European Commission

JRC SCIENTIFIC AND POLICY REPORTS

Guidelines for typology definition of European physical assets for earthquake risk assessment

SYNER-G Reference Report 2

Editors: Ufuk Hancilar and Fabio Taucer

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Publishing Editors: Fabio Taucer and Ufuk Hancilar

2013

Report EUR 25883 EN

Joint Research Centre

European Commission
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JRC80560

EUR 25883 EN

ISBN 978-92-79-28973-6

ISSN 1831-9424

doi:10.2788/68751

Luxembourg: Publications Office of the European Union, 2013

Printed in Ispra (Va) - Italy

D 8.8

DELIVERABLE

PROJECT INFORMATION

Project Title:	**Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain**
Acronym:	SYNER-G
Project N°:	244061
Call N°:	FP7-ENV-2009-1
Project start:	01 November 2009
Duration:	36 months

DELIVERABLE INFORMATION

Deliverable Title:	**D8.8 - Guidelines for typology definition of European physical assets for earthquake risk assessment**
Date of issue:	31 March 2013
Work Package:	WP8 – Guidelines, recommendations and dissemination
Deliverable/Task Leader:	Joint Research Centre
Editors:	Ufuk Hancilar, Fabio Taucer (JRC)
Reviewer:	Georgios Tsionis (UPAT)

REVISION: Final

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Foreword

SYNER-G is a European collaborative research project funded by European Commission (Seventh Framework Program, Theme 6: Environment) under Grant Agreement no. 244061. The primary purpose of SYNER-G is to develop an integrated methodology for the systemic seismic vulnerability and risk analysis of buildings, transportation and utility networks and critical facilities, considering for the interactions between different components and systems. The whole methodology is implemented in an open source software tool and is validated in selected case studies. The research consortium relies on the active participation of twelve entities from Europe, one from USA and one from Japan. The consortium includes partners from the consulting and the insurance industry.

SYNER-G developed an innovative methodological framework for the assessment of physical as well as socio-economic seismic vulnerability and risk at the urban/regional level. The built environment is modelled according to a detailed taxonomy, grouped into the following categories: buildings, transportation and utility networks, and critical facilities. Each category may have several types of components and systems. The framework encompasses in an integrated fashion all aspects in the chain, from hazard to the vulnerability assessment of components and systems and to the socio-economic impacts of an earthquake, accounting for all relevant uncertainties within an efficient quantitative simulation scheme, and modelling interactions between the multiple component systems.

The methodology and software tools are validated in selected sites and systems in urban and regional scale: city of Thessaloniki (Greece), city of Vienna (Austria), harbour of Thessaloniki, gas system of L'Aquila in Italy, electric power network, roadway network and hospital facility again in Italy.

The scope of the present series of Reference Reports is to document the methods, procedures, tools and applications that have been developed in SYNER-G. The reports are intended to researchers, professionals, stakeholders as well as representatives from civil protection, insurance and industry areas involved in seismic risk assessment and management.

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Abstract

It is an essential step in urban earthquake risk assessment to compile inventory databases of elements at risk and to make a classification on the basis of pre-defined typology/taxonomy definitions. Typology definitions and the classification system should reflect the vulnerability characteristics of the systems at risk, e.g. buildings, lifeline networks, transportation infrastructures, etc., as well as of their sub-components in order to ensure a uniform interpretation of data and risk analyses results. In this report, a summary of literature review of existing classification systems and taxonomies of the European physical assets at risk is provided in Chapter 2. The identified main typologies and the classification of the systems and their sub-components, i.e. SYNER-G taxonomies, for Buildings, Utility Networks, Transportation Infrastructures and Critical Facilities are presented in Chapters 3, 4, 5 and 6, respectively.

Keywords: elements at risk, buildings, utility networks, transportation infrastructures, critical facilities, typology definitions

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 244061.

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1 Introduction

Risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between hazards and vulnerable conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004). Population, structures, utilities, systems and socio-economic activities constitute the "Elements at Risk" in urban areas. The physical elements are the built environment such as buildings and lifelines, while the social elements are represented by the demographic data.

The main objective of an earthquake loss model is to calculate the seismic hazard at all the sites of interest and to convolve this hazard with the vulnerability of the exposed inventory of elements, such that the damage distribution of the physical elements can be predicted. Damage ratios, for instance which relate the cost of repair to the cost of demolition and replacement of the structures, can then be used to calculate the loss (Calvi et al., 2006). In order to construct such a loss model for a city, region or country, it is necessary to compile databases of earthquake activity, ground conditions, ground motion prediction equations, building stock and infrastructure exposure, and to identify vulnerability characteristics of the exposed inventory. The classification systems used to define inventories should be compatible with the fragility functions which relate the level of ground shaking with the probability of exceeding a damage state. The definition of a classification system for characterization of the exposed elements and the description of their damage is an essential step in risk analysis in order to ensure a uniform interpretation of data and results (Erdik et al., 2011). For a general building stock, building taxonomies define structure categories by various combinations of use, time of construction, construction material, lateral force-resisting system, height, applicable building code, and quality. Similarly, for all the physical elements at risk, such as water supply network, gas pipelines, electric transmission lines, etc., the structural, material and geometrical characteristics, seismic resistant features as well as the inter-regional differences in construction practices should be reflected in the classification system for the development of inventories and for vulnerability information.

SYNER-G considers four main categories of systems:

1. Buildings
2. Utility networks: Water, waste water, gas, oil, and electricity
3. Transportation infrastructures: Roadways, railways and harbour systems
4. Critical facilities: Health-care and fire-fighting facilities

The classification of the elements at risk has been done by SYNER-G partners by adopting available databases on the basis of their experiences and national practices. In this report, a summary of literature review of existing classification systems and taxonomies is provided in Chapter 2. The identified main typologies and the classification of the systems and their sub-components, i.e. SYNER-G taxonomies, for Buildings, Utility Networks, Transportation Infrastructures and Critical Facilities are presented in Chapters 3, 4, 5 and 6, respectively.

2 Literature review of existing taxonomies

2.1 BUILDINGS

A taxonomy of existing buildings should allow for the classification of buildings in an ordered system, and for the purpose of seismic risk assessment, should describe and classify buildings in terms of their seismic resistance and response. Some of the more common building taxonomies that have been proposed over the past 30 years are presented in Section 2.1.1 and then the characteristics that are deemed to be required for an ideal taxonomy are presented in Section 2.1.2, following the recommendations of Charleson (2011).

2.1.1 Existing taxonomies

A selection of the most relevant classification schemes that are deemed to be relevant for European buildings are given below in chronological order. Perhaps an important issue to highlight is that these studies generally provide a list of the most common building typologies, rather than a classification scheme from which building typologies can be defined. This literature review builds upon the work of Charleson (2011).

ATC-13 (ATC 1985)

ATC-13 (ATC 1985) represented a pioneering effort to develop a facility classification valid for California, including engineering classification and social function classification. This taxonomy accounts for construction material, soil conditions, foundation type, height, structural framing system, configuration, structural continuity, design and construction quality, age and proximity to other structures.

This taxonomy contains 78 classes of structures (40 of which buildings and 38 are other structure types such as bridges, storage tanks, towers etc.); 11 structure groups contain two or three height ranges.

This classification is based on a labelling scheme consisting of letters and symbols (i.e. slash “/” and dash “-“) to identify facility classes.

This taxonomy is not collapsible and, in addition, it is based on Californian embedded assumptions, that are often neither appropriate nor relevant internationally.

EMS-98 (Grunthal 1998)

This taxonomy is based on a few structure types (just 15). The organization into a few groups simplifies the scheme but a precise assessment is not possible because the size of these groups is too broad.

The variation in the seismic performance is distinguished only for RC frames and walls. They are defined as “*without earthquake resistant design*”, “*with moderate level of earthquake resistant design*” and “*with high level of earthquake design*”.

All steel and timber structures are covered under a single type without any distinction between ductile and non-ductile structures.

HAZUS (FEMA 2003)

In HAZUS (FEMA, 2003), the building groups are based on the classification provided in FEMA 178 (FEMA 1992). 36 structural categories, including 9 with three height ranges (low-rise, mid-rise and high-rise), are defined.

This proposed taxonomy is relatively simple in structure but it is not collapsible. In addition, the extension of this classification in order to include configuration aspects and revealing assumptions would require many more structural types. Many applications of HAZUS around the world have required engineers to add structural types to the classification, but there are no standard recommendations on how this should be done.

As in the case of ATC-13, this classification is based on US-based embedded assumptions, such as concrete strength and ductility capabilities that are not necessarily valid internationally. Furthermore, some materials and construction technologies are missing (e.g. earthen and stone constructions).

RISK-UE (2001-2004)

The European RISK-UE project named “An advanced approach to earthquake risk scenarios with applications to different European towns” began in 2001 at the end of the International Decade for Natural Disaster Reduction (IDNDR) and ended in September 2004. The aim of the project was the assessment of earthquake scenarios at a city scale within a European context.

This project was constructed based on a modular methodology comprised of different work packages (WP). The WP01 entitled ‘Distinctive features of European towns’ provided a methodology for collecting and classifying buildings and earthquake data for urban seismic risk assessment in Europe (e.g. Kappos et al., 2003; Penelis et al., 2002). For this reason, a matrix for building typology description at a European scale has been proposed within the project. In Table 2.1 the RISK-UE taxonomy is shown. The RISK-UE building classification matrix comprises 23 principal classes grouped by the structural types and material of construction. Three different height classes (low-rise, mid-rise and high-rise) represent further sub-groups. A building design code and a performance level (pre-code, low-code, moderate-code and high-code) can also be assigned to all the categories reported in Table 2.1.

Table 2.1 RISK-UE taxonomy (RISK-UE, 2001-2004)

Label	Description	Rise	Average No. of stories
M11L	Rubble Stone, fieldstone	Low-rise	1-2
M11M		Mid-Rise	3-5
M12L	Simple Stone	Low-rise	1-2
M12M		Mid-Rise	3-5
M12H		High-rise	6+
M13L	Massive Stone	Low-rise	1-2
M13M		Mid-Rise	3-5
M13H		High-rise	6+
M2L	Adobe	Low-Rise	1-2
M31L	Wooden slabs URM	Low-rise	1-2
M31M		Mid-Rise	3-5
M31H		High-rise	6+
M32L	Masonry vaults URM	Low-rise	1-2
M32M		Mid-Rise	3-5
M32H		High-rise	6+
M33L	Composite slabs URM	Low-rise	1-2
M33M		Mid-Rise	3-5
M33H		High-rise	6+
M34L	RC slabs URM	Low-rise	1-2
M34M		Mid-Rise	3-5
M34H		High-rise	6+
M4L	Reinforced or confined masonry	Low-rise	1-2
M4M		Mid-Rise	3-5
M4H		High-rise	6+

Label	Description	Rise	Average No. of stories
M5L M5M M5H	Overall strengthened masonry	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC1L RC1M RC1H	RC moment frames	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC2L RC2M RC2H	RC shear walls	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC31L RC31M RC31H	Regularly infilled RC frames	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC32L RC32M RC32H	Irregular RC frames	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC4L RC4M RC4H	RC dual systems	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC5L RC5M RC5H	Precast concrete tilt-up walls	Low-rise Mid-Rise High-rise	1-2 3-5 6+
RC6L RC6M	Precast concrete frames with concrete shear walls	Low-rise Mid-Rise	1-2 3-5

Label	Description	Rise	Average No. of stories
RC6H		High-rise	6+
S1L S1M S1H	Steel moment frames	Low-rise Mid-Rise High-rise	1-2 3-5 6+
S2L S2M S2H	Steel braced frames	Low-rise Mid-Rise High-rise	1-2 3-5 6+
S3L S3M S3H	Steel frames with URM infill walls	Low-rise Mid-Rise High-rise	1-2 3-5 6+
S4L S4M S4H	Steel frames with cast-in-place concrete shear walls	Low-rise Mid-Rise High-rise	1-2 3-5 6+
S5L S5M S5H	Steel and RC composite systems	Low-rise Mid-Rise High-rise	1-2 3-5 6+
WL WM	Wooden structures	Low-rise Mid-Rise	1-2 3-5

PAGER-STR (Jaiswal and Wald, 2008)

The US Geological Survey's Prompt Assessment of Global Earthquake for Response (PAGER) program aims to provide early post-earthquake estimates of losses to allow rapid emergency decisions to be taken. In the framework of this program is the creation of a global building stock model. PAGER developed a building stock model using housing census and other statistical data coming from different sources such as UN Statistical Database on Global Housing (United Nations, 1993), UN-HABITAT Database on Demographic and Health

Survey (obtained through personal communication), Housing Census Database (country specific), World Housing Encyclopaedia (WHE: www.world-housing.net) and data compiled from published literature. Alongside the data compilation, a taxonomy that is able to include in its classification all the different types of the existing structures worldwide was developed. The PAGER taxonomy (known as PAGER-STR and shown in Table 2.2) identifies a few main classes underlined in bold in the table and some sub-classes.

Table 2.2 PAGER-STR Taxonomy (Jaiswal and Wald, 2008 – Version 1.4)

Label	Description	Average No. of stories	Typical No. of stories
W	**WOOD**	**1-3**	**2**
W1	Wood Frame, Wood Stud, Wood, Stucco, or Brick Veneer	1-2	1
W2	Wood Frame, Heavy Members, Diagonals or Bamboo Lattice, Mud Infill	All	1
W3	Wood Frame, Prefabricated Steel Stud Panels, Wood or Stucco Exterior Walls	2-3	2
W4	Log building	1-2	1
S	**STEEL**	**All**	**1**
S1	Steel Moment Frame	All	1
S1L	Low-Rise	1-3	2
S1M	Mid-Rise	4-7	5
S1H	High-Rise	8+	13
S2	Steel Braced Frame	All	1
S2L	Low-Rise	1-3	2
S2M	Mid-Rise	4-7	5
S2H	High-Rise	8+	13
S3	Steel Light Frame	All	1
S4	Steel Frame with Cast-in-Place Concrete Shear Walls	All	1
S4L	Low-Rise	1-3	2
S4M	Mid-Rise	4-7	5
S4H	High-Rise	8+	13
S5	Steel Frame with Un-reinforced Masonry Infill Walls	All	1
S5L	Low-Rise	1-3	2
S5M	Mid-Rise	4-7	5
S5H	High-Rise	8+	13
C	**REINFORCED CONCRETE**	**All**	**1**
C1	Ductile Reinforced Concrete Moment Frame	All	1
C1L	Low-Rise	1-3	2
C1M	Mid-Rise	4-7	5

Label	Description	Average No. of stories	Typical No. of stories
C1H	High-Rise	8+	13
C2	Reinforced Concrete Shear Walls	All	1
C2L	Low-Rise	1-3	2
C2M	Mid-Rise	4-7	5
C2H	High-Rise	8+	13
C3	Non-ductile Reinforced Concrete Frame with Masonry Infill Walls	All	1
C3L	Low-Rise	1-3	2
C3M	Mid-Rise	4-7	5
C3H	High-Rise	8+	13
C4	Non-ductile Reinforced Concrete Frame without Masonry Infill Walls	All	1
C4L	Low-Rise	1-3	2
C4M	Mid-Rise	4-7	5
C4H	High-Rise	8+	13
C5	Steel Reinforced Concrete (Steel Members Encased in Reinforced Concrete)	All	1
C5L	Low-Rise	1-3	2
C5M	Mid-Rise	4-7	5
C5H	High-Rise	8+	13
PC1	Precast Concrete Tilt-Up Walls	All	1
PC2	Precast Concrete Frames with Concrete Shear Walls	All	1
PC2L	Low-Rise	1-3	2
PC2M	Mid-Rise	4-7	5
PC2H	High-Rise	8+	13
RM	**REINFORCED MASONRY**	**All**	**1**
RM1	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	All	1
RM1L	Low-Rise	1-3	2
RM1M	Mid-Rise (4+ stories)	4-7	5
RM2	Reinforced Masonry Bearing Walls with Concrete Diaphragms	All	1
RM2L	Low-Rise	1-3	2
RM2M	Mid-Rise	4-7	5
RM2H	High-Rise	8+	13
MH	**MOBILE HOME**	**All**	**1**
M	**MUD WALLS**	**1**	**1**
M1	Mud walls without horizontal wood elements	1-2	1

Label	Description	Average No. of stories	Typical No. of stories
M2	Mud walls with horizontal wood elements	1-3	2
A	**ADOBE BLOCK (UNBAKED DRIED MUD BLOCK) WALLS**	**1-2**	**1**
A1	Adobe block, mud mortar, wood roof and floors	1-2	1
A2	Same as A1, bamboo, straw, and thatch roof	1-2	1
A3	Same as A1, cement-sand mortar	1-3	2
A4	Same as A1, reinforced concrete bond beam, cane and mud roof	1-3	2
A5	Same as A1, with bamboo or rope reinforcement	1-2	1
RE	**RAMMED EARTH/PNEUMATICALLY IMPACTED STABILIZED EARTH**	**1-2**	**1**
RS	**RUBBLE STONE (FIELD STONE) MASONRY**	**All**	**1**
RS1	Local field stones dry stacked (no mortar). Timber floors. Timber, earth, or metal roof.	1-2	1
RS2	Same as RS1 with mud mortar.	1-2	1
RS3	Same as RS1 with lime mortar.	1-3	2
RS4	Same as RS1 with cement mortar, vaulted brick roof and floors	1-3	2
RS5	Same as RS1 with cement mortar and reinforced concrete bond beam.	1-3	2
DS	**RECTANGULAR CUT STONE MASONRY BLOCK**	**All**	**1**
DS1	Rectangular cut stone masonry block with mud mortar, timber roof and floors	1-2	1
DS2	Same as DS1 with lime mortar	1-3	2
DS3	Same as DS1 with cement mortar	1-3	2
DS4	Same as DS2 with reinforced concrete floors and roof	1-3	2
UFB	**UNREINFORCED FIRED BRICK MASONRY**	**All**	**1**
UFB1	Unreinforced brick masonry in mud mortar without timber posts	1-2	1
UFB2	Unreinforced brick masonry in mud mortar with timber posts	1-2	1
UFB3	Unreinforced fired brick masonry, cement mortar, timber flooring, timber or steel beams and columns, tie courses (bricks aligned perpendicular to the plane of the wall)	1-3	2

Label	Description	Average No. of stories	Typical No. of stories
UFB4	Same as UFB3, but with reinforced concrete floor and roof slabs	1-3	2
UCB	**UNREINFORCED CONCRETE BLOCK MASONRY, LIME/CEMENT MORTAR**	**All**	**1**
MS	**MASSIVE STONE MASONRY IN LIME/CEMENT MORTAR**	**All**	**1**
TU	**PRECAST CONCRETE TILT-UP WALLS** Precast Wall Panel Construction (Mid to high rise, Former Soviet Union style)	**All**	**1**
INF	**INFORMAL CONSTRUCTIONS (PARTS OF SLUMS/SQUATTERS)** Constructions made of wood/plastic sheets/GI Sheets/light metal or composite etc., not conforming to engineering standards.	**All**	**1**
UNK	**Unknown Category (Not specified)**	**All**	**1**

2.1.2 Requirements for an ideal taxonomy

Charleson (2011) describes some requirements that can be identified as fundamental in the definition of an ideal taxonomy. A sub-section of these properties, felt to be important for the purposes of SYNER-G, and their description are listed in Table 2.3:

Table 2.3 Requirements for an ideal taxonomy (adapted from Charleson, 2011)

Requirement	Description
1. Distinction between differences in seismic performance.	A distinction between earthquake-resistant and non-earthquake resistant structural system has to be considered, including the “before” and “after” states of common seismic retrofit and between ductile and non-ductile systems.
2. Observable	The taxonomy must include all engineering features relevant to the global seismic performance of a building structure
3. Complete	Two people examining the same structural system in the field or using data obtained from the field should independently assign the same taxonomic group based solely on the text definition of the taxonomic group.
4. Simple and Collapsible	The taxonomy has to have as few groups as possible. A taxonomy is said to be collapsible if its groups can be combined and the resulting combinations still distinguish differences in seismic performance.
5. Nearly exhaustive	Every structural system can be assigned to a taxonomic group.

Requirement	Description
6. User-friendly	Taxonomy has to be intuitive and easy to use as possible by both collecting data, those arranging for its analysis and the end users.
7. International in scope	As far as possible, the taxonomy should be appropriate for any region of the word.
8. Easily expandable	Users can easily create new building typologies using the taxonomy.

By assigning a score to each requirement, it is possible to compare the aforementioned taxonomies. A summary of the scores given by Charleson, and those added herein for the RISK-UE taxonomy, is given in Table 2.4.

Table 2.4 Comparisons of various structural taxonomies against stated requirements (adapted from Charleson, 2011)

	1.Differences seismic performance	**2. Observable**	**3. Complete**	**4.Simple and Collapsible**	**5.Nearly exhausted**	**6.User friendly**	**7. International in scope**	**8. Easily expandable**	**Score t=2, s=1, u=0**	**Comments**
ATC-13	s	s	s	s	u	t	u	u	6	California-focused
EMS-98	s	s	u	s	u	t	u	u	5	For U.S construction
HAZUS	t	s	s	s	u	t	u	u	7	For U.S construction
RISK-UE	t	s	s	s	u	t	u	u	7	Europe-focused
PAGER-STR	t	s	t	t	t	t	t	s	14	Most comprehensive to date
t=true (2 points); s=somewhat true (1 point); u=untrue (0 points)										

2.2 UTILITY NETWORKS

2.2.1 Electric power systems

The study of electric power systems in the HAZUS project (FEMA, 2003) has led to the distinction of three distinct groups of elements:

- Generation plants: the typologies are identified based on the type of energy used for the generation (nuclear, fossil fuel, renewable energy…) and the power output, i.e. small plants (< 200 MW) to medium/large ones (> 200 MW).
- Substations: the classification depends on the voltage level (500 kV, 350 kV and 115 kV substations, corresponding to transmission or subtransmission grids). Further distinctions are also made depending to the anchorage of the components.
- Distribution circuits: they include poles, wires, in-line equipment and utility-owned equipment at customer site. Lines can be located above ground or underground, and the components are considered anchored or unanchored.

The vulnerability of electric power systems within Risk-UE project (Alexoudi, 2003) proposes a similar classification of electric components (generation plants, substations, transmission and distribution lines). Generation plants are also classified according to their size (same limit of 200 MW between little and medium/large plants), and whether components are anchored or not. Typologies of substations are defined by several characteristics such as redundancy capabilities, voltage level or the way subcomponents are assembled (see Table 2.5).

Table 2.5 Classification of electric substations (Risk-UE)

Substation	1 (High)	2 (Medium)	3 (Low)
Redundancy capabilities	Mainly single	In-between	Mainly redundant
Transmission vs distribution	Transmission	Sub-transmission	Distribution
Voltage (kV)	High voltage (>350kV) 500kV substation	Medium voltage (150-350kV) 230kV substation	Low voltage (34.5-150kV) 115kV substation
Customer type	Large industry Essential facilities Lifelines	Smaller industry Commercial Facilities	Housing Domestic use
Station type	Manned switching Facility Multi-loop with generation Multi-loop without generation	Single-loop with generation Single loop without generation	Tap (one source) with generation Tap (one source) without generation

Finally, in the Risk-UE approach, electric lines are distinguished according to their place and role in the power grid:

- Transmission lines, connecting generation plants and high voltage substations, can be underground or aboveground. They are supported by steel towers with RC footing.
- Sub-transmission lines – connecting high, medium and low voltage substations – can be cables supported by steel towers or can be buried.
- Distribution lines, connecting low voltage substations and customers (usually at a voltage level between 4kV and 34kV), can be buried or mounted on poles (wood or RC).

Some work has also been performed lately on the identification and classification of the micro-components of substations. For instance, Straub and Der Kiureghian (2008) have focused on transformers and circuit-breakers: one of the ways to distinguish typologies is to consider the way subcomponents are assembled, as parallel systems or as K-out-of-N systems (i.e. parallel redundancy). Finally, the study by Vanzi (1996, 2000) has led to a very detailed characterisation of the various micro-components within a substation (e.g. coil bearings, switches, transformers, circuit-breakers…).

2.2.2 Gas and oil networks

Oil Network

The HAZUS (FEMA, 2003) manual constitutes the sole reference in the study of oil systems. The following components are considered:

- Refineries: they are used for processing crude oil before it can be used. A steady supply of water is critical to the functioning of the refinery. Typologies are identified according to the size (i.e. capacity) of the plant: small (> 100 000 barrels a day) and medium/large (> 100 000 barrels a day). Most common subcomponents are on-grade steel tanks, stacks, elevated pipes and miscellaneous electrical/mechanical equipment. Medium/large refineries differ from small ones in the sense that they include more components, therefore increasing the redundancy.
- Oil pipelines: they are used for the transportation of oil over long distances. Pipelines are typically made of mild steel with submerged arc-welded joints, although older gas-welded steel pipes may be present in some systems.
- Pumping plants: they are used to maintain the flow of oil in cross-country pipelines. Different configurations are possible: one or two pumps, which can be of either centrifugal or reciprocating type. A distinction is made according the anchorage of subcomponents.
- Tank farms: they are used to store fuel products. They are different from simple storage tanks, since they include also pipes and electric components. They are also classified as having either anchored or unanchored subcomponents.

Gas Network

According to the HAZUS (FEMA, 2003) methodology, the gas network system is only composed of two types of components (compressor stations and pipelines), as other elements (production facilities, treatment plants, Liquid Natural Gas (LNG) terminals) are not considered in the study:

- Compressor stations: they are considered similar to pumping plants (anchored or unanchored components, centrifugal or reciprocating compressors).
- Pipelines: they can be buried or elevated. Like oil pipelines, typologies are based on the type of material (usually steel) and the type of connections (arc-welded or gas-welded).

On the other hand, the Risk-UE study of gas components (Alexoudi and Pitilakis, 2003) has led to the characterisation of various groups of components:

- Production facilities: typology classification is based on whether they are offshore or onshore, and whether the subcomponents are anchored or not.
- Tank farms:
  - Underground storage facilities: seasonal supply or high–deliverability sites;
  - Above-ground storage tanks: many typological characteristics such as shape, capacity, dimension, seismic code level, material, construction type, roof type, anchorage of components, operation function, presence of back-up power;
  - Gas holder: they are older facilities used to store gas for future use. They are made of steel and the roof is floating according to the pressure.
- Gas pipelines: many typological characteristics such as location (elevated or buried), material type, material strength, diameter wall thickness, smoothness of coating, connection type, pressure classification, design flow. The feed can also be one-way or bi-directional.
- Gas stations: five different types have been identified:
  - Compressor stations;
  - Metering stations;
  - Metering/Pressure reduction stations (M/R);
  - Metering compressor stations (M/C);
  - LNG terminal stations;

Typologies of gas stations are mainly classified based on whether subcomponents are anchored or nor. It is also possible to consider features such as existence of a SCADA (supervisory control and data acquisition) system, proportion of electrical/mechanical components, existence of back-up power. Finally, for M/R and M/C stations, the location may also be taken into account: kiosk solution, buried equipment or equipment inside or near a building.

It is also worthy to quote the work achieved in the framework of SRM-Life Project (2003-2007), which has led to the characterisation of compressor station for the Greek network, along with the development of fault-tree analysis of the subcomponents. Finally the study by Esposito (2011) has focused on the Italian gas network in the L'Aquila area, where specific typologies (RE.MI (REgolazione e MIsura in Italian). RE) cabins and Final Reduction Groups (referred to as GRF "Gruppi di Riduzione Finale" in Italian)) have also been identified.

2.2.3 Water and waste-water systems

Potable Water Systems

In the framework of HAZUS (FEMA, 2003), various components of the potable water system are identified:

- Terminal reservoirs: they are typically lakes, whether man-made or natural.
- Transmission aqueducts: they are large size pipes or channels (canals) that convey water from the source to the treatment plant.
- Supply facilities – water treatment plants: they are composed of a number of physical and chemical unit processes, e.g. coagulation, sedimentation or filtration.
- Pumping plants: they are usually composed of a building, one or more pumps, electrical equipment and sometimes a back power system.
- Wells: they are generally the main or secondary water source for cities.
- Water storage tanks: they can differ in size, shape, material and type of foundation.
- Distribution facilities and distribution pipes: distribution of water can be accomplished by gravity, or by pumps in conjunction with on-line storage. Pipes are characterised by various types of size, material and connections.
- SCADA system, for the control and regulation of the water flow.

Among all these components, only water treatment plants, pumping plants, storage tanks and distribution pipes are associated with different typologies, which are based on several characteristics summarized in Table 2.6.

Table 2.6 Typology classification for components of potable water systems (HAZUS)

Component	Typology
Water treatment plants	Size: small, medium or large Anchored or unanchored components
Pumping plants	Size: small or medium/large Anchored or unanchored components
Storage tanks	Position: on-ground, above-ground or buried Material: concrete, steel or wood Anchored or unanchored components
Distribution pipes	Material: ductile (ductile iron, steel, PVC…) or brittle (cast-iron, asbestos-cement, concrete…) Connection: welded, cemented, bell-and-spigot, flexible joint… Diameter

Similar definition of components and typological classification are adopted in the Risk-UE vulnerability assessment of water systems (Monge, 2003a). A notable difference is the clear characterization of some components (water source, water treatment plant, pumping station, storage tank, SCADA system and conduits) via the notion of flow capacity, thus stressing the importance of a component in the whole water system (see Table 2.7).

Table 2.7 Some elements of typological classification for water systems (Risk-UE)

Component	1 (High)	2 (Medium)	3 (Low)
Water source			
Flow (m^3/day)	> 100 000	in-between	< 10 000
Capacity (terminal reservoir) – m^3	> 1 000 000	in-between	< 20 000
Users number (inhabitants)	> 200 000	in-between	< 50 000
Treatment plant			
Flow (m^3/day)	> 100 000	in-between	< 10 000
Users number (inhabitants)	> 200 000	in-between	< 50 000
Pumping station			
Flow (m^3/day)	> 100 000	in-between	< 10 000
Users number (inhabitants)	> 200 000	in-between	< 50 000
Storage tank			
Flow (m^3/day)	> 5 000	in-between	< 1 000
Capacity – m^3	> 50 000	in-between	< 1 000
Users number (inhabitants)	> 20 000	in-between	< 2 000
SCADA system			
Flow (m^3/day)	> 50 000	in-between	< 5 000
Users number (inhabitants)	> 100 000	in-between	< 25 000
Conduits			
Flow (m^3/day)	> 50 000	in-between	< 5 000
Users number (inhabitants)	> 100 000	in-between	< 25 000

Waste-Water Systems

HAZUS (FEMA, 2003) breaks down the components of waste-water systems into several groups of components:

- Collection sewers: they are generally closed conduits that carry sewage with a partial flow. The typologies in the pipe conduits are classified according to potable water system.
- Interceptors: they are large diameter sewage mains, usually located at lower elevation areas. The same typology as for collection sewers can be used.
- Lift stations: their role is to raise sewage over topographical rises, through the use of pumps. They are classified according to their size (i.e. flow capacity) and the anchorage of their components.
- Waste-water treatment plants: like potable water treatment plants, their typologies are based on their size and on whether the components are anchored or not. Extra process subcomponents are also considered, like sediment flocculation.

In the Risk-UE description of waste-water systems (Monge, 2003b), a similar typological classification is adopted, the main difference residing in the thresholds values used to distinguish small, medium and large facilities.

2.3 TRANSPORTATION INFRASTRUCTURES

2.3.1 Roadway and railway networks

The main components of highway system are roadways, bridges and tunnels. Railway network consists of tracks, bridges, tunnels, terminals and other facilities. Different classification schemes have been proposed for each component based on structural, geometrical and functional characteristics. The classification systems proposed in ATC-13/ATC-25, HAZUS and REDARS methodologies are briefly described in Table 2.8 and Table 2.9.

Tunnels are usually classified based on the method of construction, the geological/soil conditions, the geometry and their use. ALA (2001) classifies tunnels in four categories based on geology conditions and quality of construction, while HAZUS (NIBS 2004) methodology considers only two classes, bored/drilled and cut and cover tunnels.

Other elements, such as road pavements, railway tracks and quaywalls, are simpler structures and are consequently classified in fewer categories. As an example, in HAZUS, roads are classified in major and urban, while in SAFELAND project (Pitilakis et al., 2011) where the vulnerability of roads to different landslide impacts is studied, the typological distinction is between high speed and local roads.

Table 2.8 Classification systems of roadway network

ATC-13 (1985), ATC-25 (1991)	
Bridges	Major bridges (greater than 150m spans) Conventional bridges (less than 150m spans: multiple simple spans, continuous monolithic, single spans)
Tunnels	Alluvium Rock Cut and Cover
Roadways	Freeways/highways Local roads
HAZUS (NIBS 2004)	
Roadways	Major roads Urban roads
Bridges	28 classes: number of spans, material, column type, design level, continuity of superstructure
Tunnels	Bored/Drilled tunnel Cut and Cover tunnel
REDARS (Werner et al., 2006)	
Bridges	Same as in HAZUS
Approach fills	One class
Roadway pavements	One class
Tunnels	Same as in HAZUS

Table 2.9 Classification systems of railway network

ATC-13 (1985), ATC-25 (1991)	
Bridges	Same as roadway
Tunnels	Same as roadway
Tracks/roadbeds	One class
Terminal stations	Weighted average of generic buildings, mechanical equipment, railway tracks
HAZUS (NIBS 2004)	
Tracks	1 class
Bridges	10 classes: material, column type, design level, continuity of superstructure
Tunnels	Bored/Drilled tunnel Cut and Cover tunnel
Urban stations	All building types options enabled
Fuel facility	Different combinations for with or without anchored components and/or with or without backup power
Dispatch facility	Different combinations for with or without anchored components and/or with or without backup power
Maintenance facility	All building types options enabled

2.3.2 Bridges

The variation of bridge attributes is greater compared to other transportation infrastructures, and thus the existing classification systems for bridges are more diverse and are based on different criteria (e.g. ATC-13 1985, NIBS 2004, RMS 1996, Basoz and Kiremidjian 1996, Moschonas et al., 2009). The main typological features considered in practice are the number of spans, design level, material, pier type, abutment type, superstructure type and continuity. The variation of existing classification schemes (number of classes, attributes considered) is due to the construction techniques in different countries as well as the objectives of the study.

Fragility studies that are available in literature often focus on individual bridges of few types that are common in a specific region. For this reason, the typological features examined in each study are limited in number and may not be able to fully describe other types of bridges. As will be evinced in the following by the overview of existing taxonomies in Europe, there is also lack of consistency as regards the classification criteria. It is noted however, that, with the exception of the RISK-UE project, the scope of existing studies was limited to a given country and to bridges constructed during a certain period of time.

Within the RISK-UE research project, a classification system for European bridges was proposed (Argyroudis et al., 2003), considering the parameters below:

- material: concrete or steel;
- bent type: single-column or multi-column bent;
- deck continuity: continuous or simply-supported deck;

- design: conventional or seismic.

Single-span bridges were treated as a special category. Depending on the available data, bridges may be further classified on the basis of additional attributes, such as the structural type, deck-pier connection, type of bearings, year of construction (code level), number of spans, skew, span length, height, number of expansion joints and type of foundation.

A classification scheme of the modern bridges in the Egnatia motorway in Greece was developed (Moschonas et al., 2009), based on the following parameters:

- bent type: single column with cylindrical cross-section, single column with rectangular hollow cross-section, multi-column bent or wall-type;
- deck type: slab (solid or with voids), box girder (single-cell section) or simply-supported precast/prestressed beams connected through continuous RC topping slab;
- deck-pier connection: monolithic, through bearings (with or without seismic isolation) or a combination.

For what concerns Italian bridges, the typical reinforced concrete and prestressed concrete road bridges may be classified according to the following criteria (Pinto et al., 2009):

- number of spans: single-span or multi-span;
- deck continuity: continuous or simply-supported deck;
- bent type: single pier or multi-column bent.

Masonry, arch, steel truss, cable-stayed and suspension bridges are considered special structures and each specific bridge is treated individually.

Bridges on the Turkish highway network system are classified in three categories based on the hourly volume of traffic. Although there is no standard way to classify bridges concerning their fragility, in a recent study conducted at METU (Avsar et al., 2011), bridges were classified according to the following primary attributes:

- number of spans: single-span or multi-span;
- bent type: single-column or multiple-column bent;
- skew angle: 0^o, 30^o, 60^o.

With reference to the requirements in Section 2.1.2, the existing classification systems are in general simple, observable and user-friendly. They lack completeness and not all of them distinguish between bridges with or without earthquake resistance. Although each taxonomy was developed in a specific country, they may be used in other regions.

2.3.3 Harbour systems

The various components within a major port could be classified in the following categories (RISK-UE, 2001-2004; LESSLOSS, 2004-2007):

- Earthen embankments (hydraulic fills and native soil materials);
- Waterfront structures;
  - Retaining structures/dikes (e.g. at wharves, embankment, breakwaters, and dredged shipping lanes and waterway),

  - Berthing structures;
- Cargo handling and storage components;
  - Container storage areas,Liquid storage tanks,
  - Material handling equipment;
- Infrastructure components;
  - Utility systems (electric power system, water system, waste-water system, natural gas, liquid fuel system, communications system, fire-fighting system),
  - Transportation infrastructures (roadway, railway, bridges),
  - Buildings.

From an engineering point of view, waterfront structures are soil-structure systems that consist of various combinations of structural and foundation types. The basic typological parameters are: geometry, section type, construction material, foundation type, existence and type of anchorage. A more exhaustive typology may be used as proposed by Werner, (1998) and PIANC (2001). According to HAZUS (NIBS, 2004) waterfront structures include wharves, seawalls and piers, but no distinction is made regarding their vulnerability assessment. Other researchers recognize that the important features of their seismic behavior are the type of backfill and foundation soil, along with the existence of rubble foundation (Ichii, 2003), as well as the structural characteristics and soil foundation conditions (Kakderi and Pitilakis, 2010).

Cranes and cargo handling equipment are described (NIBS, 2004) with respect to whether the cranes are anchored or unanchored and stationary or rail mounted. They could also be classified according to the cargo capacity and cargo type. Other important typological parameters, especially when the interactions between port components are considered, are the type of power supply (electric or fuel), the foundation type (surface concrete beam or piles) and the location (above and/or near waterfront structures or inside the port area). A more exhaustive typology may be used (Werner, 1998).

Utility and infrastructure components follow the same classification schemes described in the respective sections of this report. Especially for fuel facilities, HAZUS (NIBS, 2004) classifies their components as anchored or unanchored, and with or without backup power. Finally, buildings at port may be traffic control buildings, passenger terminals, office buildings, maintenance buildings and sheds and warehouses.

2.4 CRITICAL FACILITIES

2.4.1 Health-care facilities

The seismic vulnerability of health-care facilities can be attributed to two main causes: the vulnerability of the physical component and, at the organisational level, the inability to cope with a mass-casualty event, i.e. to a massive incoming of patients.

As it regards the physical component, past experience has shown that the functionality of hospital systems can be impaired as much by structural as by non-structural damage. For structural damage, mitigation measures exist and have effectively been implemented in some countries, as, for example, in California. The comparison of structural damage incurred in the 1971, San Fernando and in the 1994, Northridge earthquakes show the significant improvement achieved due to the effective mitigation strategy applied ("Hospital Safety Act" of 1972 – Senate Bill 519) as a consequence of the San Fernando earthquake. However, prevention of structural damage alone is found to be not sufficient to guarantee the functionality. Past experiences, including Northridge, have shown that functionality is strictly related to the behaviour of non-structural elements and to the existence of backup resources of power and water for the functioning of essential basic installations. More in detail, anchorages of equipment, interior partitions, water and power systems, elevators and medical gas network are the most commonly damaged among non-structural elements.

From an organisational perspective, past experience has highlighted the need for procedures to quickly assess the effects of the earthquake within the hospital system, to avoid un-necessary evacuations, as well as for emergency plans to guarantee the effective use of the resources still available.

Several causes of different nature concur to make hospital facilities particularly vulnerable to a seismic event. The most relevant ones, according to past experiences, are short-listed in the following.

Complexity

A hospital is an extremely peculiar structure having the most diversified functions, ranging from those typical of hotels, offices or laboratories, to those of warehouses (Monti and Nuti, 1996).

Occupancy

Hospitals have a high level of occupancy, with patients, medical, support staff and visitors present 24 hours a day. Many patients require assistance and continued specialised care. They may be surrounded by medical equipment, use potentially dangerous gases, or be connected to life-support equipment that requires an uninterrupted power supply (PAHO, 2000).

Basic installations

No facility depends on public services or lifeline more than a hospital, which needs 24 hours a day water, electricity, oxygen and communications to work efficiently without service interruption. Moreover, equipment such as lifts and litter-lifts, essential for ensuring internal communications and service, should always be functioning.

Critical Supplies

Most of the supplies required by hospitals (medicine, bandages, etc.) are essential to patients' survival and crucial to the treatment of disaster victims. On the other hand, many products found in hospitals can represent an hazard if they spill or leak. The collapse of shelves holding medicines or chemicals can release poisonous liquid or gas. Spilled chemicals, damaged gas cylinders and ruptured oxygen lines can cause fires. Moreover the items can directly produce casualties: medical equipment and other appliances are often located above or near patients' beds or on high shelves. Much damage can be averted through simple, inexpensive mitigation measures, such as securing shelves to the walls and placing equipment strategically in safe locations. Regular inspections and appropriate maintenance can assure that equipment is kept in good working order (PAHO, 2000).

To the authors' knowledge, no taxonomies for a hospital system have been proposed in literature but the study by Lupoi et al. (2006, 2008).

2.4.2 Fire-fighting systems

For fire-fighting systems there is not any particular taxonomy in the literature. The classification systems for water system are applied (see Section 2.2.3).

3 Buildings

3.1 PROPOSED TAXONOMY FOR BUILDINGS

The main requirements of an ideal taxonomy are that it should be detailed, simple, collapsible and expandable (see Chapter 2 for additional details). Existing taxonomies can be seen to leave out a large number of characteristics that could be used to identify the buildings (and distinguish between vulnerability), and, in many cases, it is not clear how these taxonomies should be simply expanded to include such information (see Chapter 2 for a summary of some existing building taxonomies). In order to address this issue, a new taxonomy was developed in the SYNER-G project for RC and masonry buildings, as described below, which has the aim of allowing European building typologies to be classified by the users, all of whom use the same underlying classification scheme.

Different main categories have been identified to describe a building and they are presented in Table 3.1 such as the lateral force resisting mechanism, material, elevation, cladding, etc. It has to be noted that a hierarchy is used for some categories where additional information might or might not be available. For example, the material is masonry but a user may or may not know whether it is reinforced or unreinforced, fired brick or stone. In the case of RC, for instance, the user may or may not know the type of concrete has been used (e.g. high, average or low strength) or which kind of reinforcements (e.g. smooth or non-smooth (ribbed) rebars). In both cases the definition of the second (unknown) parameters is optional.

The building typology is defined using the label put in the brackets for each parameter within a given category.

Example: FRM1-FRM2/FRMM1-FRMM2/P/E/C-CM/D/FS-FSM/RS-RSM/HL-NS/CL

More than one label can be used for the category separated by a dash. For example, a building with moment resisting frames and walls (i.e. dual system) would be MRF-W, a building with mixed construction of reinforced concrete and masonry would be RC-M. Not all categories need to be defined due to the fact that there might be lack of information about the structure. In this case, where information is unknown, an X symbol is used. In the following, three examples are shown:

- MRF/C-RC/X/X/RI-FB-H%/ND/R-RC/X/L-2/NC: moment resisting frame, in reinforced concrete with regular external infill panels in brick with a high percentages of voids, with non-ductile design details, with rigid reinforced concrete floor, low-rise, 2 storeys, not designed to a seismic code;
- CM/M-RM/R/R/RI-FB/ND/F-T/X/L-2/MC: structure in confined reinforced masonry characterized by regular layout in both plan and elevation with regular brick cladding, with non-ductile design, flexible timber floor, low-rise, 2 storeys, designed for moderate seismic code;
- BW/M/X/X/X/X/X/X/L/X: low-rise masonry bearing wall structure.

The proposed taxonomy is constructed with a modular structure. In this way, other categories and sub-categories can easily be added and all the different kinds of European buildings can be taken into account. Subsequently, additional categories for describing the non-structural elements might be added in the future.

Table 3.1 SYNER-G Taxonomy for RC and Masonry Buildings

CATEGORY	CLASSIFICATION
Force Resisting Mechanism (FRM1) • Moment Resisting Frame (MRF) • Structural Wall (W) • Flat Slab (FS) • Bearing Walls (BW) • Precast (P) • Confined Masonry (CM)	**Force Resisting Mechanism (FRM2)** • Embedded beams (EB) • Emergent beams (EGB)
FRM Material (FRMM1) • Concrete (C) • Masonry (M)	**FRM Material (FRMM2)** • Reinforced Concrete (RC) • Unreinforced Masonry (URM) • Reinforced Masonry (RM) • High strength concrete (>50MPa) (HSC) • Average strength concrete (20-50 MPa) (ASC) • Low strength concrete (<20 MPa) (LSC) • Adobe (A) • Fired brick (FB) • Hollow clay tile (HC) • Stone (S) • High yield strength reinforcing bars (>300MPa) (HY) • Low yield strength reinforcing bars (<300MPa) (LY) • Classification of reinforcing bars based on EC2 (A,B,C) • Lime mortar (LM) • Cement mortar (CM) • Mud mortar (MM) • Smooth rebars (SB) • Non-smooth rebars (NSB) • Concrete Masonry Unit (CMU) • Autoclaved Aerated Concrete (AAC) • High % of voids (H%) • Low % of voids (L%) • Regular Cut (Rc) • Rubble (Ru)
Plan (P) • Regular (R) • Irregular (IR)	
Elevation (E)	

CATEGORY	CLASSIFICATION
• Regular geometry (R) • Irregular geometry (IR)	
Cladding (C) • Regular infill vertically (RI) • Irregular infill vertically (IRI) • Bare (B)	**Cladding Characteristics (CM)** • Fired brick masonry (FB) • High % voids (H%) • Low % voids (L%) • Autoclaved Aerated Concrete (AAC) • Precast concrete (PC) • Glazing (G) • Single layer of cladding (SL) • Double layer of cladding (DL) • Open first floor (Pilotis) (P) • Open upper floor (U)
Detailing (D) • Ductile (D) • Non-ductile (ND) • With tie rods/beams (WTB) • Without tie rods/beams (WoTB)	
Floor System (FS) • Rigid (R) • Flexible (F)	**Floor System Material (FSM)** • Reinforced concrete (RC) • Steel (S) • Timber (T)
Roof System (RS) • Peaked (P) • Flat (F) • Gable End Walls (G)	**Roof System Material (RSM)** • Timber (Ti) • Thatch (Th) • Corrugated Metal Sheet (CMS)
Height Level (HL) • Low-rise (1-3) (L) • Mid-rise (4-7) (M) • High-rise (8-19) (H) • Tall (20+)(Ta)	**Number of stories (NS)** [Here the number of stories is explicitly given, if known]
Code Level (CL) • None (NC) • Low (<0.1g) (LC) • Moderate (0.1-0.3g) (MC) • High (>0.3g) (HC)	

3.2 COMPARISON WITH OTHER CLASSIFICATION SYSTEMS

The proposed classification for buildings is characterized by a modular structure. This aspect represents a new and a different approach in categorizing and classifying buildings. It has a flexible structure and it can be used to describe a considerable amount of different buildings. It can be updated at any time by inserting new categories and different features can be added to existing categories.

If compared with the other mentioned existing taxonomies for buildings, using a simple scoring system, the one defined in the SYNER-G project emerges as the one with the greatest potential (Table 3.2).

Table 3.2 Comparisons of various structural taxonomies against stated requirements

	1.Differences seismic performance	2. Observable	3. Complete	4.Simple and Collapsible	5.Nearly exhausted	6.User friendly	7. International in scope	8. Easily expandable	Score t=2, s=1, u=0	Comments
ATC-13	s	s	s	s	u	t	u	u	6	California-focused
EMS-98	s	s	u	s	u	t	u	u	5	For U.S construction
HAZUS	t	s	s	s	u	t	u	u	7	For U.S construction
RISK-UE	t	s	s	s	u	t	u	u	7	Europe-focused
PAGER-STR	t	s	t	t	t	t	t	s	14	Most comprehensive to date
SYNER-G	**t**	**s**	**t**	**t**	**t**	**t**	**t**	**t**	**15**	**Best Potential**

t=true (2 points); s=somewhat true (1point); u=untrue (0 points)

4 Utility networks

4.1 ELECTRIC POWER NETWORK

4.1.1 General description

Electric power networks are very complex systems, which spatial distribution can reach the continental scale (e.g. the European interconnected power grid as depicted in Fig. 4.1).

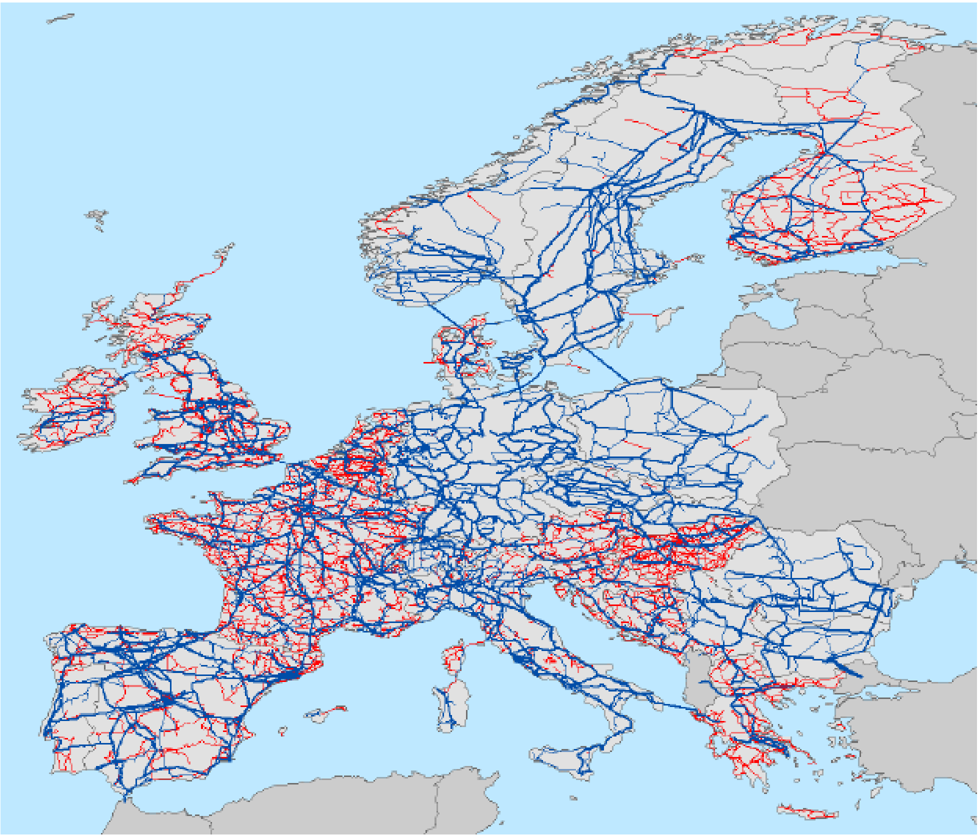

Fig. 4.1 European high voltage transmission grid (V≥220kV). Higher voltage lines in blue, lower voltage lines in red. Line thickness is proportional to voltage (Poljansek et al., 2010)

This type of system is usually broken down into three main functions:

- Generation of electric power;
- Transmission of high-voltage electric power from generation plants to consumption areas;
- Distribution of low-voltage electric power to the consumers and the electric appliances.

These functions are carried out by a wide range of components that can be regrouped into different generic categories:

- Power generation plants;
- Transformation stations;
- Transmission and distribution grid;
- Electric devices of the ends-users, referred as loads;
- Control and regulation systems,

The characteristics and the role of these elements are detailed in the next subsections, based on the review by Pinto et al. (2011). More details are also to be found in the work by Saadi (2002).

Generation Plants

Production facilities generate electric power by converting mechanical power through the use of synchronous generators or alternators: these generators are composed of a rotating part (i.e. rotor) that moves at synchronous speed and a static part (i.e. stator) that is usually composed of a set of three windings, thus generating three-phase current. If no commutator is used, which is the case for the vast majority of large production plants, the generators produce alternative current (AC), usually at high voltage (e.g. 30kV) and high power level (e.g. 50 to 1 500 MW). The AC frequency has been standardized over time, yet some differences still remain: in the US and Canada for instance, the standard frequency is 60 Hz while in most European countries it is 50 Hz.

Mechanical power used to feed the alternators can be converted from various sources: hydraulic power at waterfalls or dams, thermal power (i.e. burning of coal, gas, oil, nuclear fuel or biomass) (Fig. 4.2), geothermal power, tidal power or wind power.

Production of direct current (DC) is also achieved in smaller facilities, mainly through the conversion of chemical power to electric power: this is for instance the case of solar panels or batteries.

Fig. 4.2 Example photo of a thermal power plant

Transformers

Transformers are crucial components of the electric power grid, as their function is mainly to change the characteristics of the power with very high efficiency (Fig. 4.3). The rule is that the power transferred from the emitting winding to the receiving one is conserved, except for the minor loss in the transformer. As a result, transformers are used to modify the voltage level (and the current level, as a consequence), and two main types can be identified, depending on their positions in the power grid:

- Step-up transformers: they are usually located at the output of a generation plant in order to greatly increase the voltage in the transmission grid, consequently reducing the current and keeping the losses in the transmission lines to a minimum, even over several hundreds of kilometres.
- Step-down transformers: they are the interface between transmission and distribution lines, transforming high-voltage/medium-voltage (HV/MV) power into medium-voltage/low-voltage (MV/LV) power, which can be readily used by consumers.

Other classes of transformers are also present in an electric power network, namely phase-shifters, which are used to transform three-phase current into monophasic current, or voltage regulators, which automatically adjust the voltage to the constant required level.

Fig. 4.3 Example photo of a high-voltage transformer

Transmission and Distribution Grid

This group of components, also referred as the power delivery system (Fig. 4.4), has the role to transfer electric power from the power generation facilities to all the consumers that are distributed in various locations.

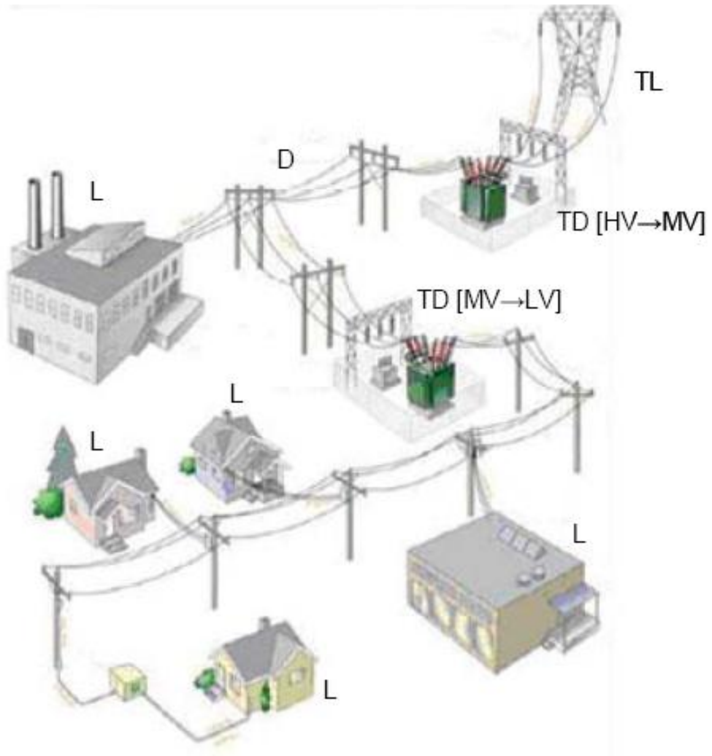

Fig. 4.4 Sketch of a power delivery system (TL = transmission line, D = distribution line, L = load, TD [HV ➔ MV] = transformation from high to medium voltage and distribution station, TD [MV ➔ LV] = transformation from medium to low voltage and distribution station)

The power delivery system can be broken down into two levels:

- The transmission grid transfers electric power from the generation plants to the vicinity of built areas (e.g. cities). The long distances covered require using very high voltage (e.g. 60 to 750kV) in order to reduce to the losses to due to thermic effects.
- The distribution grid is composed of low-voltage (e.g. 220 to 240 V in Europe) electric wires or cables that are directly connected to the domestic or commercial loads. The lowest level cables that connect individual loads are usually called feeders and can be either overhead or underground.

Usually, intermediate levels of transmission lines are also present, transmitting the power at the smaller scale than the high voltage transmission grid. They operate at medium voltage, usually at values in the tens of kV.

The respective structural organisation of transmission and distribution grids mainly relies on two different typologies (Fig. 4.5):

- Grid-like: it consists of a highly interconnected redundant grid, composed of stations as nodes and transmission lines as edges.
- Tree-like: the distribution lines follow the main streets and arteries of a city and several subdivisions occur until the end-users are reached in each branch.

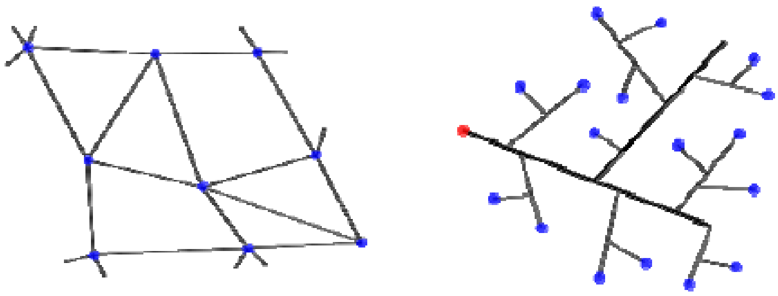

Fig. 4.5 Typical topological structures, grid-like (on the left) and tree-like (on the right), respectively for transmission and distribution systems

Besides electric lines, the power delivery system comprises also various substations, which can be seen as the end nodes of the distribution system (Fig. 4.6): they serve as a source of power supply for the local distribution area (while the transmission from the substation to individual loads is performed by feeders). Substations can have various functions, depending on their position and role in the power grid:

- Changing or switching voltage level, by means of transformers;
- Providing points where safety devices such as disconnect switches, circuit-breakers and other equipment can be installed;
- Regulating voltage to compensate for system voltage changes;
- Eliminating lightning and switching surges from the system;
- Converting AC to DC and reciprocally, as needed;
- Changing frequency, as needed.

Substations can be entirely enclosed in buildings where all the equipment is assembled into one metal clad unit. The alternative is to some substation's components located outside of the building. Typologies of substations can be identified based on their specific functions and the type of components they harbour. Finally, a common approach with respect to seismic risk is also to distinguish between anchored or unanchored components.

Fig. 4.6 Example photo of a substation

Loads

Loads consist of all appliances, whether domestic or industrial, which need electric power to operate. Their quantity and operating hours influence the demand level on the power grid, which is expressed in terms of kilowatts (kW) or megawatts (MW).

Loads can be divided into industrial, commercial or residential type. Industrial or large commercial loads are usually directly connected to the high or medium voltage transmission lines and can use three-phase current. Small commercial or residential loads are supplied through low-voltage distribution lines and usually require single-phase current. The census of loads is necessary to evaluate the power demand at each distribution stations, which can be done on a daily, monthly or yearly basis.

Control Systems

Control and regulation systems are present in the electric power network in order to adjust the quality of the delivered power in terms of frequency or voltage and to prevent any disturbances in the service.

SCADA (Supervisory Control and Data Acquisition) and EMS (Emergency Management System) systems are usually centralized and located at strategic points of the power grid. On the other hand, decentralized systems are also used to provide local measurements or specific protections of equipment and loads.

4.1.2 Proposed taxonomy for electric power network components

In the framework of SYNER-G, the review by Pinto et al. (2011) has enabled to identify a set of EPN components with their corresponding analysis level (see Table 4.1). It has been chosen to consider two levels of substation's components: micro-components and macro-components. This distinction is useful when a capacity analysis of the network is carried out and partial functioning of substations is modelled, as opposed to binary states (fail/safe) in connectivity analyses. The extra computational effort of modelling intermediate states in substations can then be reduced by assembling sub-sets of micro-components that are serially arranged within the substation in order to reduce them to a single element characterised by a single fragility: the macro-component. The substation layout is then composed of general (i.e. non-serial) arrangement of macro-components which can lead to partial functioning states, depending on the distribution of damage.

For each EPN component, the review of fragility curves by Pinto et al. (2011) provides an indication of which typologies to consider:

- **Electric power grid**: Power delivery system as a whole can be distinguished according to the voltage level of the substations: high-voltage (V > 350 kV), medium voltage (150 kV < V < 350 kV) and low voltage (V < 150 kV). The electric lines can also have various characteristics, i.e. underground or aboveground lines, supported by steel towers or wooden or RC pylons, with shallow or deep foundations.
- **Generation plants** are treated as a whole and are distinguished according to their power capacity: small (< 200 MW) or medium/large (> 200 MW). Their fragility is also based on whether the components are anchored or unanchored (i.e. no seismic provisions).

- **Substations** have also typologies based on the voltage level (low, medium or high voltage) and the anchorage of their components.
- **Distribution circuits**: Classification is based on whether the components are anchored or unanchored.
- **Macro-components**: Different typologies are already included in the definition of the macro-components (e.g. auto-transformer line, line without transformer, bars-connecting line, bars, and cluster) and their respective fragility is conditioned by the type of micro-components they comprise.
- **Circuit-breaker:** Typologies are based on the voltage level, usually 230 kV or 500 kV.
- **Lightning arrester:** Typologies are based on the voltage level, usually 230 kV or 500 kV.
- **Disconnect switch:** Typologies are based on the voltage level (230 or 500 kV) and the seismic anchorage of the component.
- **Transformer:** Typologies are based on the voltage level (230 or 500 kV) and the seismic anchorage of the component.

Other micro-components are also distinguished according to their anchorage level, whether they comply to seismic provisions or not.

Table 4.1 SYNER-G Taxonomy for Electric Power Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Network • Electric Power Grid (EPN01)	
Station • Generation Plant (EPN02) • Substation (EPN03)	
Distribution System • Distribution Circuits (EPN04)	
Substation's Component • Macro-Components	○ Autotransformer line (EPN05) ○ Line without transformer (EPN06) ○ Bars-connecting line (EPN07) ○ Bars (EPN08) ○ Cluster (EPN09)
• Micro-Components	○ Circuit breaker (EPN010) ○ Lightning arrester or discharger (EPN011) ○ Horizontal disconnect switch or horizontal sectionalizing switch (EPN012) ○ Vertical disconnect switch or vertical sectionalizing switch (EPN013) ○ Transformer or autotransformer (EPN014) ○ Current transformer (EPN015) ○ Voltage transformer (EPN016) ○ Box or control house (EPN017) ○ Power supply to protection system (EPN018) ○ Coil support (EPN019) ○ Bar support or pothead (EPN020) ○ Regulator (EPN021) ○ Bus (EPN022) ○ Capacitor tank (EPN023)
Line • Transmission or Distribution Line (EPN024)	○ Voltage (kV) ○ Resistance (Ω/km) ○ Reactance (Ω/km) ○ Susceptance (S/km) ○ Voltage ratio

4.2 GAS AND OIL NETWORKS

4.2.1 General description

Oil and gas fields are not evenly distributed around the world, whereas demand in those important sources of energy is widespread. Gas and oil networks are therefore large and complex systems which aim at delivering natural gas and oil from few production sites to numerous end-users, over hundreds of kilometres. For instance in Europe, gas supply essentially comes from four sources outside the domestic production (Russia, Norway, Algeria and to a lesser extent Nigeria), therefore forming a huge transmission grid of various pipelines all across the continent (Fig. 4.7).

Fig. 4.7 Overview of the gas networks in Europe (Nies, 2008)

Usually, an on-shore oil or gas field is exploited by several wells, which form the gathering system. This system is connected to the production and processing facilities, which role is to treat the gas and oil to the required quality standards through various processes (chemical and heating operations, separation of water and sediments, etc.). The fossil fuels can then be sent to storage areas, from which they are ready to be transported to the distribution zones through pipelines. It is common practice to break down the gas and oil networks into two distinct levels:

- Production and processing
- Transmission and distribution

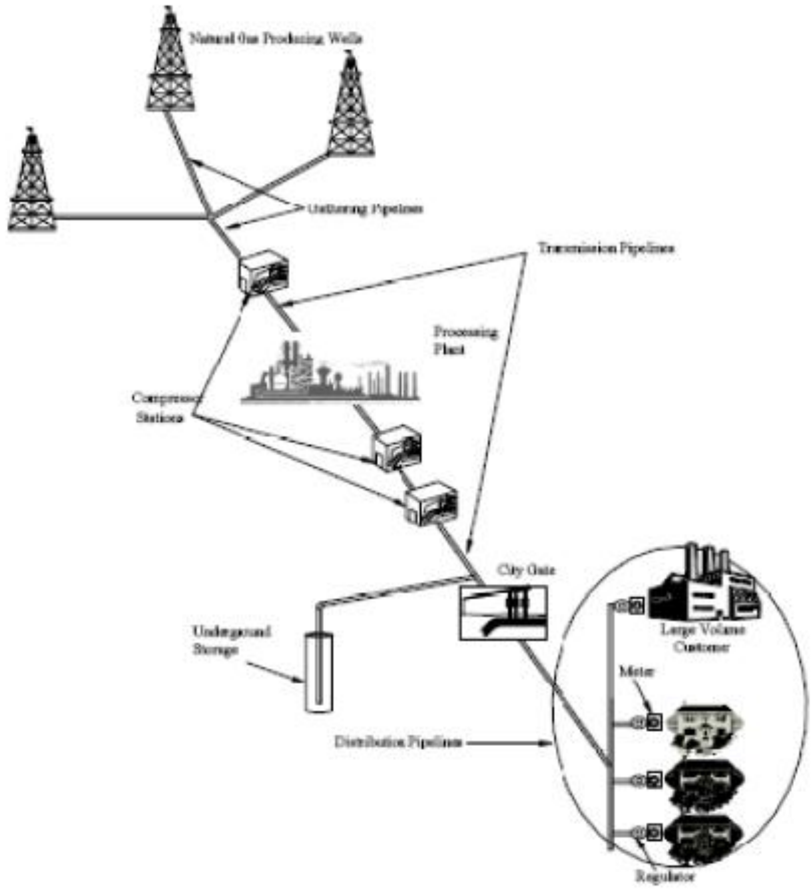

Fig. 4.8 Description of the natural gas production, transmission and distribution system (Thompson, 2001)

The different wells are grouped to form a gathering system where crude oil and gas are processed by chemical and heating treatments. After being separated from water and sediments, oil and gas are stored into tanks. The purified resources can then be pumped into the transmission/ distribution systems, which are composed of pipelines and compressor, reduction and measuring stations, to be delivered to end-users (Fig. 4.8).

The description of gas and oil networks is more detailed in Gehl et al. (2010), Esposito et al. (2011) and Esposito and Iervolino (2011), on which the following section is strongly based.

Description of the two levels of gas networks:

Production and Processing

Raw natural gas comes from three types of wells: oil wells, gas wells, and condensate wells. The natural gas that comes from oil wells is typically referred to as 'associated gas'. The ‘associate gas’ can exist separate from oil (free gas), or dissolved in the crude oil (dissolved gas). The natural gas that comes from gas and condensate wells, where there is little or no crude oil, is termed 'non-associated gas'. Gas wells typically produce raw natural gas, while condensate wells produce free natural gas along with a semi-liquid hydrocarbon condensate. The natural gas must be purified before it can be transported. Therefore, after its extraction, the natural gas is processed in order to obtain 'pipeline quality gas', namely dry natural gas.

The dry natural gas is obtained by eliminating different hydrocarbons and fluids normally contained in the pure natural gas, mainly ethane, propane, butane, and pentanes. Similarly the oil is sent to a refiner after the extraction process and from there the to a tanker terminal or to a transmission pipeline system. In the refinery plant, the crude oil is converted into high-octane motor fuel (gasoline/petrol), diesel oil, liquefied petroleum gases (LPG), jet aircraft fuel, kerosene, heating fuel oils, lubricating oils, asphalt and petroleum coke.

Transmission/Distribution

The purpose of the natural gas gathering and transmission pipelines is similar to the one of crude oil gathering line and crude oil trunk lines; however, the operating conditions and equipment for natural gas and oil gathering and transmission pipeline are quite different. The gas transmission pipelines use compressors to force the gas through the pipe instead of pumps; when the natural gas leaves the processing plant, it enters into the compressor station where it is pressurized for the transmission. Before reaching a major metropolitan area, the natural gas is diverted through an intermediate station where the pressure is reduced, measured, and sold to the local gas company. The natural gas company distributes the natural gas through an underground network of smaller pipelines called "mains." Smaller lines called "services" connect the mains to the end-users. Natural gas is often treated in scrubbers or filters to ensure that it is dry prior to the distribution. Crude oil must undergo refining before it can be used as a product. Once oil is refined, product pipelines transport the product to a storage and distribution terminal. Different modes of transportation are used to move the oil from the production site to the refineries and from the refineries to the consumers. Crude oil and refined products are transported across the water in barges and tankers. On land crude oil and products are moved using pipelines, trucks, and trains. The pressure in the trunk lines is initiated and maintained by pumps to overcome friction, changes in elevation, or other pressure-decreasing factors.

4.2.2 Proposed taxonomy for gas network components

The various components of a gas network have been regrouped under the following generic elements, which are described below:

a) Production and gathering facilities;

b) Treatment plants;

c) Storage plants;

d) Stations;

e) Transmission and distribution pipelines;

f) SCADA system.

SYNER-G Taxonomy for Natural Gas Network is presented in Table 4.2.

Table 4.2 SYNER-G Taxonomy for Natural Gas Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Production and Gathering Facility (GAS01)	
• Onshore Production Facilities (Production Field)	○ Oil and gas pools and wells (oil, gas and condensate wells)
• Offshore Production Facilities (Marine-water Platforms)	
• Gathering Facilities	○ Radial line ○ Trunk line
Treatment Plant (GAS02)	
• Amine Process	○ Absorber ○ Regenerator ○ Accessory equipment (re-boiler, pumps, condenser, valve, reflux drum, etc.)
• NGL Fractionation	○ Fractionating column ○ Accessory equipment (re-boiler, reflux drum, condenser, etc.)
• Water Removal	○ Regenerator ○ Contactor ○ Accessory equipment (Absorption/ Adsorption Towers)
Storage Tanks (GAS03)	
• Underground Storage Facilities	○ Depleted gas reservoirs ○ Aquifers ○ Salt caverns
• Storage Tanks for Liquefied Natural Gas- LNG (including pipes and electric components)	○ Anchored/Unanchored
Stations (GAS04)	
• Compression Stations	

CATEGORY	CLASSIFICATION/SUB-COMPONENT
• Metering/Pressure Reduction Stations • Regulator Stations • Metering Stations	○ Turbine ○ Motor ○ Engine ○ Scrubber ○ Filter ○ Equipment for monitoring and managing
Pipelines (GAS05) • Gathering System (from wellhead to treatment plant, low pressure and diameter pipelines) • Transportation System (from treatment plant to distribution systems, high pressure and large diameter pipelines) • Distribution System (from regulator stations to the city, low pressure and small-diameter pipelines)	○ Location : Buried/Elevated ○ Material type: PVC, PEAD, cast iron, ductile iron, steel ○ Material strength ○ Diameter: Φ75, Φ 100, Φ 150, Φ 200, Φ 400, Φ 500 ○ Wall thickness ○ Type of connection: Rubber gasket, lap-arc welded, heat fusion. Arc or oxyacetylene-gas welds, screwed, mechanical restrained ○ Pressure classification: Low/High ○ Design flow ○ One way feed / Bi-directional feed
SCADA System (GAS06)	

a) Oil Production and gathering facilities

The typology of production facilities can at first be defined on whether they are located, at sea or on-land:

- Offshore platforms: they are many kinds of production platforms, such as fixed or gravity-based platforms, semi-submersible platforms, floating production systems… The gas is usually transported to the mainland through pipelines on the seabed.
- Onshore facilities: the production field is an area encompassing a group of oil and gas pools and wells. The production facility is complemented by a gathering facility, which is a low-line network (surface pipeline) and by process facilities that transport and control the flow of oil and gas from the wells to the main storage facility, the processing plant or the shipping point. There are two types of gathering systems, radial and trunk line. The radial type brings all the flow-lines to a central header, while the trunk-line uses several remote headers to collect fluid. The latter is mainly used in

large fields. The gathering line consists of low pressure, low diameter pipelines that transport raw natural gas from the wellhead to the processing plant.

b) Treatment plant

The gas is treated to remove any contaminants, water, and dust. The processing can be done at the wellhead and at centralized processing plants. The actual practice of processing natural gas to obtain pipeline dry gas quality levels usually involves four main processes:

- Oil and condensate removal
- Water removal
- Separation of natural gas liquids
- Sulfur and carbon dioxide removal

The treatment plant can thus be classified according to the type of processes they cover, which influences their size and the type of equipment they harbour. For instance, the water removal process is constituted of various components such as regenerators, contactors, absorption and adsorption towers.

c) Storage tank farm

Storage facilities are used as buffer between production/transportation and distribution network. There are two types of storages:

- Underground storage facilities (e.g. depleted gas reservoirs, aquifers or salt caverns): they are usually used to balance seasonal variations in demand. For instance, they can be classified as seasonal supply reservoirs (mostly depleted gas/oil fields and aquifers that are designed to be filled during the non-heating season) and as high-deliverability sites (mostly salt cavern reservoirs for the heating season).
- Storage tanks for liquefied natural gas (LNG) that include pipes, pumps and other micro-components. These LNG tanks differ from conventional tanks (e.g. for water) as they are designed to minimize any heat ingress. The insulation of the tanks will not keep the temperature of LNG low by itself: LNG will stay at near constant temperature if kept at constant pressure. As long as the steam (LNG vapour boil off) is allowed to leave the tank, in a safe and controlled manner, the temperature will remain constant. This vaporisation loss is collected from the tank and either reabsorbed as a liquid, sent to the gas output line connecting to the national grid, or used as fuel on the site. The LNG tanks would be of a full containment design. In a full containment system, two tanks are employed: an inner tank which contains the stored liquid, and an outer tank which provides security in the event of any loss of containment or leak from the inner tank. Sophisticated automatic protection systems are employed to monitor the tank levels, pressures, temperatures and any potential leakage from the inner tank.

d) Stations

Compression Stations

A compression station is a facility that supplies gas with energy to move in transmission lines (Fig. 4.9). Otherwise compression stations are operated at underground storage facilities to raise the pressure of the gas injected into storage or to compress the natural gas as it leaves storage to be fed into the pipeline. The distance between compression stations along a transmission trunk is usually between 100 and 250 km.

The natural gas enters into the compressor station, where it is compressed by either a turbine, a motor, or an engine to ensure that the flowing of the natural gas, through any pipeline, remains pressurized. The turbine operates a centrifugal compressor that, using a fan, compresses and pumps the natural gas through the pipeline. Natural gas engines are also used to power some compressor stations. Compressor stations usually contain scrubbers and filters that capture any undesirable particles or liquids that might be still contained in the natural gas flowing through the pipeline. Two or more compressors at a station can be used either in parallel or in series (FEMA 233, 1992): however, no differentiation is made between these two types of compressors in the analysis of natural gas systems.

Typological classification is performed by considering whether the components are anchored or unanchored. The presence a back-up generator for power supply is also an important factor to take into account.

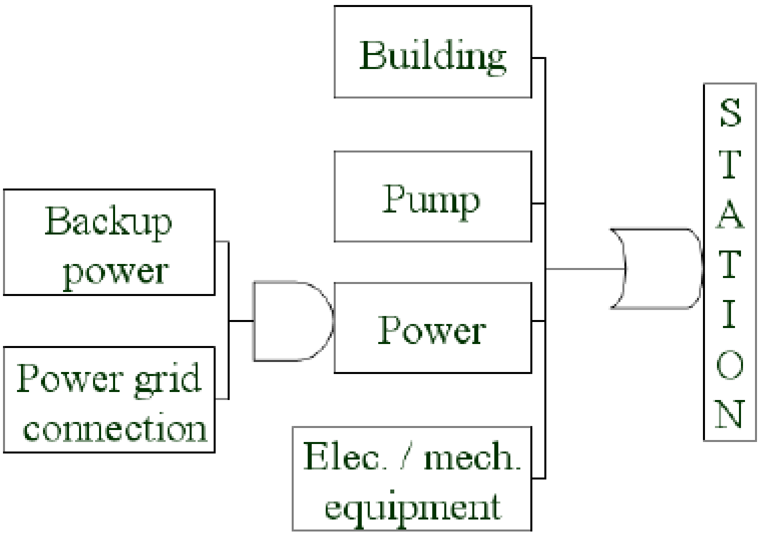

Fig. 4.9 Decomposition of a compression station into a fault-tree

The typology of the building has a strong influence: buildings housing compression stations are usually low-rise and made of masonry or RC.

Metering /Pressure Reduction Stations:

Metering/Pressure Regulator Stations contain metering equipment for monitoring and managing the natural gas in their pipes, including the reduction of the gas pressure before its distribution into the pipe system.

In the L'Aquila (Italy) area, the medium pressure network is connected to the high pressure transmission lines through three M/R stations (referred to as RE.MI "REgolazione e MIsura" in Italian). RE.MI stations are one-story masonry buildings with steel roofs (Fig. 4.10).

Fig. 4.10 RE.MI cabin in the L'Aquila area - outside view (courtesy of Enel Retel Gas)

Inside the M/R stations the gas undergoes the following operations and processes (Fig. 4.11):

- Gas preheating;
- Gas pressure reduction and regulation;
- Gas odorizing;
- Gas pressure measure.

The specificities of the operations performed within these stations prevent them from being included in the generic typology of compression stations.

Fig. 4.11 RE.MI cabin in the L'Aquila area - inside view (courtesy of Enel Rete Gas)

Regulator Stations:

At regulator stations gas pressure is reduced as required for the gas to arrive to the end-user.

In the L'Aquila area, about 300 Final Reduction Groups (referred to as GRF "Gruppo di Riduzione Finale" in Italian) allow for the transformation of the medium distribution pressure into the low distribution pressure (Fig. 4.12). These facilities can be either buried, sheltered in a kiosk or housed within a building.

Fig. 4.12 View of a reduction group in the L'Aquila area (courtesy of Enel Rete gas)

Metering Stations:

Metering stations are only measurement points.

e) Gas pipelines

There are three major types of pipelines used in three different systems:

1. Gathering system: connects the wellhead to the treatment plant and it is characterized by low pressure and diameter pipelines.
2. Transportation system: transports gas from the treatment plant to the distribution systems, often across long distances; it is characterized by high pressure and large diameter pipelines.
3. Distribution system: connects regulator stations to the city, communities and it is characterized by low pressure and small-diameter pipelines.

Individual pipes (buried and unburied) connect residential buildings and businesses to the distribution system. However the description and vulnerability analysis of these pipeline systems is out of the scope of the SYNER-G project. Pipeline systems may include a great number of valves along their entire distributed network. These valves work like gateways: they are open to allow the flow of the natural gas; they can be closed to stop the gas flow along a certain section of pipe.

Classification of pipelines is at first based on the pressure levels at which they operate. Three groups can be identified:

1. Supra-regional transmission pipelines: these pipelines operate at very high pressures (~100 bar) and present large diameters (up to 1.40 m). such pipelines can cover large distances (e.g. from west Siberia to Europe, from Norway to France).
2. Regional transmission/distribution pipelines: these pipes still operate at high pressure (from 1 to 70 bar) and are used to connect local distribution systems.
3. Local distribution pipelines: these smaller pipeline typologies mainly rely on the following parameters:
   - Material type;
   - Material strength;
   - Diameter;
   - Wall thickness;
   - Smoothness of coating;
   - Type of connection;
   - Design flow.

Focusing mainly on the typologies inherent to the SYNER-G case studies (Thessaloniki, Vienna and L'Aquila), pipeline components from Greece present the following characteristics, for instance:

- Transmission pipelines (19 bar): welded-steel, diameters ranging between 100 – 250 mm and wall thickness from 4.37 mm to 5.56 mm;
- Distribution pipelines (4 bar): made of PVC (with electro-fusion connections), with diameters between 125 and 160 mm and wall thickness ranging from 11.4 mm to 14.6 mm.

These natural gas pipelines are located at a conventional depth, i.e. 1.10 m + pipeline diameter + 0.15 m.

In Austria, there are several long distance transmission pipelines going through (TAG, WAG, HAG, etc.). They consist of welded-steel and have diameters ranging from 200 to 1 400 mm. They are operated at 84 bar and are buried at an average depth of 1 m. The regional transmission/distribution pipelines operate at a pressure of about 16 bar and they get down to 1 bar locally: these pipelines are made of PVC.

In L'Aquila, the transmission network (operated by SNAM at a national level) is made of welded-steel pipes, with an internal diameter of 103.9 mm and wall thickness of 5 mm. the transmission and delivery pressure for the L'Aquila area is 64 bar. Locally, the gas is distributed via a 621 km pipeline network: 234 km of pipes operating at medium pressure (2.5-3 bar), and the remaining 387 km with gas flowing at low pressure (0.025-0.035 bar): these pipelines are either made of steel or HDPE (High Density Polyethylene). HDPE pipes have a nominal diameter ranging from 32 to 400 mm, whereas diameter of steel pipes is usually between 25 and 300 mm.

As a result, it is reasonable to identify pipelines typologies based on the following known features:

- Material type: welded-steel, PVC or HDPE;
- Operation pressure;

- Pipe diameter;
- Connection type (if known).

f) SCADA system

Control and communication systems are critical for the safe and continuous conveyance of both gas and liquid fuels, and are vital to guarantee an effective and timely emergency response. In particular, SCADA, which stands for Supervisory Control and Data Acquisition, are sophisticated communications systems that take measurements and collect data along the pipeline network (usually in metering or compressor stations and valves) and transmit them to centralized control stations. This enables a quick reaction to equipment malfunctions, leaks, or any other unusual activity along the pipeline. Some SCADA systems incorporate the ability to remotely operate certain equipment along the pipeline, including compressor stations, allowing engineers in a centralized control centre to immediately and easily adjust flow rates in the pipeline.

4.2.3 Proposed taxonomy for oil network components

Similarly to the gas network, the various components of an oil network have been regrouped under the following generic elements, which are described below:

a) Production and gathering facilities;

b) Refineries;

c) Storage tank farms;

d) Pumping plants;

e) Pipelines;

f) SCADA system.

SYNER-G Taxonomy for Oil Network is presented in Table 4.3.

a) Oil production and gathering facility

Oil is found in reservoirs deep underground or beneath the ocean floor and it is extracted vertically through high-pressure tubing. The process extracts oil, water and mixed gases from the rock formations. Once at the surface, the production stream runs through a control wellhead into horizontal flow lines that carry the three phases into a separator vessel. In particular the gas from the top of the vessel may be injected again into the reservoir, flared or refined and marked, separating all the various hydrocarbons and fluids from the pure natural gas, to produce the ‘pipeline quality’ dry natural gas. The oil is sent to a pipeline for delivery to a refinery, tanker terminal or transmission pipeline system.

b) Oil refineries

In the refineries the crude oil is converted into high-octane motor fuel (gasoline/petrol), diesel oil, liquefied petroleum gases (LPG), jet aircraft fuel, kerosene, heating fuel oils, lubricating oils, asphalt and petroleum coke.

c) Oil storage tank farms

There are four basic types of tanks used to store petroleum products:

1. Floating roof tank used for crude oil, gasoline, and naphtha.
2. Fixed roof tank used for diesel, kerosene, catalytic cracker feedstock, and residual fuel oil.
3. Bullet tank used for normal butane, propane, and propylene.
4. Spherical tank used for isobutane and normal butane.

The focus is set here on liquid products (oil and fuel) that are stored in atmospheric storage facilities, which include tanks (vertical cylinders), pipes and electric components. The tank typologies are usually classified according to the following characteristics:

- Material: steel or reinforced-concrete;
- Construction type: at-grade or elevated;
- Anchored or unanchored components;
- Roof type (floating or fixed);
- Capacity
- Shape factor: height vs diameter ratio;
- Amount of content in the tank: empty, half-full, full.

d) Oil pumping plants

Pumping plant allows maintaining the flow of the oil in the pipelines. Pumping plants usually use two or more pumps. Pumps can be of either centrifugal or reciprocating type. However, no differentiation is made between these two types of pumps in the analysis of oil systems.

e) Oil pipelines

Pipelines are used to move crude oil from the wellhead to gathering and processing facilities and from there to refineries and tanker loading facilities. Product pipelines ship gasoline, jet fuel, and diesel fuel from the refinery to local distribution facilities. After crude oil is converted into refined products such as gasoline, pipelines are used to transport the products to terminals for movement to gasoline stations. In addition to gasoline, products pipelines are used to ship diesel fuel, home heating fuel, kerosene, and jet fuel.

f) SCADA system

It is same as the *Scada System* for gas network components.

Table 4.3 SYNER-G Taxonomy for Oil Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Production and Gathering Facility (OIL01)	
• Onshore Production Facilities (Production Field)	○ Oil and gas pools and wells (oil, gas and condensate wells)
• Offshore Production Facilities (Marine-water Platforms)	
• Gathering Facilities	○ Radial line ○ Trunk line
Refineries (OIL02)	○ Equipment: Centrifuges, compressors, cooling towers, crushers, crystallizers, distillation towers and pressure vessels, electric power generators, transformers and electric motors, electrolysis cell, evaporators, filters, furnaces, gas flares, mixers and blenders, monitoring and control systems, piping and valves, pumps, steam generators, steam turbines and gas turbines, storage tankers, wastewater treatment.
Storage Tank Farms (OIL03) • Floating roof tank • Fixed roof tank • Bullet tank • Spherical tank	
Pumping Plants (OIL04) • Centrifugal • Reciprocating	
Pipelines (OIL05)	
• Gathering System (from wellhead to treatment plant, low pressure and diameter pipelines) • Transportation System (from treatment plant to distribution systems, high pressure and large diameter pipelines)	○ Location : Buried/Elevated ○ Material type: PVC, PEAD, cast iron, ductile iron, steel ○ Material strength ○ Diameter: Φ75, Φ 100, Φ 150, Φ 200, Φ 400, Φ 500 ○ Wall thickness

CATEGORY	CLASSIFICATION/SUB-COMPONENT
• Distribution System (from regulator stations to the city, low pressure and small-diameter pipelines)	o Type of connection: Rubber gasket, lap-arc welded, heat fusion. Arc or oxyacetylene-gas welds, screwed, mechanical restrained o Pressure classification: Low/High o Design flow o One way feed/Bi-directional feed
SCADA System (OIL06)	

4.3 WATER SUPPLY AND WASTE-WATER NETWORKS

4.3.1 General description

Potable water supply is necessary for drinking, food preparation, sanitation, fire-extinguishing etc. Water (which may be non-potable) is also required for cooling equipment.

A water supply network consists of transmission and distribution systems:

- Transmission system stores “raw” water and delivers it to treatment plants. Such a system is made up of canals, tunnels, elevated aqueducts and buried pipelines, pumping plants and reservoirs.
- Distribution system delivers treated water to customers.

The water supply system as a whole is composed of a number of point-like critical facilities (water sources, treatment plants, pumping stations, storage tanks) and of the water distribution network itself. The network portion of the system is made of: pipelines, tunnels and canals and the supervisory control and data acquisition (SCADA) sub-system.

Waste-water system can alternatively be called sewer network. Is comprised of components that work together to: collect, transmit, treat and dispose of sewage

The waste-water system as a whole is composed of a number of point-like facilities (treatment plants, pumping stations) and of the distribution network itself. The network portion of the system is made of: pipelines, tunnels.

For obvious reasons pipes usually follow the plan layout of the road network. From a topological point of view, they can be either tree-like networks or grid-like networks, as shown in Fig. 4.5.

4.3.2 Proposed taxonomies for water supply and waste-water networks

The typological features and classification considered in SYNER-G are summarized in Table 4.4 and Table 4.5.

Table 4.4 SYNER-G Taxonomy for Water Supply Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Source (WSN01) • Springs • Rivers • Natural Lakes • Impounding Reservoirs • Wells (Shallow/Deep) (Anchored/Unanchored Sub-components)	○ Electric power ○ Electric equipment ○ Well pump ○ Building
Treatment Plant (WSN02) • Small • Medium • Large (Anchored/Unanchored Sub-components)	○ Electric power ○ Electric equipment ○ Chlorination equipment ○ Sediment floculation ○ Basins ○ Baffles ○ Paddles ○ Scrapers ○ Chemical Tanks ○ Elevated pipe ○ Filter gallery
Pumping Station (WSN03) • Small • Medium • Large (Anchored/Unanchored Sub-components)	○ Electric power ○ Equipment ○ Vertical/horizontal pump ○ Building
Storage Tanks (WSN04) • Closed Tanks • Open Cut Reservoirs	○ Material type: wood, steel, concrete, masonry ○ Capacity: small, medium, large ○ Anchorage: yes/no ○ Position: at grade, elevated by columns or frames) ○ Type of roof: RC, steel, wood ○ Seismic design: yes/no ○ Construction type: elevated by columns, built “at- grade” to rest directly on the ground, build “at grade” to rest on a foundation, concrete pile foundation ○ Presence of side-located inlet-outlet

CATEGORY	CLASSIFICATION/SUB-COMPONENT
	pipes ○ Volume: height, diameter ○ Thicknesses ○ Operational function: full, nearly full, less than full
Pipes (WSN05)	○ Location: buried/elevated ○ Type: continuous/segmented ○ Material (type, strength): ductile iron, steel, PVC (acrylonitrile-butadienestyrene/ABS), polyethylene/PE, reinforced plastic mortar/RPM, resin transfer molding/RTM- asbestos-cement pipes, cast iron, concrete, clay ○ Type of joints: rigid/flexible ○ Capacity: diameter ○ Geometry: wall thickness ○ Type of coating and lining ○ Depth ○ History of failure ○ Appurtenances and branches ○ Corrosiveness of soil conditions ○ Age ○ Pressure
Tunnels (WSN06)	○ Construction technique ○ Liner system ○ Geologic conditions
Canals (WSN07) • Open cut or built up using levees • Reinforced, unreinforced liners or unlined embankments	○ Material: wood, steel, concrete ○ Appurtenances and branches location ○ Age of construction ○ Geometrical characteristics: width, depth, capacity ○ Section: orthogonal, trapezoid, etc. ○ Inclination
SCADA System (WSN08)	

Table 4.5 SYNER-G Taxonomy for Waste-Water Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Treatment Plant (WWN01) • Small • Medium • Large (Anchored/Unanchored Sub-components)	○ Electric power ○ Electric equipment ○ Chlorination equipment ○ Sediment floculation ○ Chemical Tanks ○ Elevated pipe ○ Building
Pumping (Lift) Station (WWN02) • Small • Medium • Large (Anchored/Unanchored Sub-components)	○ Electric power ○ Equipment ○ Vertical/horizontal pump ○ Building
Pipes (WWN03)	○ Location: buried/elevated ○ Type: continuous/segmented ○ Material (type, strength): ductile iron, steel, PVC (acrylonitrile-butadienestyrene/ABS), polyethylene/PE, reinforced plastic mortar/RPM, resin transfer molding/RTM- asbestos-cement pipes, cast, iron, concrete, clay ○ Type of joints: rigid/flexible ○ Capacity: diameter ○ Geometry: wall thickness ○ Type of coating and lining ○ Depth ○ History of failure ○ Appurtenances and branches ○ Corrosiveness of soil conditions ○ Age ○ Pressure
Tunnels (WWN04)	○ Construction technique ○ Liner system ○ Geologic conditions
SCADA System (WWN05)	

5 Transportation infrastructures

5.1 ROADWAY NETWORK

5.1.1 General description

Roadway elements are categorized as earth structures, therefore a main typological feature is the soil type, which characterizes either the construction or its foundation and supporting material. Different soil classification systems are available based on various soil properties. A widely used classification scheme is the one provided by Eurocode 8 (EC8 2004), which is based on the shear wave velocity in the top 30m of the soil profile (V_{s30}).

Another important parameter for the description of typology is the hierarchy of roads according to their functions and capacities. The available sources differ on the terminologies and classifications schemes; however, the basic hierarchy comprises the following:

- Freeways or motorways: limited access roads, including most toll roads. They provide largely uninterrupted travel, often using partial or full access control, and are designed for high speeds.
- Arterials: are major through roads that are expected to carry large volumes of traffic. They are often divided into major and secondary arterials, and rural and urban arterials.
- Collectors: collect traffic from local roads, and distribute it to arterials. Traffic using a collector is usually going to or coming from somewhere nearby. They are often divided into major and secondary collectors.
- Local roads: have the lowest speed limit, and carry low volumes of traffic

In addition to the above main attributes, other important typological features are given in the following for each roadway element.

- Tunnels: The basic parameters for the description of the typology are the construction method (bored or mined, cut-and-cover, immersed), the shape (circular, rectangular, horseshoe etc), the depth (surface, shallow, deep), the geological conditions (rock, alluvial), and supporting system (concrete, masonry, steel etc). Tunnels are used for metro structures, highway/railway tunnels, and large water and sewage transportation ducts.
- Embankments, Trenches and Slopes: The main typological features considered in this project are the geometrical parameters of the construction (i.e. slope angle and height). These elements are mainly presented in highways (non urban networks).
- Road pavements: The basic parameter is the number of traffic lanes which is based on the functional hierarchy of the network.
- Bridge abutments: The main typological features are the depth and the soil conditions of foundation and fill material behind the abutment. The depth is dependent on the surrounding topography and bridge abutment geometry, while the fill material behaviour depends on its compaction level.

5.1.2 Proposed taxonomy for roadway network

The typological features and classification considered in SYNER-G are summarized in Table 5.1.

Table 5.1 SYNER-G Taxonomy for Roadway Network

CATEGORY	CLASSIFICATION
Bridges (RDN01) See Table 5.3	
Tunnels (RDN02)	○ Construction method: bored or mined, cut-and-cover, immersed ○ Shape: circular, rectangular, horseshoe, etc. ○ Depth: surface, shallow, deep ○ Geological conditions: rock/alluvial ○ Supporting system: concrete, masonry, steel, etc.
Embankments (road on) (RDN03)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Trenches (road in) (RDN04)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Unstable Slopes (road on or running along) (RDN05)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Road pavements (ground failure) (RDN06)	○ Number of traffic lanes
Bridge abutments (RDN07)	○ Geometry of the abutment, i.e. height, width ○ Soil conditions of foundation ○ Fill material behind the abutment

5.2 RAILWAY NETWORK

5.2.1 General description

The track is a fundamental part of the railway infrastructure. It consists of elements with different elasticity that transfer static and dynamic loads to the foundation soil. The classical railway track consists of a flat framework made up of rails and sleepers which are supported on ballast. The ballast bed rests on a sub-ballast layer which forms the transition layer to the formation (subgrade in Fig. 5.1). The rails and sleepers are connected by fastenings (Fig. 5.1). These components and other structures such as switches and crossings are all considered as part of the track.

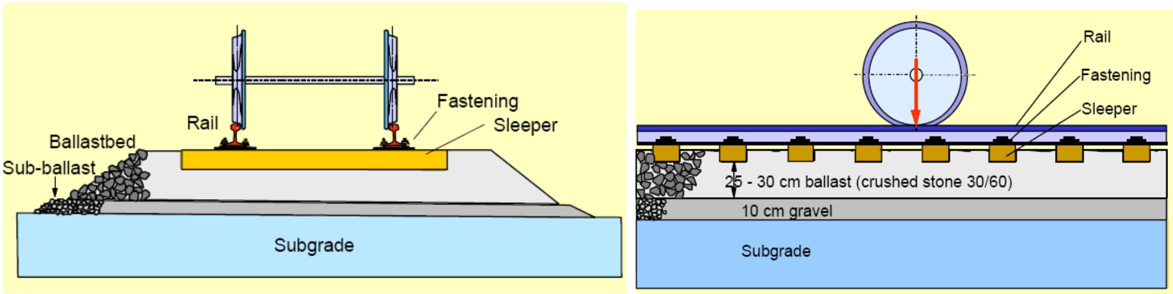

Fig. 5.1 Principle of track structure: cross (left) and longitudinal (right) section (Esveld 2001)

The substructure consists of three main elements; the formation, the sub-ballast and the ballast. The formation is the ground upon which supports the track. It can be the natural ground level or "grade" or it can be an embankment or cutting. Ballast is provided to give support, load transfer and drainage to the track.

The usual track form consists of the two steel rails, secured on sleepers (ties) so as to keep the rails at the correct distance apart and capable of supporting the weight of trains. Sleeper’s material could be wooden, steel or concrete block.

5.2.2 Proposed taxonomy for railway network

The description and classification of the other railway elements is similar to the corresponding roadway elements. The classification considered in SYNER-G is summarized in Table 5.2.

Table 5.2 SYNER-G Taxonomy for Railway Network

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Bridges (RWN01) See Table 5.3	
Tunnels (RWN02)	○ Construction method: bored or mined, cut-and-cover, immersed ○ Shape: circular, rectangular, horseshoe, etc. ○ Depth: surface, shallow, deep ○ Geological conditions: rock/alluvial ○ Supporting system: concrete, masonry, steel, etc.
Embankments (track on) (RWN03)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Trenches (track in) (RWN04)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Unstable Slopes (track on or running along) (RWN05)	○ Geometrical parameters of the construction, i.e. slope angle, height ○ Soil conditions ○ Water table
Tracks (RWN06)	○ Steel rails ○ Sleepers (ties): wooden, steel, concrete, twin block ○ Support ballast
Bridge Abutments (RWN07)	○ Geometry of the abutment i.e. height, width ○ Soil conditions of foundation ○ Fill material behind the abutment
Stations (RWN08)	○ Passenger buildings ○ Track exchanges ○ Control houses ○ Maintenance buildings ○ Warehouses

5.3 BRIDGES

5.3.1 Proposed taxonomy for bridges

As shown in Table 5.3 different categories have been identified to describe a bridge, such as the material, characteristics of the deck, spans, pier-deck connection, etc. A hierarchy is used for some categories where additional information might or might not be available. For example, when the material is concrete, the user may or may not know whether it is reinforced or pre-stressed reinforced, thus the definition of such second parameter is optional.

Table 5.3 SYNER-G Taxonomy for Bridges

<table>
<tr><th>CATEGORY</th><th colspan="2">CLASSIFICATION</th></tr>
<tr><td>Material (MM1)
• Concrete (C)
• Masonry (M)
• Steel (S)
• Iron (I)
• Wood (W)
• Mixed (MX)</td><td colspan="2">Material (MM2)
• Reinforced concrete (RC)
• Pre-stressed reinforced concrete (PC)
• Unreinforced masonry (URM)
• Reinforced masonry (RM)
• High strength concrete (HSC)
• Average strength concrete (ASC)
• Low strength concrete (LSC)
• Fired brick (FB)
• Hollow clay tile (HC)
• Stone (S)
• Lime mortar (LM)
• Cement mortar (CM)
• Mud mortar (MM)
• Concrete masonry unit (CMU)
• Autoclaved aerated concrete (AAC)
• High % of voids (H%)
• Low % of voids (L%)
• Regular Cut (Rc)
• Rubble (Ru)</td></tr>
<tr><td>Type of Deck (TD1)
• Girder bridge (Gb)
• Arch bridge (Ab)
• Suspension bridge (Sb)
• Cable-stayed bridge (Csb)
• Moveable bridge (Mb)</td><td>Type of Deck (TD2)
• Solid slab (Ss)
• Slab with voids (Sv)
• Box girder (B)
• Modern arch bridge (MA)
• Ancient arch bridge (AA)
• Precast beams with concrete topping (Pbc)</td><td>Deck characteristics (DC)
[Here the width of the deck is explicitly given if known]</td></tr>
</table>

	• Steel beams with concrete topping (Sbc)	
Deck Structural System (DSS) • Simply supported (SSu) • Continuous (Co)		
Pier to deck connection (PDC) • Not Isolated (monolithic) (NIs) • Isolated (through bearings) (Is) • Combination (Com)	• Fixed bearings (Fb) • Elastomeric bearings (Eb) • Sliding bearings (Sb) • Seismic isolation/dissipation devices (SeisD)	
Type of pier to deck connection (TC1) • Single-column pier (ScP) • Multi-column piers (McP)	**Number of piers for column (NP)** [Here the number of piers for column is explicitly given if known]	
Type of section of the pier (TS1) • Cylindrical (Cy) • Rectangular (R) • Oblong (Ob) • Wall-type (W)	**Type of section of the pier (TS2)** • Solid (So) • Hollow (Ho)	**Height of the pier (HP)** [Here the height of piers is explicitly given if known]
Spans (Sp) • Single span (Ssp) • Multi spans (Ms)	**Spans characteristics (SC)** • Number of spans (Ns) - [Here the number of spans is explicitly given if known] • Span length (SL) - [Here the length of spans is explicitly given if known]	
Type of connection to the abutments (TCa) • Free (F) • Monolithic (M) • Isolated (through bearings, isolators) (Isl)	• Free transverse translation (Ftt) • Constrained transverse translation (Ctt) • Fixed bearings (Fb) • Elastomeric bearings (Eb) • Sliding bearings (Sb) • Seismic isolation/dissipation devices (SeisD)	
Skew (Sk) • Straight • Skewed	[Here the skew angle is explicitly given if known]	
Bridge Configuration (BC) • Regular or semi-regular (R) • Irregular (IR)		
Foundation Type (FT) • Shallow foundation (SF) • Deep foundation (DF)	• Single pile (Sp) • Multiple piles with pile cap (Mpc)	

	• Multiple piles without pile cap (Mp)
Seismic Design Level (SDL) • No seismic design (design for gravity loads only) (NSD) • Low-code (LC) • Medium-code (MC) • High-code (HC)	

The bridge typology is defined using the label between brackets for each parameter within a given category.

Example:

MM1-MM2/TD1-TD2-DC/DSS/PDC/TC1-NP/TS1-TS2-HP/Sp-SC/TCa/Sk/BC/FT/SDL

More than one label can be used per category, separated by a dash. For example, a concrete bridge made up of pre-stressed reinforced concrete would be C-PC, whereas a bridge with cylindrical and solid cross-section piers would be Cy-So. Not all categories need to be defined due to the fact that information about the structure might be missing. In this case, for the categories where information is unknown, an X symbol is used. In the following, a couple of examples are presented:

- C-RC/Gb-B/SSu/Nis/McP-2/R-Ho-10/Ms-3/M/IR/SD: Reinforced concrete bridge with box girder, simply supported non-isolated deck with 2-column rectangular hollow piers; 3-span deck monolithically connected to the ground; with irregular pier configuration and seismically designed.
- C-RC/Gb-B-X/X/NIs/X/W-X-X/X-X/X/X/X: Reinforced concrete bridge with box girder and deck monolithically connected to wall-type piers.

The proposed taxonomy has been set up with a modular structure, a new and different approach in categorizing and classifying bridges. Such flexible structure, which easily enables the future addition of other categories and sub-categories, as well as different features to existing ones, can be used to describe a considerable amount of different bridges. This will cater for the consideration of different kinds of European bridges.

5.4 HARBOUR ELEMENTS

5.4.1 General description

Port transportation systems are vital lifelines whose primary function is to transport cargos and people. They contain a wide variety of facilities for passenger operations and transport, cargo handling and storage, rail and road transport of facility users and cargoes, communication, guidance, maintenance, administration, utilities, and various supporting operations.

The following elements exist within port facilities:

- Waterfront structures
- Cargo handling and storage components
- Infrastructures

- Buildings (sheds and warehouses, office buildings, maintenance buildings, passenger terminals, traffic control buildings).
- Utility systems (electric power system, water system, waste-water system, natural gas system, liquid fuel system, communications system, fire-fighting system).
- Transportation infrastructures (roadway system, railway system, bridges).

The main characteristic of these complex systems is the multiple interactions existing within their elements and with the external supplying or/and supplied systems and infrastructures. The ports' functionality is dependent on the functioning of each system/ component, taking also into consideration the interactions between them.

The internal classification and distribution of the utilities and infrastructures within port facilities can be in general distinguished in "point-like" critical facilities and "line-like" (network) components. Especially for port facilities, cargo handling and storage components comprise point-like critical facilities, whose internal logic and function in the management of the whole system should be modelled explicitly. Waterfront structures are "line-like" (network) components. From a topological point of view, they follow the external boundaries of piers and/of the coastline.

5.4.2 Proposed taxonomy for harbour elements

The typological features and classification of port facilities considered in SYNER-G are summarized in Table 5.4. For the classification of buildings, utility systems and transportation infrastructures, the reader is referred to the respective chapters.

Table 5.4 SYNER-G Taxonomy for Harbour Elements

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Waterfront Components (HBR01)	
• Gravity Retaining Structures (along the waterfront, quay walls/piers)	○ Concrete block walls ○ Massive walls ○ Concrete caissons ○ Cantilever structures ○ Cellular sheet pile structures ○ Steel plate cylindrical caissons ○ Crib-work quay walls
• Sheet Pile Wharves	○ Sheet pile ○ Pile ○ Fill-soil foundation
• Piers	○ Deck slabs ○ Pile caps: wood, steel or concrete (with or without batter piles)
• Breakwaters	○ Gravity structure

CATEGORY	CLASSIFICATION/SUB-COMPONENT
• Mooring and Breasting Dolphins	o Piled structure o Rubble mound
Earthen Embankments (HBR02) • Hydraulic Fills • Native Soil Materials	o Native soils o Rock and sand dike with back land fills o Bulkheads o Sea walls o Breakwaters
Cargo Handling and Storage Components (HBR03) • Cranes	o Rail, tire and track mounted gantry and revolver cranes o Mobile cranes o Crane foundations o Power supply systems
• Tanks	o Anchored/unanchored o Above grade and partially buried o Tank foundations o Containment berms
• Other Cargo Handling and Storage Components (cargo)	o Port equipment (stationary or mounted on rails) o Structural systems used for material handling o Transport (cranes, conveyors, transfer towers and stacker/reclaimer equipment) o Tunnels and pipelines o Temporary transitional storage and containment components
Buildings (HBR04) • Sheds and Warehouses	o Braced in one or two directions o Concrete walls o Masonry/metallic siding
• Office Buildings	o Single/multi-storey o Steel/Timber/Concrete/Masonry

CATEGORY	CLASSIFICATION/SUB-COMPONENT
• Maintenance Buildings	○ Braced in one or two directions ○ Concrete walls ○ Masonry/metallic siding
• Passenger Terminals	○ Concrete/Masonry/Steel/Wood
• Control and Clock Towers	
• Older Buildings	○ Unreinforced masonry ○ Non-ductile concrete ○ No seismic design
Liquid Fuel System (HBR05) ○ Fuel storage tanks ○ Buildings ○ Pump equipment ○ Piping ○ Backup power	

6 Critical facilities

6.1 HEALTH-CARE FACILITIES

6.1.1 General description

Hospital facilities belong to the category of the so-called “complex-social” systems. From an engineering point of view these systems are made of many components of different nature that jointly contribute to provide an output, which are the medical services in the case of hospital. From a social point of view, hospitals provide a fundamental assistance to citizens in every-day life; their function becomes of paramount importance in the case of a disaster.

Though each complex-social system has its own peculiarities, they share common elements in the procedure through which their performance can be assessed. Complex systems can be described by the taxonomy proposed in Bea (2003), which identifies the following major components: procedures, organisation, operators, physical (structures and hardware) and environment. This system taxonomy applies very well to hospitals as illustrated in Fig. 6.1.

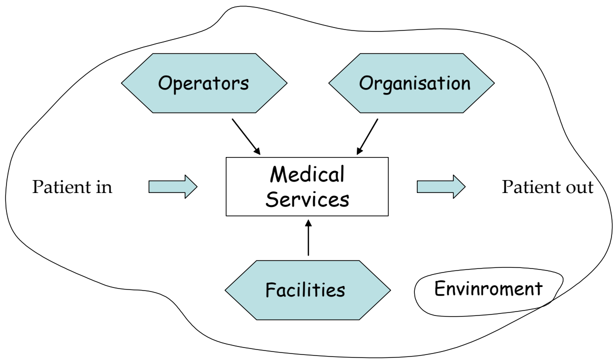

Fig. 6.1 System taxonomy of a hospital

At the core of the system there are the medical services, which consist of standardized procedures established to guarantee an adequate treatment of patients. The medical services are delivered to patients by a joint contribution of the three “active” components of the system:

1. The operators, which are the doctors, nurses and in general whoever plays an active role in providing medical care;
2. The facility (physical component) where the medical services are delivered.
3. The organisation, which is responsible of setting up the adequate conditions so that the medical services can be delivered. In general, this is up to the hospital management through the development, the implementation and the supervision of the standardized procedures.

The environment includes all external influences to the functioning of a hospital system, which encompasses such diverse factors as cultural background and soil properties. It acts on all the “active” components both directly, through characteristics such as accessibility, soil conditions, etc., and indirectly, through social context, economic pressures, standards, educational system, etc.

This description should by itself be sufficient to recognise the complexities associated with the performance assessment of a hospital system, which is indeed a task significantly more demanding with respect to the assessment of “simple” systems such as residential buildings or bridges. In fact, for a correct evaluation of the system performance, contributions of all components, and their interactions, have to be appropriately accounted for.

The main features of the four components of a hospital system are described in this section.

The Physical Component

The physical component of a hospital system consists of *structural elements* and *non-structural elements*. While the former are critical to preserve the life-safety of the building occupants, the latter are fundamental to preserve the hospital functionality.

The structural elements are sub-systems, elements, or components that are part of the load-bearing system such as beams, slabs, columns, joints, walls, etc.

Non-structural elements are sub-systems, elements, or components that are not part of the load-bearing system (but nevertheless are part of the building dynamic environment caused by the earthquake). Typical classification subdivides the non-structural elements into three categories:

1. architectural elements
2. basic installations
3. equipment/contents.

Examples of architectural elements are stairs, exterior and partition walls, doors, parapets and cornices, ceilings, windows, cladding, etc.

Examples of basic installations are power system, water system, HVAC (heating, ventilation, and air conditioning) system, medical gases, fire protection, communication system (internal and external), conveying system, ductwork and piping systems, lighting system, etc.

Examples of equipment/contents are mechanical and electrical equipment, shelves and rack systems, kitchen appliances, vending machines, medical and laboratory equipment, medicine containers, etc.

The organizational component

In the proposed model of the hospital system, the role of the *organizational component* consists of developing, implementing and supervising all activities and procedures which have to be immediately activated after a seismic event in order to prevent as much as possible, and to promptly recover from, the negative impact of the earthquake on the hospital performance. In simple words, this essentially means to set up a sound *emergency plan*.

Some examples of the provisions which should be included in an emergency plan are the following:

- the adequate storage of medical supplies to face the possible disruption to the supply-chain;

- the adequate autonomy of water and power to face possible breakdown of the normal system of supply;
- the additional human resources to be made available in case of need through an effective system alert;
- additional equipment;
- the re-allocation of human resources, by moving some of them from the basic medical services to the essential ones;
- the re-location of the “essential medical services” so that they are provided in areas of the hospital which remain operational after the occurrence of the seismic event;
- a procedure to assess correctly the need of evacuation due to the damage suffered by the hospital buildings.

The human component

The *human component* consists of the medical doctors, of the facility staff and of the manager that operate in the hospital.

They have to be appropriately trained to perform in a state of emergency, when the operating conditions are physically and mentally much more demanding with respect to normal standard.

To positively evaluate the response capability of the hospital system, it has to be checked that simulation of emergency procedures involving both medical doctors and staff have been actually carried out periodically. At the current state-of-the-art, the capability of the human resources can be assessed only empirically, usually by means of questionnaires distributed to medical personnel and staff.

The environment component

The environment includes all external influences to the functioning of a hospital system. The large and diversified collection of elements included in the environment can be classified into elements that can be quantitatively accounted for in the analysis (Type 1) and elements that cannot be accounted for at the component level but only through global criteria (Type 2).

Examples of Type 1 elements are:

- Soil properties
- the demography
- the vulnerability of the building stock in the tributary area (related to the expected number of casualties to be treated in the case of an event), etc.

Examples of Type 2 elements are,

- social context
- economic pressures
- educational system
- National standards, etc.

6.1.2 Proposed taxonomy for health-care facilities

The taxonomy derived for a health-care facility is presented in Table 6.1.

Table 6.1 SYNER-G Taxonomy for Health-Care Facilities

CATEGORY	SUB-COMPONENT
Organisational Component (HCS01)	
Human Component (HCS02)	
Physical Component (HCS03)	
• Structural Elements (HCS03-1)	○ Force mechanisms ○ Deformation mechanisms
• Non-structural Elements (HCS03-2)	○ Drift sensitive ○ Acceleration sensitive ○ Differential displacement sensitive
• Architectural Elements (HCS03-3)	○ Walls (internal and external) ○ Ceilings ○ Windows, doors, glazing
• Basic Installations (HCS03-4)	○ Generation (electrical generator, water tank, gas tank) ○ Distribution (pipes for water, waste-water, gas, fuel and electrical conduits)
• Basic Installation: Medical Gas (HCS03-5)	○ Oxygen (bottle, cylinders) ○ Nitrogen (cylinders) ○ Supply line ○ Equipments
• Basic Installation: Power System (HCS03-6)	○ Transformation station (medium voltage-MV and low voltage-LV) ○ Emergency generator (UPS and EPG) ○ Transmission lines ○ Distribution stations
• Basic Installation: Water System (HCS03-7)	

CATEGORY	SUB-COMPONENT
• Basic Installation: Conveying System (HCS03-8)	o Supply (city water and tanks) o Equipments (electric power, electric pumps and boilers) o Piping
• Building Contents (HCS03-9)	o Motor (power and engine) o Counter weights o Doors o Guide rails
	o Furnishings o Medical, office and industrial equipments o General supplies o Shelves etc.

6.2 FIRE-FIGHTING SYSTEMS

6.2.1 General description

The fire-fighting system plays a major role in the management of crisis situations, such as floods and strong earthquake events. It is comprised not only by the pipeline network and fire faucets (either separate or dependent on the water supply system), but also a whole crisis management system (special units, fire fighters, etc).

In case of an earthquake event, the primary role of the fire-fighting system is:

a) Rescue of people from collapsed buildings.
b) Rescue of trapped people to non-structural elements due to interactions of the lifeline systems with the urban fabric (e.g. loss of electric power supply may cause entrapments in elevators).
c) Suppression of fires caused by the earthquake.

The fire-fighting system as a whole can be a separate system or part of the water supply network (WSS). In case it is a separate system, it is composed of a number of point-like facilities (fire-fighting stations, pumping stations, storage tanks, fire-hydrant) and of the distribution network itself.

6.2.2 Proposed taxonomy for fire-fighting systems

Usually fire-fighting system is part of water system and the same pipelines and storage tanks are used.

In the case that is a separate network, storage tanks are usually made of steel, and pipes are made of PVC. For pumping stations the same typological categories as in WSS can be used. Fire-hydrants can be classified according to their condition: operational (yes, no), pressure and demand. Separate fire-fighting systems are more common to find in harbours, hospitals (small, well- defined area, with known needs) and not in large regions or urban cities.

For fire-fighting buildings the same typological categories proposed in Chapter 3 can be used.

Table 6.2 SYNER-G Taxonomy for Fire-Fighting system

CATEGORY	CLASSIFICATION/SUB-COMPONENT
Fire-fighters Stations (FFS01) • Buildings	
Pumping Stations (FFS02) • Small • Medium • Large (Anchored/Unanchored Sub-components)	○ Electric power ○ Equipment ○ Vertical/horizontal pump ○ Building
Storage Tanks (FFS03) • Closed Tanks • Open Cut Reservoirs	○ Material type: wood, steel, concrete, masonry ○ Capacity: small, medium, large ○ Anchorage: yes/no ○ Position: at grade, elevated by columns or frames) ○ Type of roof: RC, steel, wood ○ Seismic design: yes/no ○ Construction type: elevated by columns, built “at- grade” to rest directly on the ground, build “at grade” to rest on a foundation, concrete pile foundation ○ Presence of side-located inlet-outlet pipes ○ Volume: height, diameter ○ Thicknesses ○ Operational function: full, nearly full, less than full
Fire-hydrant (FFS04)	○ Pressure ○ Demand ○ Operational: yes/no
Pipelines (FFS05)	○ Location: buried/elevated ○ Type: continuous/segmented ○ Material (type, strength): ductile iron, steel, PVC (acrylonitrile-

CATEGORY	CLASSIFICATION/SUB-COMPONENT
	butadienestyrene/ABS), polyethylene/PE, reinforced plastic mortar/RPM, resin transfer molding/RTM- asbestos-cement pipes, cast, iron, concrete, clay ○ Type of joints: rigid/flexible ○ Capacity: diameter ○ Geometry: wall thickness ○ Type of coating and lining ○ Depth ○ History of failure ○ Appurtenances and branches ○ Corrosiveness of soil conditions ○ Age ○ Pressure

7 Closing remarks

Classification of the inventories of elements at risk is an important step in seismic risk analysis for appropriate identification of damageability characteristics of the exposed stock and for uniform interpretation of results. The classification systems used to define inventories should reflect seismic resistance and response characteristics of an element in particular and of a system in general. This is achieved by categorising the elements at risk on the basis of pre-defined typologies for which certain features such as structural, material and geometrical characteristics, seismic resistant features as well as the inter-regional differences in construction practices are considered. Typology definitions of systems and their sub-components should also allow taking into account inter- and intra-dependencies for the purpose of systemic vulnerability evaluation. As being the first time for dealing with systemic seismic vulnerability and risk assessment in Europe, SYNER-G project aimed at providing unified/harmonised typology definitions for the European physical elements at risk. A comprehensive summary of literature review on the existing taxonomies were provided in this report. The identified main typologies and the classification of the systems and their sub-components, i.e. SYNER-G taxonomies, for Buildings, Utility Networks, Transportation Infrastructures and Critical Facilities were presented.

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European Commission
EUR 25883 EN– Joint Research Centre – Institute for the Protection and Security of the Citizen

Title: Guidelines for typology definition of European physical assets for earthquake risk assessment

Authors: Ufuk Hancilar, Fabio Taucer, Georgios Tsionis

Luxembourg: Publications Office of the European Union

2013 – 100 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-28973-6

doi:10.2788/68751

Abstract
It is an essential step in urban earthquake risk assessment to compile inventory databases of elements at risk and to make a classification on the basis of pre-defined typology/taxonomy definitions. Typology definitions and the classification system should reflect the vulnerability characteristics of the systems at risk, e.g. buildings, lifeline networks, transportation infrastructures, etc., as well as of their sub-components in order to ensure a uniform interpretation of data and risk analyses results. In this report, a summary of literature review of existing classification systems and taxonomies of the European physical assets at risk is provided in Chapter 2. The identified main typologies and the classification of the systems and their sub-components, i.e. SYNER-G taxonomies, for Buildings, Utility Networks, Transportation Infrastructures and Critical Facilities are presented in Chapters 3, 4, 5 and 6, respectively.

LB-NA-25883-EN-N

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ISBN 978-92-79-28973-6

9 789279 289736