Restoration scenarios graphs of case 6a.*

Case 6b – two different components and five damage states

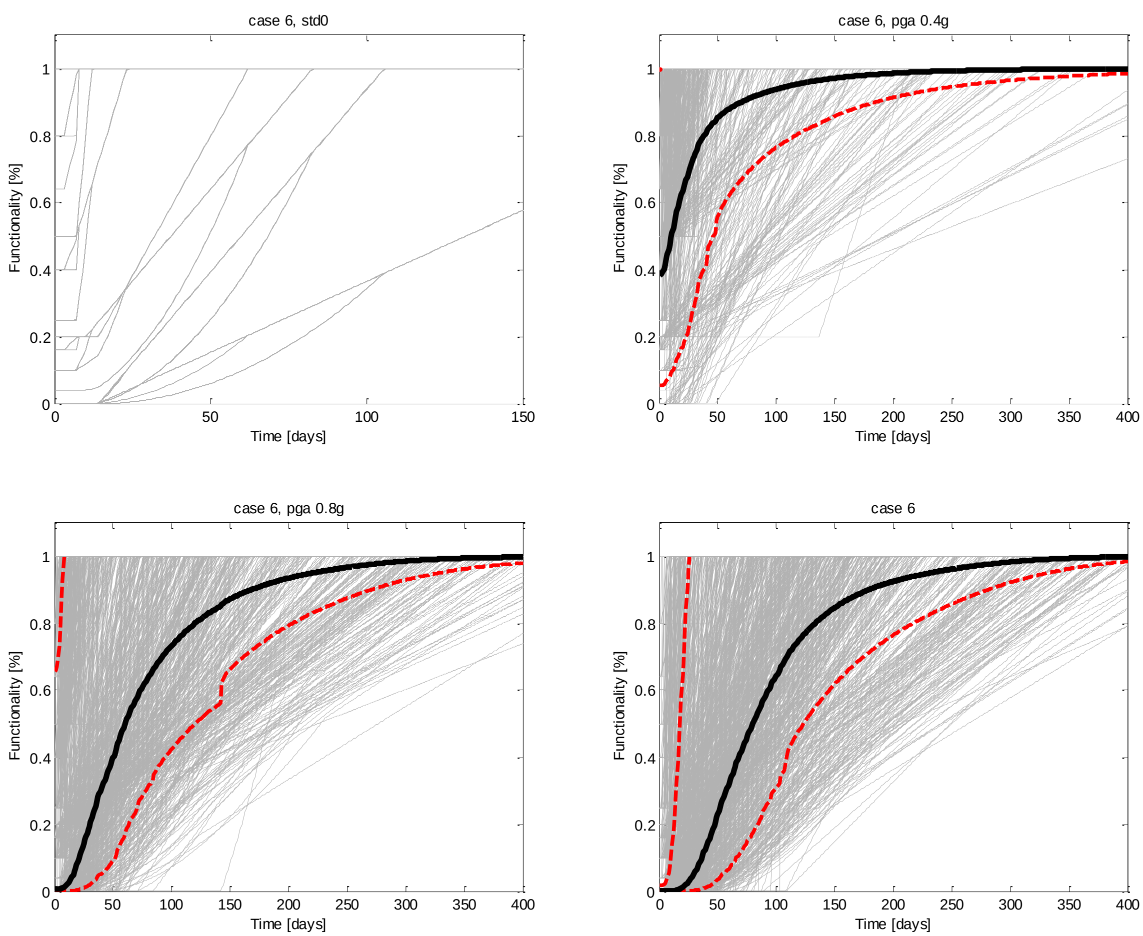
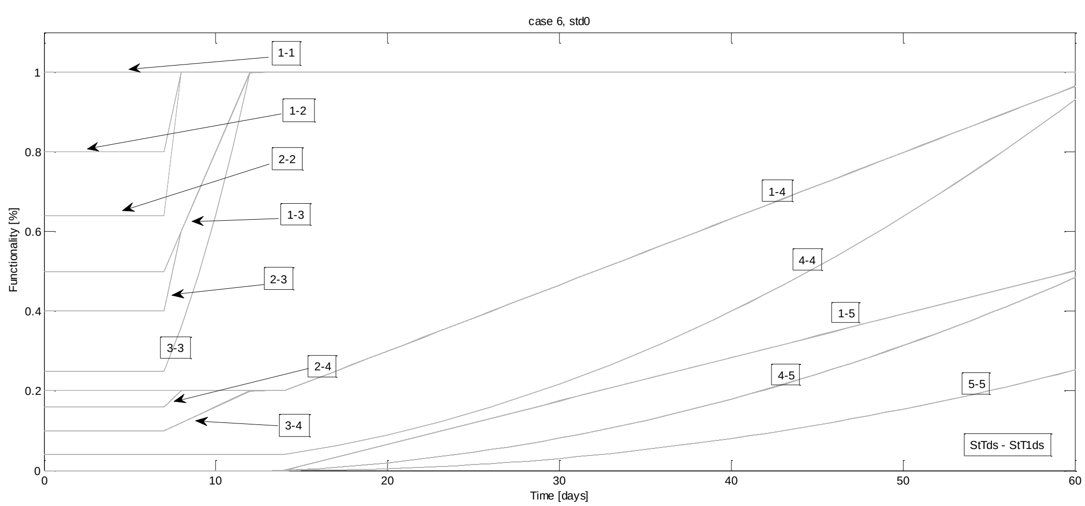


Fig 5.15 – 5.19. *Restoration scenarios graphs of case 6b.*

Concerning zero value standard deviation graphs, the first graph shows for case 6a illustrates the labelling of all possible combinations between components restoration curves. In particular, cases 2-5 and 3-5 are not present since they are “absorbed” from case 1-5, being to the left of this. This graph typology is not reported for cases 6b since, as it is possible to observe, using two different components, upset combinations involves different restoration scenario and the labelling results problematic.

Concerning restoration scenarios graphs, as is deducible, increasing the earthquake PGA intensity restoration scenarios are subjected to a right shift. Considering the restoration flex point is possible assess a time difference of about 100 days between the 0.4g PGA case and the 1.2g PGA case. Analyzing differences between case 6.a graphs and case 6.b graphs, it is possible to observe, as expected, longer restoration curves considering different components since machinery restoration time is longer than steel tanks restoration time.

Case 7a – two same components and five damage states



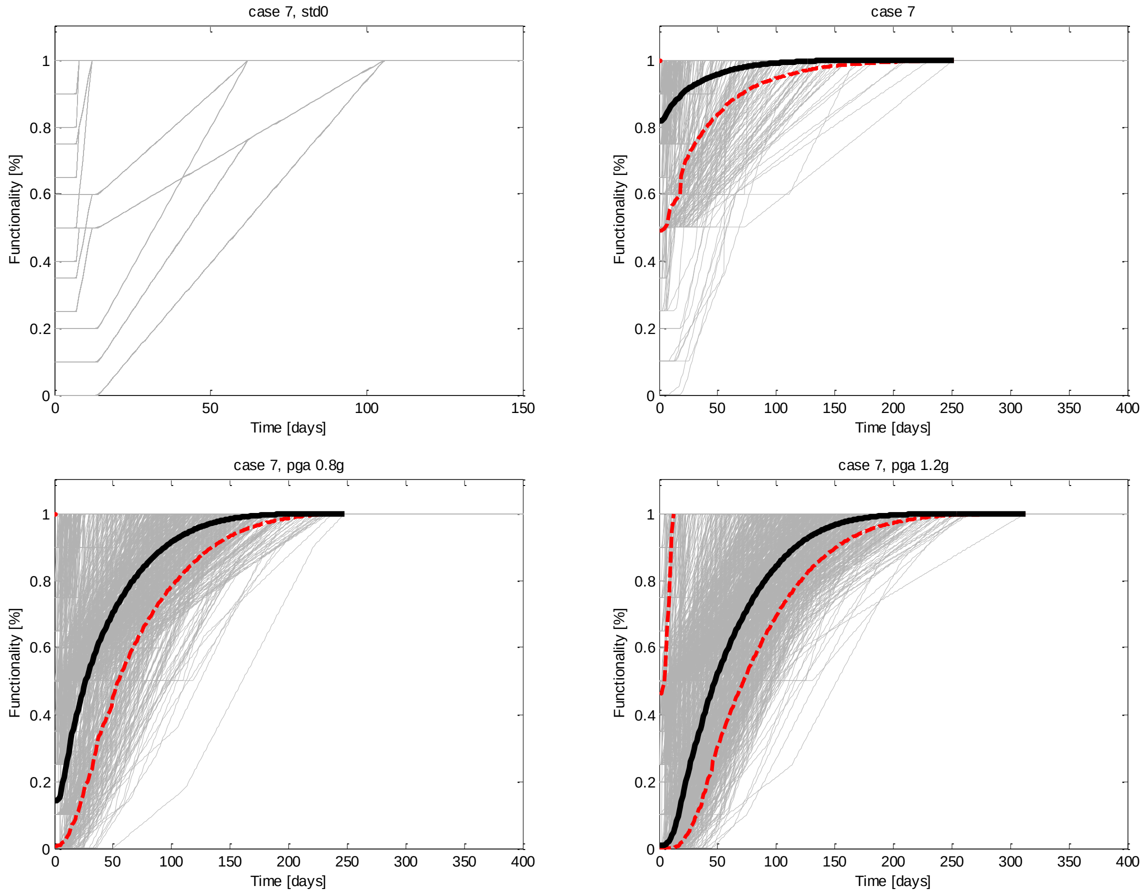
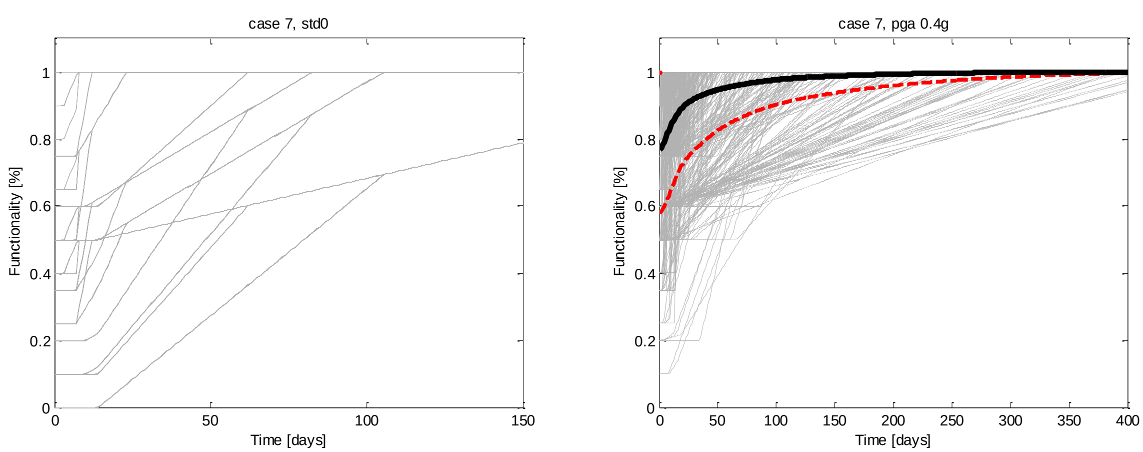


Fig 5.20 – 5.24. *Restoration scenarios graphs of case 7a.*

Case 7b – two different components and five damage states



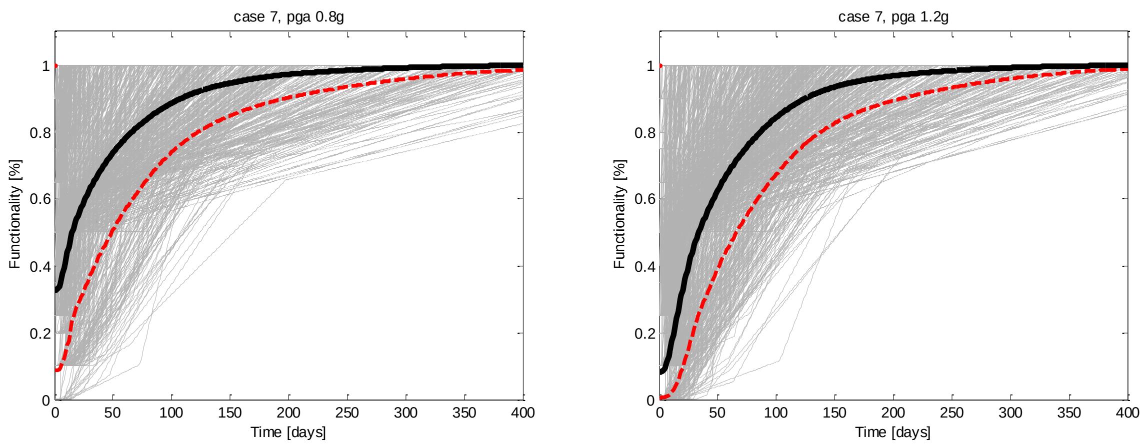


Fig. 5.25 – 5.28. *Restoration scenarios graphs of case 6b.*

Considering zero value standard deviations graphs of cases 7a and 7b, it is possible to observe as components in parallel shows a completely different behavior from the previous ones in series cases. In fact, restoration times of components in parallel are not influenced by each other, hence resulting system restoration scenarios consist in “arithmetic means” between single components restoration curves. This fact involves a characteristic linear shape for components in parallel. In the first graphs of case 7a are enumerated all possible DS components combinations.

Comparing cases 7a and 7b, the influence due to consideration of two different components involves also here a right shift of restoration scenarios. Finally, considering comparison between in series cases and parallel cases, it is possible to note that, on equal starting terms, restoration scenarios for parallel cases are shorter than restoration scenarios for in series cases.

5.3. Case 10

Finally, the case 10, representing the complete winery model is analyzed. It presents all the possible characterization earlier discussed and the correspondent model simulation has been described in section 3.5.2.

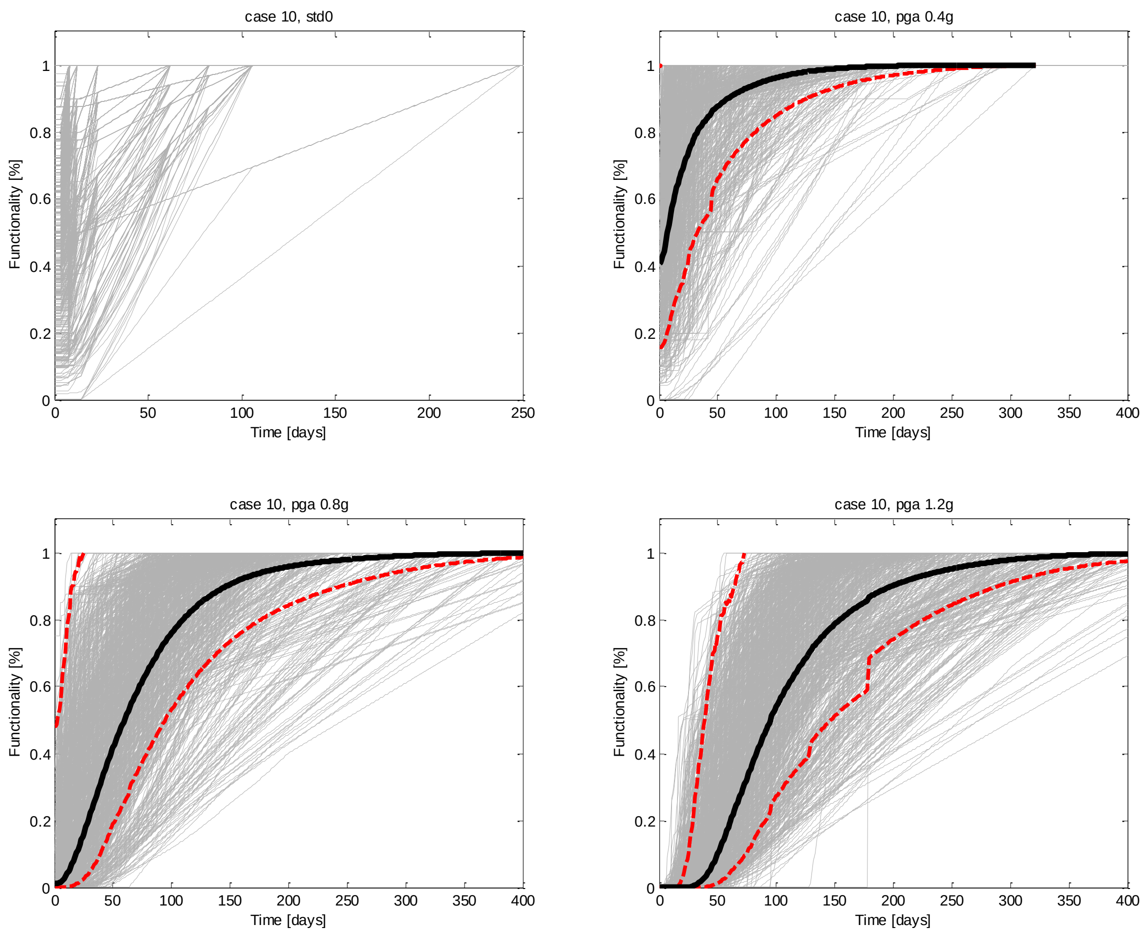


Fig 5.29 – 5.32. *Restoration scenarios graphs of case 10.*

Reminding as winery model is composed of eleven components of three different typologies and two different connection typologies, zero value standard deviation graph is hard to read since it shows all the possible restoration scenarios combinations.

Considering the system restoration scenarios graphs, it is evident that even increasing the number of system components, the mean restoration time does not change considerably, if compared for example with case 6b that considers only two components. On the other hand, a big number of correlated components reduce the deviation from the average restoration curves. This is clear comparing the 1.2g PGA graph with 1.2g PGA graph of case 6b. In fact, in case 10, the shortest system restoration scenarios are not present because their realization is unlikely feasible for a complex system subjected to a strong ground motion, where there is an high probability that al least one component is damaged. Moreover the average restoration scenarios, depending on multiple components, show a smooth restoration flex point.

5.4. Influence Factors

As already said in section 3.4.2, for implementing the restoration scenarios analysis, restoration curves parameters from ATC13 with some additional assumption have been used. The modifications which have been carried out have had meaningful effects on restoration scenarios behavior, thus permitting to improve the level of reliability of the output restoration scenario compared with real cases. In order to verify this, in the present section the differences between the restoration model with exact ATC13 parameters and the winery restoration model with modified ATC13 parameters are shown and commented.

It is possible to identify two main implemented modifications added to ATC13 parameters :

- Definition of a starting residual functionality;
- Definition of a starting delay in restoration process.

5.4.1. Residual functionality effect

The definition of different residual functionalities (RF) for damaged components after an earthquake, permits to optimize ATC13 restoration curves behavior. In fact, ATC13 provides three types of restoration parameters with different levels of RF (0%,40% and 70%) hence, in the restoration analysis all the components are considered with the same RF, without depending on damage state level. Instead, RF additional assumption evaluates different residual functionality levels directly correlated to component damage state extent. Obviously, the method to classify residual functionality levels, illustrated in section 3.4.2, consists in to define bigger residual functionalities for slighter damage states and conversely. Inevitably, this causes changes in restoration processes starting shape.

On the other hand, the resulting modified restoration functions involve the achievement of complete restoration in a different period respect ATC13 means. Hence it is necessary to correct the slope of restoration functions in order to keep the residual functionality not correlated with the function slope. The correction is applied considering as a slope numerator the complementary value of the residual functionality of the damage state observed. In this case, the correction allows to maintain the same number of restoration days expressed by ATC13. The effect of this double operation is shown in the figure below.

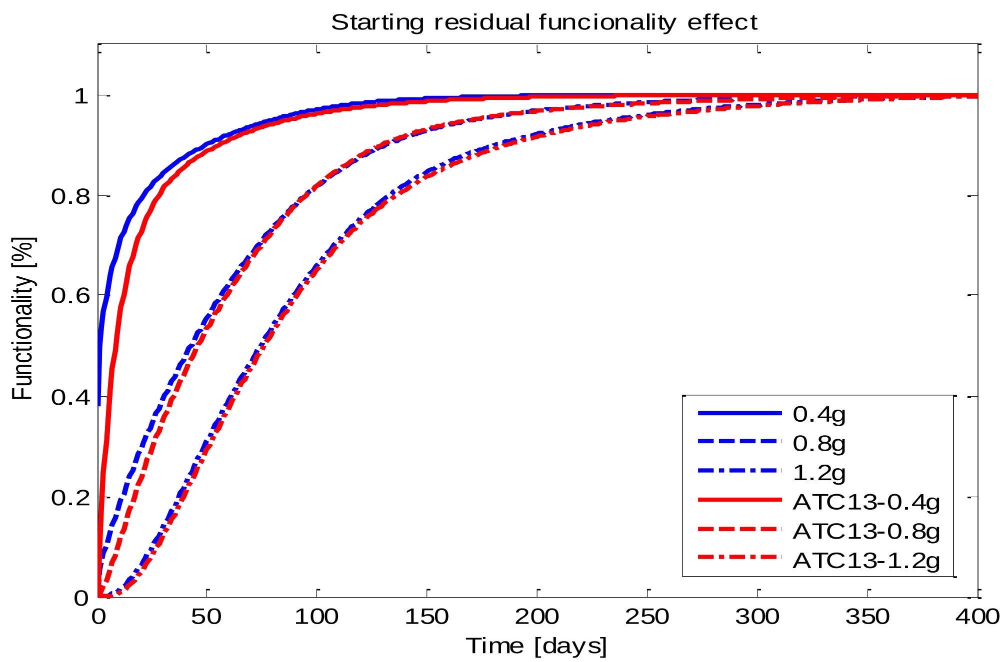


Fig 5.33. *Effect of starting residual functionality on restoration curves.*

It is easy to realize as the assumption of different RF implies a left shift of restoration curves, partially balanced by slopes correction. The figure shows a shift increase of restoration process as the earthquake intensity decreases. Probably, this is caused from the fact that for strong earthquakes slighter damage states do not happen and residual functionalities of heavier damage states are close or equal (for DS 5) to 0% of RF defined by ATC13 method. On the other hand, the total restoration achievement and the curves flex point happen at the same time than ATC13 restoration curves. Considering that the most part of occurring earthquakes involves damages for PGA smaller than 1g, the starting residual functionality involves a significant effect on the restoration process.

5.4.2. Starting delay effect

The other important assumption concerns the starting time delay into the restoration process. In fact, even if ATC13 restoration curves parameters already consider lifelines and other structures damages connected with the analyzed component, their linear functions are built starting immediately after the earthquake. In this way they do not take into account the normal post earthquake delay due to emergency context causes, for example to find fixation companies which are available in an emergency background or to wait the recovery of damaged infrastructures. Hence, in order to consider these aspects, the assumption reported in section [] defines a starting delay correlated to the component typology and DS level. In order to keep a good reliability it has been considered as a probabilistic variable described by a lognormal density distribution, and it depends from component DS levels. The effect on restoration scenarios is showm below.

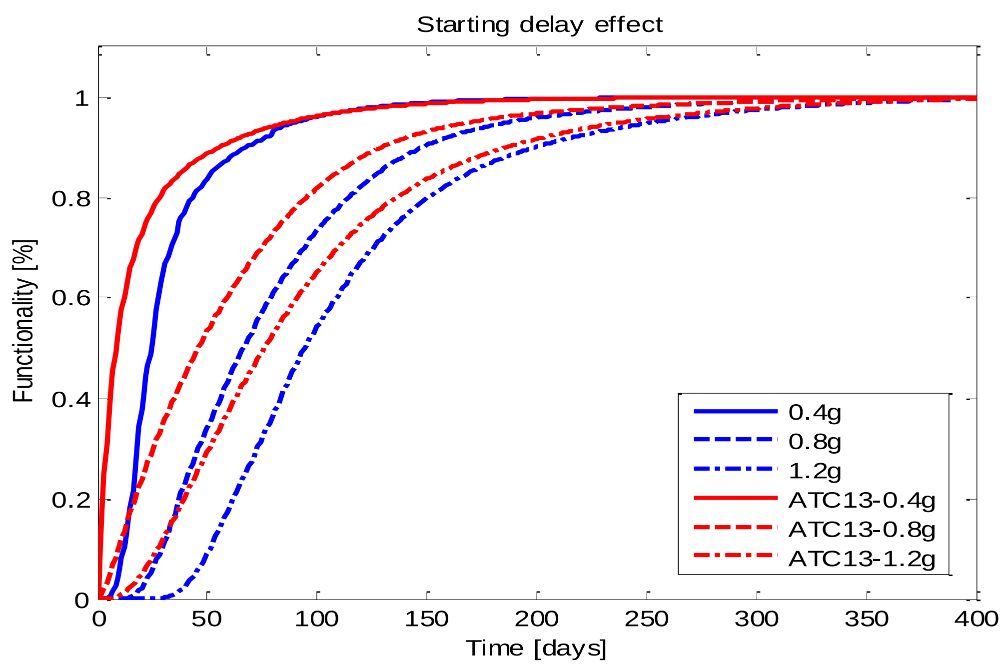


Fig 5.34. *Effect of starting delay on restoration curves.*

Analyzing the figure, it is possible to note as starting delays do not involve changes in the achievement of total functionality, while they influence the starting behavior of restoration processes involving, obviously, a right shift of curves in respect to ATC13 functions. In particular, here the shift seems more marked for stronger seismic scenarios, probably because, since delay means are greater for heavier DS and these are more common for strong earthquakes, the average delay increases. Generally speaking, it is possible to assert that delay assumption gets close to real behavior of restoration processes.

5.4.3. Combined effect

Finally, it is interesting to assess the combined effect given by starting delays and residual functionalities. Resulting curves correspond to model output restoration scenarios. Analyzing the figure below, it is evident that the two assumptions tend to mitigate their effect one other, with a left shift due to residual functionality effect and a right shift due to stating delay effect. In detail, it is possible to observe:

- Considering PGA 0,4g curves, the effects seem to become void in respect to ATC13 curves if combined together. However, ATC13 scenario, starting from a zero functionality even for small earthquakes, reduces its affinity with realistic scenarios.

- Considering PGA 0,8g and 1,2g curves, the final restoration scenarios have an evident right shift in respect to ATC13 scenarios, given by the prevalence of starting delay effect for greater damage states, that is greater earthquakes.

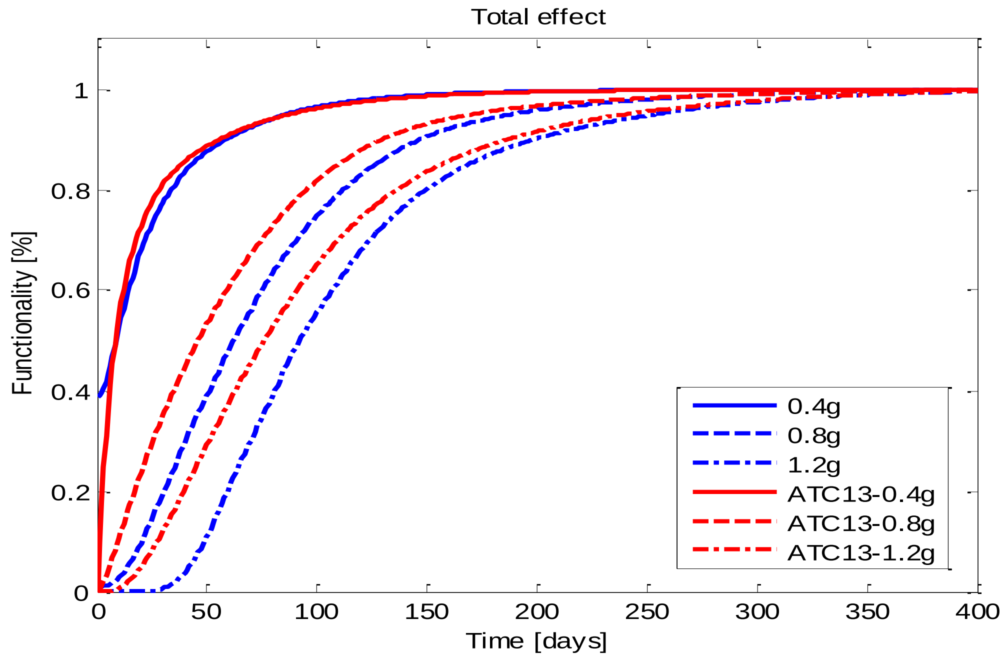


Fig 5.35. *Total effect of our assumptions on restoration curves.*

One last consideration regarding these effects graphs, is that, while additional assumptions involve different behaviors between research scenarios and ATC13 scenarios, the achievement of the total restoration has been reached almost at the same time. This suggests that the modifications taken into account change substantially just the shape of restoration scenarios, making them more realistic.

6. Conclusions

In the present research, a model to calculate restoration scenarios after earthquake for a linear industrial system has been presented. As business case study, a winemaking cycle of an hypothetical industrial winery has been considered. The model framework can be resumed by any mains steps:

- Disaggregation of the system process in seismic vulnerable components;
- Definition for each component of damage and restoration assessment;
- Aggregation of components into the system;
- Definition of system restoration scenarios.

The damage and restoration assessment has been obtained through the use of probabilistic fragility and restoration functions. Fragility curves have been used as fragility functions and restoration curves have been used as restoration functions. In order to improve restoration curves reliability, some additional assumptions have been considered. Firstly, a starting residual functionality, depending on component damage state, then a correspondent restoration curve slope correction and finally a starting probabilistic delay, depending on component damage state. The system assembly has been implemented using a process flow diagram. The model output is a restoration scenario, describing winery functionality recovery during a time interval. Considering a certain earthquake intensity measure, an average restoration scenario has been obtained using Monte Carlo simulation, a probabilistic sampling method. Monte Carlo simulation assesses model probabilistic variables, which are fragility curves and restoration curves, generating multiple variables values and consequently multiple restoration scenarios. From all generated scenarios, an average restoration scenario has been calculated to analyze correspondent characteristics and to assess effects of model assumptions.

An easy winery framework has been used for the model implementation. Three different vulnerable components and two types of connection (in series and in parallel) have been considered. The model has been implemented using Matlab and Simulink software and considering three different input PGAs and 1000 Monte Carlo runs for each average restoration scenario generated. In order to calibrate the model, ten different diagram flows in ascending order of complexity have been implemented.

The analysis of the resulting restoration scenarios shows some trends:

- As expected, elementary parallel systems express a longer restoration time then in series systems;
- Interaction between different components typologies affects the restoration scenarios shape;
- Increasing the number of the system components, the mean restoration time does not change considerably, but the deviation from the average restoration curve tends to decreasing;
- Additional assumptions for restoration curves calculation optimize the shape of restoration scenarios, while they don't affect the time of the full recovery achievement.

Generally speaking, the model seems to provide reliable restoration scenarios for the winery system. Concretely, the proposed procedure can have many applications, all related to a decision maker function. It can be used by companies to check the vulnerability level of production system and to fix possible weak points. In a greater prospective, it can sustain industrial supply chains and associations in business strategy planning and disaster recovery management. Finally, it can be used in natural disaster insurance markets in order to price insurance policies of business seismic risk. Obviously, these applications request an opportune model improvement and customization starting from:

- Model implementation using a real recorded case for evaluating the goodness of fit of the model respect to the reality.
- Definition of a second level of the model structure to consider process interaction with lifelines, logistics, suppliers, costumers, etc.
- Definition of a method to calculate financial business flow and its impact in business recovery.

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Annex A
Steel tanks database

Dataset of damaged steel tanks has been created considering several earthquakes from ALA and NIST, two engineering reports. In ALA database, damaged steel tanks for water system and industrial storage have been considered, while in NIST database, damaged steel tanks for oil refinery and petroleum storage have been classified. Hence, even if some earthquakes are taken into account from both two studies, it is possible to exclude the repetitions of any samples. In the table below are reported earthquake and number of samples considered.

ALA		**NIST**	
Earthquakes	**# samples**	**Earthquakes**	**# samples**
1989 Loma Prieta	139	1989 Loma Prieta	12
1992 Lenders	29	1992 Lenders	14
1994 Northeridge	68	1994 Northridge	14
1933 Long Beach	49	1992 Costa Rica	44
1952 Kern County	24	Others	66
1964 Alaska	39		
1971 San Fernando	20		
1979 Imperial Valley	24		
1983 Coalinga	39		
1992 Costa Rica	38		
TOT samples	**469**	**TOT samples**	**150**

Tab A.1. *Earthquakes and number of samples taken from ALA and NIST databases.*

Considering the PGA of each damaged tank, the 619 samples have been split in 8 different PGA ranges. Samples damage states, already calculated from ALA and NIST databases, described particular damages typologies reported in the table below. In particular, the tanks collapse always correspond to a damage states 5, while just the identification of elephant foot buckling correspond to a damage state 4. Obviously, the presence of more damages on the same tanks increase the correspondent damage states.

Damages typologies			
Elephant foot buckling	EFB	Roof damage	RD
Piping side penetration	OPSP	Upper shell buckling	SBR
Piping bottom penetration	OPBP	Tank lateral movement	TLM
Shell-bottom plate failure	SBP	Total failure	Collapse
Leakage of bottom flange	LBF	None	
Damages to shell cladding	OFL	Unknown	

Tab A.2. *Damages typologies observed on damaged steel tanks.*

The following tables illustrates the database created for the research. The first table illustrate damages typologies and PGA sizes in absolute values, while the second table is created using percentage values. It is important to point out as the total number of damaged tanks do not taken into account samples with a unknown PGA since it is not possible define these samples as realizations of a certain PGA range. Moreover, the total of types of damaged observed exceed the total number of damaged tanks because some samples presented many types of damages.

PROBABILITIES														
PGA (g)	**N tanks**	**DS**	**Damage typologies**											
			Unknow	**None**	**EFB**	**OPSP**	**OPBP**	**SBP**	**LBF**	**OFL**	**RD**	**SBR**	**TLM**	**Collapse**
			ABS	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**	**ABS**
0,10-0,25	220	1	0	220	0	0	0	0	0	0	0	0	0	0
	64	2	0	0	2	20	6	2	6	2	26	4	6	0
	21	3	0	0	19	8	0	1	2	0	5	0	5	0
	11	4	0	0	9	2	1	4	3	0	2	2	0	1
	4	5	0	0	1	0	0	1	0	0	1	0	0	4
TOT	320		0	220	31	30	7	8	11	2	34	6	11	5
0,26-0,35	35	1	0	35	0	0	0	0	0	0	0	0	0	0
	28	2	0	0	0	7	2	0	3	0	17	2	6	0
	17	3	0	0	14	1	0	0	1	0	1	2	2	0
	8	4	0	0	7	3	2	2	1	0	1	4	0	1
	2	5	0	0	0	0	0	0	0	0	0	0	0	3
TOT	90		0	35	21	11	4	2	5	0	19	8	8	4
0,36-0,45	8	1	3	5	0	0	0	0	0	0	0	0	0	0
	11	2	0	0	0	4	3	0	4	0	3	0	2	0
	4	3	0	0	3	1	0	0	1	0	0	0	0	0
	1	4	0	0	1	1	0	0	1	0	0	0	1	0
	1	5	0	0	0	1	0	0	0	0	0	0	0	1
TOT	25		3	5	4	7	3	0	6	0	3	0	3	1
0,46-0,55	50	1	0	50	0	0	0	0	0	0	0	0	0	0
	18	2	8	0	0	2	3	0	4	0	9	3	1	0
	1	3	0	0	0	0	0	0	0	0	0	1	0	0
	4	4	0	0	4	3	1	3	0	0	1	0	1	0
	2	5	0	0	1	0	1	2	0	0	0	0	0	2
TOT	75		8	50	5	5	5	5	4	0	10	4	2	2
0,56-0,65	13	1	0	13	0	0	0	0	0	0	0	0	0	0
	18	2	8	0	0	4	0	0	0	0	5	0	3	0
	9	3	0	0	8	3	0	2	0	0	4	1	3	0
	4	4	0	0	4	2	3	2	1	0	2	0	1	0
	2	5	0	0	2	2	2	1	0	0	0	0	0	1
TOT	46		8	13	16	11	5	5	1	0	11	1	7	1
0,7-0,8	10	1	0	10	0	0	0	0	0	0	0	0	0	0
	1	2	0	0	0	1	0	0	0	0	0	0	0	0
	2	3	0	0	0	0	0	0	0	0	1	1	0	0
	2	4	0	0	2	0	0	0	2	0	0	0	0	0
	1	5	0	0	0	0	0	0	0	0	0	0	0	1
TOT	16		0	10	2	1	0	0	2	0	1	1	0	1

PROBABILITIES														
PGA (g)	N tanks	DS	Damage typologies											
			Unknow	None	EFB	OPSP	OPBP	SBP	LBF	OFL	RD	SBR	TLM	Collapse
			ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS	ABS
0,81-0,9	11	1	0	11	0	0	0	0	0	0	0	0	0	0
	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	1	3	0	0	1	0	0	0	0	0	1	0	0	0
	4	4	0	0	4	1	0	0	4	0	1	1	0	0
	1	5	0	0	0	0	0	0	0	0	0	0	0	1
TOT	17		0	11	5	1	0	0	4	0	2	1	0	1
1,2	1	1	0	1	0	0	0	0	0	0	0	0	0	0
	3	2	0	0	0	0	3	0	0	0	0	0	0	0
	0	3	0	0	0	0	0	0	0	0	0	0	0	0
	0	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	5	0	0	0	0	0	0	0	0	0	0	0	5
TOT	9		0	1	0	0	3	0	0	0	0	0	0	5
Unknow	10	1	8	2	0	0	0	0	0	0	0	0	0	0
	2	2	1	0	0	0	0	0	0	0	1	1	0	0
	5	3	0	0	3	1	2	3	0	0	1	0	2	0
	2	4	0	0	2	1	1	2	0	0	1	0	0	0
	2	5	0	0	1	1	0	0	0	0	0	0	0	2
TOT	21		9	2	6	3	3	5	0	0	3	1	2	2
TOT	598	0	19	345	84	66	27	20	33	2	80	21	31	20

Tab A.3. *Damages steel tanks database in absolute values.*

PROBABILITIES														
			Damage typologies											
PGA (g)	N tanks	DS	Unknow	None	EFB	OPSP	OPBP	SBP	LBF	OFL	RD	SBR	TLM	Collapse
			% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT
0,10-0,25	68,75	1	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	20,00	2	0,00	0,00	3,13	31,25	9,38	3,13	9,38	3,13	40,63	6,25	9,38	0,00
	6,56	3	0,00	0,00	90,48	38,10	0,00	4,76	9,52	0,00	23,81	0,00	23,81	0,00
	3,44	4	0,00	0,00	81,82	18,18	9,09	36,36	27,27	0,00	18,18	18,18	0,00	9,09
	1,25	5	0,00	0,00	25,00	0,00	0,00	25,00	0,00	0,00	25,00	0,00	0,00	100,00
TOT	100,00		0,00	68,75	9,69	9,38	2,19	2,50	3,44	0,63	10,63	1,88	3,44	1,56
0,26-0,35	38,89	1	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	31,11	2	0,00	0,00	0,00	25,00	7,14	0,00	10,71	0,00	60,71	7,14	21,43	0,00
	18,89	3	0,00	0,00	82,35	5,88	0,00	0,00	5,88	0,00	5,88	11,76	11,76	0,00
	8,89	4	0,00	0,00	87,50	37,50	25,00	25,00	12,50	0,00	12,50	50,00	0,00	12,50
	2,22	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	150,00
TOT	100,00		0,00	38,89	23,33	12,22	4,44	2,22	5,56	0,00	21,11	8,89	8,89	4,44
0,36-0,45	32,00	1	37,50	62,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	44,00	2	0,00	0,00	0,00	36,36	27,27	0,00	36,36	0,00	27,27	0,00	18,18	0,00
	16,00	3	0,00	0,00	75,00	25,00	0,00	0,00	25,00	0,00	0,00	0,00	0,00	0,00
	4,00	4	0,00	0,00	100,0	100,0	0,00	0,00	100,0	0,00	0,00	0,00	100,00	0,00
	4,00	5	0,00	0,00	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00		12,00	20,00	16,00	28,00	12,00	0,00	24,00	0,00	12,00	0,00	12,00	4,00
0,46-0,55	66,67	1	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	24,00	2	44,44	0,00	0,00	11,11	16,67	0,00	22,22	0,00	50,00	16,67	5,56	0,00
	1,33	3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00	0,00	0,00
	5,33	4	0,00	0,00	100,0	75,00	25,00	75,00	0,00	0,00	25,00	0,00	25,00	0,00
	2,67	5	0,00	0,00	50,00	0,00	50,00	100,0	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00		10,67	66,67	6,67	6,67	6,67	6,67	5,33	0,00	13,33	5,33	2,67	2,67
0,56-0,65	28,26	1	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	39,13	2	44,44	0,00	0,00	22,22	0,00	0,00	0,00	0,00	27,78	0,00	16,67	0,00
	19,57	3	0,00	0,00	88,89	33,33	0,00	22,22	0,00	0,00	44,44	11,11	33,33	0,00
	8,70	4	0,00	0,00	100,0	50,00	75,00	50,00	25,00	0,00	50,00	0,00	25,00	0,00
	4,35	5	0,00	0,00	100,0	100,0	100,0	50,00	0,00	0,00	0,00	0,00	0,00	50,00
TOT	100,00		17,39	28,26	34,78	23,91	10,87	10,87	2,17	0,00	23,91	2,17	15,22	2,17
0,7-0,8	62,50	1	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	6,25	2	0,00	0,00	0,00	100,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	12,50	3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	50,00	50,00	0,00	0,00
	12,50	4	0,00	0,00	100,0	0,00	0,00	0,00	100,0	0,00	0,00	0,00	0,00	0,00
	6,25	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00		0,00	62,50	12,50	6,25	0,00	0,00	12,50	0,00	6,25	6,25	0,00	6,25

PROBABILITIES														
PGA (g)	N tanks	DS	Damage typologies											
			Unknow	None	EFB	OPSP	OPBP	SBP	LBF	OFL	RD	SBR	TLM	Collapse
			% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT	% TOT
0,81-0,9	64,71	1	0,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	5,88	3	0,00	0,00	100,00	0,00	0,00	0,00	0,00	0,00	100,00	0,00	0,00	0,00
	23,53	4	0,00	0,00	100,00	25,00	0,00	0,00	100,00	0,00	25,00	25,00	0,00	0,00
	5,88	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00		0,00	64,71	29,41	5,88	0,00	0,00	23,53	0,00	11,76	5,88	0,00	5,88
1,2	11,11	1	0,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	33,33	2	0,00	0,00	0,00	0,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	4	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	55,56	5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00		0,00	11,11	0,00	0,00	33,33	0,00	0,00	0,00	0,00	0,00	0,00	55,56
Unknow	47,62	1	80,00	20,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	9,52	2	50,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	50,00	50,00	0,00	0,00
	23,81	3	0,00	0,00	60,00	20,00	40,00	60,0	0,00	0,00	20,00	0,00	40,00	0,00
	9,52	4	0,00	0,00	100,00	50,00	50,00	100,	0,00	0,00	50,00	0,00	0,00	0,00
	9,52	5	0,00	0,00	50,00	50,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00
TOT	100,00	0	42,86	9,52	28,57	14,29	14,29	23,8	0,00	0,00	14,29	4,76	9,52	9,52

Tab A.4. *Damages steel tanks database in percentage values.*