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REVIEW ARTICLE

Perspectives on global dynamic exposure modelling for geo-risk assessment

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Abstract The need for a global approach to natural hazard and risk assessment is becoming increasingly apparent to the disaster risk reduction community. Different natural (e.g. earthquakes, tsunamis, tornadoes) and anthropogenic (e.g. industrial accidents) hazards threaten millions of people every day all over the world. Yet, while hazards can be so different from each other, the exposed assets are mostly the same: populations, buildings, infrastructure and the environment. Exposure should be regarded as a dynamic process, as best exemplified by rapid urbanization, depopulation of rural areas and all of the changes associated with the actual evolution of the settlements themselves. The challenge is thus to find innovative, efficient methods to collect, organize, store and communicate exposure data on a global scale, while also accounting for its inherent spatio-temporal dynamics. The aim of this paper is to assess the challenge of implementing an exposure model at a global scale, suitable for different geo-hazards within a dynamic and scalable framework. In this context, emerging technologies, from remote sensing to crowd-sourcing, are assessed for their usability in exposure modelling and a road map is laid out towards a global exposure model that will continuously evolve over time by the continuous input and updating of data, including the consideration of uncertainties. Such an exposure model would lay the basis for global vulnerability and risk assessments by providing reliable, standardized information on the exposed assets across a range of different hazards.

Keywords Exposure · Global exposure · Natural hazards · Risk assessment · Remote sensing · Crowd-sourcing · Uncertainty

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1 Introduction

Even a cursory glance at the available statistics on the occurrence of natural disasters around the world (Fig. 1) highlights the extent of their impact. Between 1994 and 2014, a total of more than 3 billion people worldwide were affected by disasters and an estimated USD 2 trillion of damage was sustained (Guha-Saphir 2015; Guha-Saphir et al. 2015). Such figures will probably worsen in the future, considering that more than half of the population of the Earth currently lives in cities, and by 2050 this proportion is expected to exceed 66 % (United Nations 2014), leading to the ever-increasing concentration of people, infrastructure, economic activities and cultural assets (Bilham 2009). Natural catastrophes moreover tend to exact a significant toll in human lives in less developed countries (e.g. Haiti earthquake 2010), while in more developed countries the impact is increasingly shifted towards the financial side (e.g. Tohoku earthquake and tsunami 2011). Given the increasing interdependencies between economies and societies, natural disasters show no respect for national boarders, hence calling for a global perspective on risk assessment (see also World Bank 2013, Chapter 8).

Risk is generally treated as a function of three components: hazard, the actual event of concern, whether it be natural (e.g. earthquakes), anthropogenic (e.g. industrial accident) or a combination of the two (e.g. the Fukushima nuclear disaster); vulnerability, meaning how susceptible a population, asset or structure is to the loading imposed upon it by the hazardous event, and the theme of this work, exposure. Exposure refers to the compilation of all the elements (people, property, systems, societal functions, the economy, traditional and cultural heritage and the environment) present in hazard zones that are potentially subject to losses (e.g. UN-ISDR 2009), where a given element may be exposed to one or more hazards.

The purpose of this paper is to engage with the perspective realization of a harmonized model providing a globally consistent description of exposure data. This does not

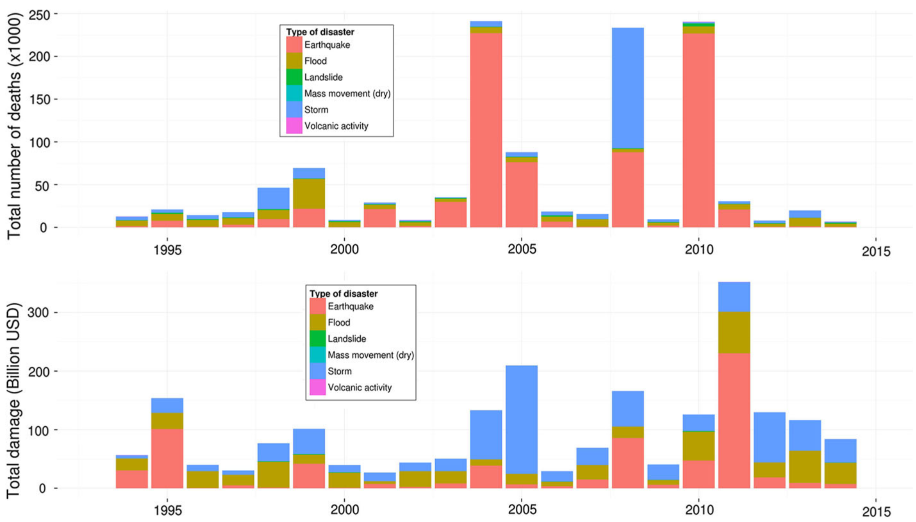

Fig. 1 Total number of deaths (*upper*) and total economic damage (*lower*) caused by reported natural disasters between 1994 and 2014. *Source* EM-DAT (Guha-Saphir et al. 2015)

necessarily imply global coverage, which is to be considered a long-term objective, but in general aim at the wide-scale, transboundary assessment of risk arising from concurrent geo-hazards in a standardized way, that would be beneficial in many ways. For instance, economically developing regions, where information on population assets and infrastructure exposed to geo-hazards is often incomplete and unreliable, could take advantage of a set of transparent and shared standards, clear methodologies and possibly freely available tools (see for instance, Wieland et al. 2015, for a discussion on regional exposure harmonization). Globally consistent exposure data would allow international organizations to reliably estimate losses in case of major disasters, thus optimizing the prompt provision of aid and other coping support. Also, international financial support measures, such as pooling risk across countries, would benefit from a reliable quantification of risk and the anticipated wide-scope impact of natural hazards on society and the economy.

A dynamic exposure model would be useful for regions that are experiencing rapid social and economic change, emphasizing the importance of capturing the dynamics by which exposure evolves over time. Unplanned urbanization, urban sprawling, abrupt demographic changes and modifications to building practices can considerably alter the type and spatial distribution of exposure, therefore, contributing to modifying the expected risk over a relatively short period of time (i.e. months, years).

Since keeping pace with exposure dynamics is difficult, it is of paramount importance to be able to assess and communicate the reliability of the exposure data by quantifying the associated uncertainties and its spatial distribution. Coupled with this is the need to make such data (and their resulting products) available to those end-users, stakeholders and decision-makers in a manner that is useful to their needs and readily understandable. Tackling these issues over wide spatial scales is undoubtedly a challenge, but it would also set an important milestone in improving risk awareness and in providing to policy makers and risk practitioners critical information to allow them to undertake informed and efficient risk-mitigation actions.

This paper focuses on the four main tasks of *describing and storing, collecting, validating* and *communicating* exposure data globally. It also considers the emergence of relevant data collection methodologies ranging from remote sensing to crowd-sourcing. These tasks, sketched out in Fig. 2, encompass several topics of interest which will be addressed in this work. Given the breadth of the area, an exhaustive review of the individual topics is beyond the scope of this paper. Nevertheless, with this work we intend to provide some basis to foster an open, cross-disciplinary discussion on the scientific, technological and cultural challenges related to the implementation of global exposure models.

Alongside infrastructure, buildings constitute one of the most important physical components of exposure, determining the functional, morphological and socio-economic structure of most settlements. Currently, there is a severe lack of relevant data describing the housing stock, such as its structure (e.g. shape, age, structural components and materials), parameters of use (e.g. number of households and resident population) and dynamics (e.g. demolition/collapse, new construction, retrofitting, structural modifications). Throughout this paper, we will mainly focus on housing stock, although we will also mention human exposure, which is an essential component when considering losses (i.e. casualties).

However, particular attention should be devoted considering infrastructure other than buildings. On the one hand, they are—at a basic level—conceptually representable by their geometry and a set of attributes, and therefore most of the following considerations apply. On the other hand, the modelling of infrastructure systems exposure should include the

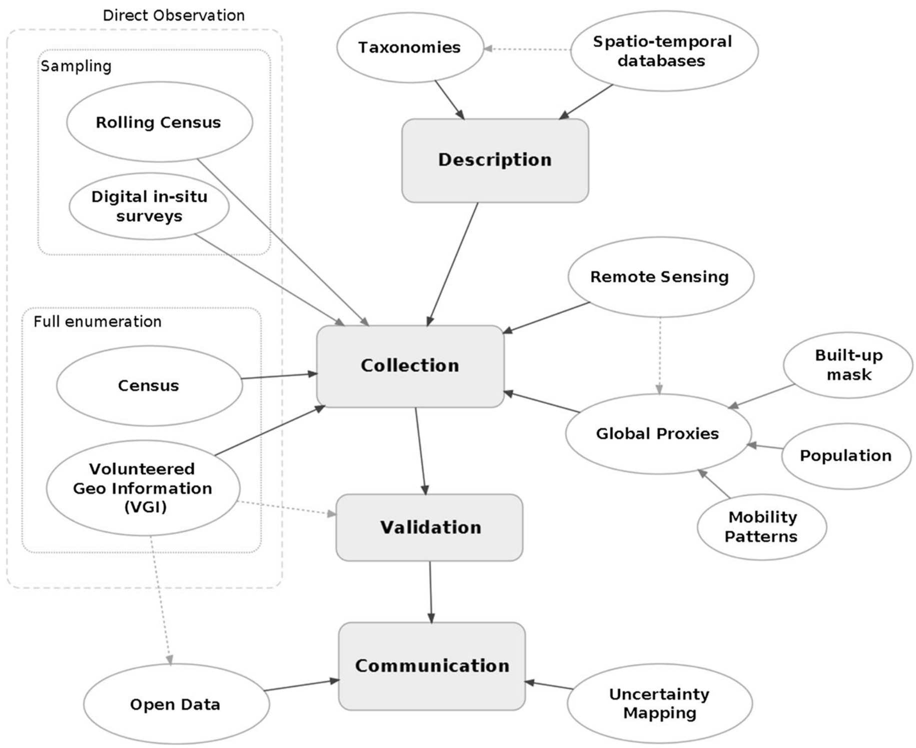

Fig. 2 Main tasks (in *grey*) and related methodologies (as discussed in this paper) that are considered relevant for a global assessment of exposed assets

mapping of the functional interdependence since the systemic impact of damage to infrastructure caused by natural disasters is usually much higher than the direct one (that is, the direct cost of repairing the infrastructure versus the indirect costs arising from their loss, see e.g. Hallegatte and Przyluski 2010).

2 State of the art

Several international initiatives have and are tackling the issue of collecting and mapping geo-hazards and related risk from a global perspective. In most cases, a stronger emphasis was given to the geographical distribution of individual hazards and their estimated rate or intensity as the main impacting factor (Alexander 2006; Dilley 2005). Efforts aiming at providing useful global models have given rise to freely available, web-based databases, ranging from Preview, started by the UNEP in 1999 (UNEP 2000), to the most recent Global Assessment Report (GAR) Risk Data Platform (GAR-2015),[1] each acting as a collator of the different types of data and models representing geophysical and meteorological risks.

1 www.preventionweb.net/english/hyogo/gar/2015.

Considering databases that specifically include physical exposure information, some of the most promising include the US Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER, Wald et al. 2008), the Global Exposure Database for GAR 2015 (GEG-15) and the Global Exposure Database for the Global Earthquake Model (GED4GEM). GEG-15 (De Bono and Chatenoux 2014) aims to create an open global building and population inventory suitable mainly for the probabilistic risk modelling of earthquakes and cyclones using the CAPRA platform[2] (Cardona et al. 2012). It includes building-type classifications for different size categories of settlements as developed by the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) (Wyss et al. 2013). The GED4GEM (Dell'Acqua et al. 2012) project aims to create an open homogenized database of the global building stock and population distribution, containing spatial, structural and occupancy-related information at different scales as input to the Global Earthquake Model[3] (GEM) risk platform OpenQuake (Pagani et al. 2014). GED4GEM uses building-type classifications following a standard taxonomy and a multi-scale database structure that provides information on buildings and population from the country scale down to the per-building scale. The initial version of GED4GEM contains aggregate information on population, built-up area and reconstruction cost of residential and non-residential buildings at 1-km resolution. Detailed data sets on single buildings will over time be integrated for selected areas, the number of which growing as more information comes available.

3 Describing and storing exposure data

Reliable information on existing physical exposure is often missing or incomplete and only a few examples of national exposure databases of buildings and infrastructure exist, such as in Turkey, Australia and New Zealand (see for instance, Dunford et al. 2014). Generally, it is mainly human exposure data that have been aggregated, since most countries have already developed their own National Statistical Classifications (NSC) to classify population information in a systematic manner. In order to achieve comparability, International Statistical Classifications (ISC, see Hoffmann and Chamie 1999) have been produced by international agreements among national authorities responsible for statistics in different fields. Compared to NSC, the ISC requires approval by the United Nations Statistical Commission (UNSC) or another intergovernmental body, depending on the subject area (Hoffmann and Chamie 1999). A start has been made to overcome the general lack of physical exposure data, to integrate it with human exposure information and to harmonize different existing data sets at a global scale with the aforementioned global exposure databases that are published within GAR15 (De Bono and Chatenoux 2014) and the GEM initiative (Dell'Acqua et al. 2012). These databases aim to provide information on population and buildings, along with their structural properties on a global scale, while using unifying taxonomies. In the following, the elements and considerations that are deemed to be important for describing and storing global and dynamic exposure data are elaborated upon.

[2] www.ecapra.org.

[3] www.globalquakemodel.org.

3.1 Ontologies and taxonomies

In information science, an ontology represents a domain of knowledge as a set of concepts, using a shared vocabulary, to denote the types, properties and interrelationships of those concepts (Gruber 1993). The unambiguous classification of an exhaustive set of objects defining the ontology is called a taxonomy. Given the complex elements composing the physical exposure of the built human environment (for instance, the structural components of a building), a clearly defined ontology that also accounts for the functional relationships between these elements would contribute significantly to overcoming possible misunderstandings among data collectors and analysts, especially at transnational and global scales.

The preparation of a taxonomy, or classification, involves the creation of an exhaustive and structured set of mutually exclusive and well-described attributes, which can be structured hierarchically or faceted, and encoded in numerical or alphabetical codes (Hoffmann and Chamie 1999). A taxonomy suitable for describing global exposure should be international in scope, detailed, collapsible, extendible, user-friendly and applicable to different types of exposed assets and hazard types (Brzev et al. 2013). The harmonization of information between classification schemes or taxonomies is of particular importance in order to be able to combine or compare data that have been collected about different populations, or over different time periods, and which may potentially have involved different data collection methods and/or spatial units. Harmonization can be achieved by applying consistent standards and taxonomies across assorted data sets and by using a common ontology. Also, the provision of dictionaries linking the categories of different taxonomies would streamline the process (Hoffmann and Chamie 1999).

3.2 Structural taxonomies

Despite the availability of national and international statistical databases that provide socio-economic or census-related exposure information, data sets and analysis tools specifically for measuring structural—potentially hazard-dependent—aspects of exposure are often not available. Within the earthquake engineering community, building codes have been developed in many countries of the world in order to define guidelines and rules for the construction of buildings, including seismic resistant construction practices [e.g. National Building Code of Canada (NRC 2010), Eurocode (Bisch et al. 2012)].

Although the practice of designing, approving and applying building codes varies considerably between countries, several structural taxonomies have been developed in order to classify and characterize building inventories in standardized and comparable ways. Widely used structural taxonomies include ATC-13 (Applied Technology Council (ATC) 1985), European Macroseismic Scale 1998 (EMS-98, Grünthal et al. 1998), HAZUS (FEMA 2003), PAGER-STR (PAGER structural taxonomy, Jaiswal et al. 2010) and the GEM classification (Brzev et al. 2013). ATC-13 provides a comprehensive classification of structures and related seismic vulnerability functions for 78 classes of Californian (USA) industrial, commercial, residential, utility and transportation structures, including 40 categories of buildings. ATC-13 has continued to be employed, with minor modifications (Applied Technology Council (ATC) 1997). The European Macroseismic Scale (EMS) is based on the earlier MSK-64 scale, which was widely used in Europe for 30 years. EMS-98 is intended primarily for the estimation of damage intensity after an earthquake. Its simple structure consists of only 15 structure types, which has proved useful for assessing the vulnerability range of buildings at the pre-event stage. However, most of the structural definitions are very broad and, moreover, they are region-dependent. HAZUS, developed by the Federal Emergency Mapping Agency (FEMA), is also a US-specific taxonomy; however, with 36 structural categories, it is considerably more detailed. PAGER-STR provides a taxonomy of global building types for use in near-real-time post-earthquake loss estimation and pre-earthquake risk analysis for the PAGER program (Wald et al. 2008). The PAGER-STR taxonomy captures most of the key structural attributes that affect seismic performance. The taxonomy is collapsible and international in scope, aiming at including a wide range of structural types. However, due to its hierarchical structure, the taxonomy is difficult to extend. A recently established structural taxonomy which follows the concept of a faceted taxonomy (Broughton 2006) is the GEM building taxonomy (Brzev et al. 2012). A facet is an attribute of a building under consideration that is clearly defined, mutually exclusive and collectively exhaustive. In comparison with traditional (hierarchical) taxonomies, where the data is organized in a tree-like structure, the hierarchy of classes in faceted taxonomies is not fixed and can be changed. Faceted taxonomies allow one to navigate information along multiple paths corresponding to different arrangements of the facets and items can be described in more than one dimension.

A structural taxonomy, however, is just one of several taxonomies that together contain all the relevant data about a particular exposed asset. For example, other taxonomies, such as the non-structural taxonomy proposed by Porter (2005), need to cover issues related to general building information and non-structural elements, or the omni-comprehensive ICS (International Organization for Standardization 2005) could be used to describe the entire urban ecosystem the buildings are embedded in. However, as yet, a unified, comprehensive and flexible description of exposure to the authors' best knowledge is still missing.

3.3 Spatio-temporal databases

Taxonomy is closely linked to data storage, since it should be transferable to a clean and flexible data model. Data models define object data types, relationships, operations and rules to maintain database integrity. In order to consider the time dependency of exposed assets, a data model must allow for spatial, temporal and spatio-temporal queries to be performed. A dynamic exposure database should be able to track an object's evolution over space and time. Earlier works in the direction of spatio-temporal database design were characterized by separate research in either the spatial (Paredaens et al. 1994) or temporal (Snodgrass 1992) domains. Since the emergence of technologies, in terms of both the collection and storage of information that allow combined spatio-temporal databases, numerous approaches have been proposed for data modelling and a number of reviews have categorized and compared the existing work (e.g. Abraham and Roddick 1999; Sellis 1999; Peuquet 2001; Pelekis et al. 2004). A specific application of spatio-temporal databases within the context of exposure assessment is, however, yet to be undertaken.

3.4 Multi-hazard exposure description

It is important to stress that the vulnerability of the built structures (that is, their propensity to be damaged) depends on the particular geo-hazard of interest. On the other hand, the description of the built-up structures which compose the exposure model can include attributes that are independent of any particular hazard, such as their position, the footprint geometry or the occupancy type. Other attributes can be relevant for different hazards (e.g. the number and size of wall openings provide useful information for both floods and earthquake vulnerability). For instance, Blanco-Vogt and Schanze (2014) propose a taxonomic approach to flood exposure characterization, which is strongly based on the GEM taxonomy developed by Brzev et al. (2012, 2013) for earthquakes. Bautista et al. (2014) describes an integrated exposure model used to analyse the risk from floods, severe wind and earthquakes (which may occur concurrently) in the densely populated Greater Manila Metropolitan Area (GMMA). Likewise, the HAZUS Multi-Hazard (HAZUS-MH[4]) platform, also developed by FEMA, for estimating losses related to floods, earthquakes and hurricanes, largely relies upon a common inventory of building stock, demographics, utilities and transportation lifelines.

A multi-hazard taxonomy is therefore possible, combining structural and non-structural attributes, which over different extents contribute to specifying vulnerability with respect to different hazards. For instance, the type of lateral load resisting system will have a critical role in constraining the seismic performance of a building, while its roof type and material would play a bigger role in defining the structure's performance in case of storms. Extending the scope of a taxonomy by considering a larger set of attributes would have multi-fold advantages:

- a more complete structural and functional description of the assets;
- a harmonized approach to taxonomic description would be beneficial for a more holistic consideration of risk arising from multiple natural hazards;
- a more thorough description of buildings' structural attributes would increase the chances of exploiting data mining and other statistical inference approaches to fill gaps in the data's availability. Dependency relationships among attributes could be estimated empirically and would allow for a more reliable probabilistic description of exposure;
- in situ collection of exposure data would be more efficient, since most of the burden associated with the implementation of surveys does not depend on the particular attributes recorded.

4 Collection and assessment of exposure data

Several alternative or complementary approaches have been proposed to collect exposure-related data. In the following, we will introduce them within the perspective of a global dynamic assessment, and how they may potentially lead to global databases.

4.1 Remote sensing

Remote sensing is generally defined as the process of acquiring information about an object without any physical contact. In the framework of this paper, the term refers to the use of Earth Observation Satellites (EOS) or other aerial sensor technologies (such as drones) able to infer information by means of propagated signals (usually electromagnetic radiation at different wavelengths, ranging from radio waves to visible light to ultraviolet coherent radiation). This technology can be either active, when signals are also emitted by the sensors platforms, or passive, when the sensors just record the signals emitted by other sources (e.g. the light from the Sun). EOS observations offer the advantage of global coverage and a temporal resolution adequate for identifying urban changes (Eguchi et al.

[4] www.fema.gov/hazus.

2008; Müller et al. 2011). Remote sensing is increasingly being recognized as an important technique for deriving exposure characteristics for rapid assessment over various scales (Geiß and Taubenböck 2013). This includes the direct and indirect assessment of exposure related to the built environment. In particular, in this section we refer to the context of the largely automatized processing of remotely sensed data which aims to extract information over wide scales in an unsupervised way. Manual approaches exploiting remotely sensed information, such as, crowd-sourcing data collection, will be discussed in the following section.

Automated processing of very high-resolution satellite image data with spatial resolutions of 1 m and finer are mainly used for a full enumeration of exposed assets and their geometric characterization. On the level of individual buildings, exposure attributes that can be extracted from EOS data include building location and footprint, shape irregularities, heights, roof materials, location (e.g. Sarabandi et al. 2008; Geiß et al. 2014; Wieland and Pittore 2014). However, studies using purely very high-resolution earth observation data still show limitations in terms of covering large areas (with possible global coverage) due to data availability, processing requirements or limited levels of process automation.

Medium-resolution satellite image data with a spatial resolution of about 10–60 m on the contrary are used to derive proxies (land use/land cover) that can support an indirect characterization of exposure (built-up areas, population) over large (possibly global) areas with comparatively little time and resources required. In addition to global built-up area products (see Sects. 4.3.1 and 4.3.2 for more details), the period of construction can also be estimated by using multi-temporal satellite images, such as the LANDSAT data archive (dating back until 1972) at an aggregated urban block level. Some studies also derive aggregated urban structure zones from medium- or very high-resolution satellite images that can provide information about the spatial distribution of predominant building types and define a spatial stratification of the urban environment into meaningful structural zones. Such a zonation can be used as the basis for the aggregation or disaggregation of exposure data and for defining a sampling scheme for in situ data collection (Wieland et al. 2012a). The forthcoming availability of higher-grade, global imagery from the ESA Sentinel-2 mission[5] is expected to further extend the potential of multi-spectral observation.

In terms of active remote sensing, the airborne Synthetic Aperture Radar (SAR) technology is increasingly being considered to infer information about natural and man-made structures on Earth (as well as on other planets). This technology is based on the emission, and later recording by a moving sensor, of a pulse of radio waves which is reflected by physical (solid or liquid) objects. Applications of this type of remote sensing have been recently proposed at very different scales, from the global mapping of the urban footprint extent (see also Sect. 4.3.2), to the characterization of the structure of urban areas (Aoki et al. 1999), to the estimation of buildings' height (Marconcini et al. 2014; Liu et al. 2015).

Remote sensing studies also show capabilities for mapping human exposure. A commonly used strategy to derive global population distribution at a subdistrict resolution of 1 km and finer is based on the analysis of spatial data, including EOS data, and dasymetric mapping to disaggregate census counts within an administrative boundary (Bhaduri et al. 2007). In addition, approaches that use a spatial extrapolation of punctual population data have been presented in the literature (e.g. Taubenböck et al. 2007). Aubrecht et al. (2013) provides an overview of the different approaches used to derive spatially refined population distributions at different scales.

[5] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/overview.

It should be noted, however, that satellite remote sensing approaches only provide exposure information that can be inferred from the top view. Considering the case of building stock, in order to provide a fully fledged description of exposure, the analysis of the lateral structure and façades of buildings also has to be carried out. Oblique aerial imaging, providing a lateral perspective of the buildings, therefore disclosing details of at least one of the façades, can be used to partly overcome this issue. Furthermore, in general, remote sensing should be efficiently combined with direct observation methods (e.g. Pittore and Wieland 2013; Wieland et al. 2012b). Several approaches for direct data collection are discussed in the next section.

4.2 Direct observation

Direct observation refers to the manual collection of exposure information, as opposed to the automatized processing of remote sensing data. Direct observation can be either realized in situ, that is by having an operator physically moving closer to the structure to be examined, or remotely, for instance exploiting high-resolution imagery from satellites or from street-view cameras. Two principle strategies for direct observation can be distinguished: full enumeration and statistical sampling. Full enumeration refers to the detection and definition of each exposed asset within a study area. It can therefore potentially achieve high levels of accuracy and detail; however, usually it requires a great deal of work and involves greater investment in terms of time and resources. It may in turn be subdivided into *census methods*, and so-called *volunteered geographical information* procedures. Statistical sampling on the other hand has the advantage that only small subset areas need to be analysed in detail to estimate summary statistics for a larger area of interest, or for a well-defined strata if a stratified sampling is used.

4.2.1 Full enumeration

Census methods are the elective reference for national demographic data and the most known approach based on direct collection. Globally monitored census data had not been available until the World Population Prospects estimates (United Nations, Department of Economic and Social Affairs, Population Division 2014). National censuses have proved inefficient (being mostly concerned with the full enumeration of people and housing) as they rely on resource-intensive methodologies for data collection. In 2005, for example, at the end of the first year of the 2010 census round, only an estimated 5.5 % of the world's population had been enumerated. By the end of 2009, this proportion had increased to 21 % while by the end of the census round in 2014, more than 96 % of the world population is expected to be enumerated (the most recent report was provided mid-2015). Notably, an increasing number of countries are adopting self-enumeration schemes based on web technologies (United Nations, Department of Economic and Social Affairs, Population Division 2014).

Volunteered Geographical Information (VGI) is the result of the joint efforts of many individuals who voluntarily, and usually with no direct economic reward, collect and submit data observed either on the ground or by using support imagery. This process can be further distinguished between structured and unstructured VGI. Unstructured VGI includes spontaneous, non-authoritative initiatives (authoritative refers hereafter to initiatives proceeding from official sources, e.g. governmental) such as OpenStreetMap,[6] a pure bottom-

[6] www.openstreetmap.org/.

up approach where the collection activity is not systematic and is left to the interests and motivation of the participants (Coleman et al. 2009). Structured VGI, on the other hand, still builds on volunteering citizens, but has an authoritative component that aims at focusing the efforts towards specific tasks and objectives (Chapman 2012). Unstructured VGI can be regarded as a continuous, low-cost source of useful information, although consistent efforts must be foreseen for harvesting and restructuring the information, while the coverage and data quality are not guaranteed. Although structured VGI requires resources to coordinate the collection activity, it provides better control of the resulting data and also entails direct contact with the volunteers (usually part of a local community), thus further helping to improve risk awareness. VGI in fact represents a potential opportunity for large mapping organizations as a complementary source of information for authoritative databases, but strongly relies on the commitment and motivation of the individual users (Coleman et al. 2009). A system of incentives has therefore to be devised to foster and coordinate the community efforts. For instance, rewarding the sharing of professional experience would foster the involvement of skilled individuals, such as structural engineers or civil protection volunteers.

4.2.2 Statistical sampling

Census methodologies are progressively changing from full enumeration to advanced sampling and statistical modelling (United Nations and Statistical Division 2008). By using a *rolling census* approach, for instance, the frequency of updates would be annual, compared with the 5–10 years of a standard enumeration census as referred to above (United Nations and Statistical Division 2008). The rolling census approach involves the full enumeration of small settlements and the continuous sampling of the most populated ones (around 10 % every year). By reducing the burden required by traditional methodologies, the rolling census allows the integration of highly complex collection and modelling techniques into an efficient sampling framework.

Digital in situ *data capturing systems* have recently been proposed as time- and cost-effective supplements to commonly used in situ screening techniques (FEMA 154 2002); Applied Technology Council (ATC) 1985). Womble et al. (2006) introduced the VIEWS system, a notebook-based field data collection system that integrates real-time GPS tracking with map layers and remote sensing imagery in combination with a digital video system to collect geo-referenced in situ data. The Inventory Data Capture Tools initiative of GEM (GEM-IDCT) provides a suite of free and open-source (FOSS) tools to generate exposure information from remote sensing and field observations (Bevington et al. 2012). Several initiatives have also started proposing guidelines for efficient sampling and for the statistical inference of structural parameters. For instance, Sarabandi et al. (2008) employs multinomial logistic regression to statistically infer marginal probability distributions of the structural type and occupancy of buildings. Remotely sensed and in situ observations can also be efficiently combined. Pittore and Wieland (2013), for instance, employed satellite remote sensing and in situ omni-directional imaging within the framework of an integrated sampling scheme to infer specific, scale-dependent information about an exposed building stock.

4.3 Indirect characterization of exposure

Often, the amount, spatial coverage and/or the quality of the information collected on the ground are insufficient for populating global exposure databases. It is then customary to rely on several indicators, called proxies, to infer further information about the objects of interest.

4.3.1 Population

A global distribution of population data, in terms of counts or density per unit area, is considered the primary source of information for exposure assessment. In particular, this approach copes well with empirical models of vulnerability, where direct estimates of losses are obtained by considering past events, and where the main loss metrics accounts for fatalities (Jaiswal et al. 2010). Many global models use human exposure as a basic ingredient to define a more refined “hazard-specific exposure” (Dilley 2005; Peduzzi et al. 2009; Allen et al. 2009).

Global models of human exposure mostly describe population data either on a regular grid or considering specific settlement coordinates or geographical boundaries. A widely used product is the Gridded Population of the World (GPWv3, see Tobler et al. 1997; Doxsey-Whitfield et al. 2015), a gridded data set that provides a spatially disaggregated population layer constructed from national or subnational input units of varying resolutions. Population estimates are provided for the years 1990, 1995 and 2000 and projected to 2005, 2010 and 2015. Other global human exposure models include LandScan (Bhaduri et al. 2007) and WorldPop (see e.g. Sorichetta et al. 2015). These models are based on the integration of several information sources, including census and remote sensing, and are affected by a significant range of uncertainties (Potere et al. 2009; Mondal and Tatem 2012).

4.3.2 Built-up area and land-cover products

A further step with respect to population distribution is the spatial delineation of built-up areas. This can be considered as an intermediate description of exposure, where the characterization of the built-up environment is improved upon with respect to a simple population layer. Spatial descriptions of built-up areas can be used for downscaling, or disaggregating (that is, obtaining higher-resolution spatial representations) information about population and building stock, therefore increasing the spatial resolution of the resulting estimates, for instance, in order to match the resolution of available hazard data (see e.g. World Bank 2012, p. 170; Aubrecht et al. 2013).

Examples of global built-up area products include the Global Rural–Urban Mapping Project[7] (GRUMPv1, see Balk et al. 2005), the Global Human Settlement Layer[8] (GHSL, Pesaresi et al. 2013) and the Global Urban Footprint (GUF, Esch et al. 2010). The GHSL is being developed and maintained by the Joint Research Centre[9] (JRC) of the European Commission. GHSL integrates several available sources about human settlements with information extracted from multi-spectral satellite images. The underlying automatic image information extraction work-flow makes use of multi-resolution (0.5–10 m), multi-platform, multi-sensor (pan, multi-spectral) and multi-temporal satellite image data (Pesaresi et al. 2013). The GUF is developed by the German Aerospace Center[10] (DLR) and is

[7] sedac.ciesin.columbia.edu/data/collection/grump-v1.

[8] ghslsys.jrc.ec.europa.eu/.

[9] ec.europa.eu/jrc/en/institutes/ipsc.

[10] www.dlr.de/dlr.

based on the analysis of SAR and optical satellite data. The project intends to cover the extents of the large urbanized areas of mega cities at four time steps: 1975, 1990, 2000 and 2010 (Taubenböck et al. 2012). Both projects are in progress, and no official information is currently available on the expected release date and sharing policy.

At higher scales, land-use/land-cover products can also be considered. These products, such as the CORINE Land Cover in Europe (Bossard et al. 2000), can provide high-resolution spatial and thematic description of the urban fabric, therefore further improving the disaggregation processes described above.

4.3.3 Mobility patterns

Short-term (daily and weekly) variations in exposure refer to the temporal change in the occupancy of buildings due to patterns of social mobility. This temporal variation can strongly affect the quantification of human exposure in cases of extreme natural events with rapid onsets, such as earthquakes, landslides or tsunamis. Models of building occupancy considering daily patterns have already been proposed (Coburn and Spence 1992, 2002), but collecting the necessary data to update such models can be very time and resource intensive. A promising approach to derive mobility patterns is based on the analysis of cellular phone data provided by telephone companies (Wesolowski et al. 2013; Lu et al. 2013).

4.3.4 Multi-source integration

Due to the increasingly large variety of possible exposure information sources, the issue of the need for the flexible integration of existing information from different acquisition techniques, scales and accuracies in order to not discard available information needs to be confronted. An example for a probabilistic information integration approach is given in Pittore and Wieland (2013), which is based on Bayesian networks, and allows for the sound treatment of uncertainties and for the seamless merging of different data sources, including legacy data, expert judgement and data mining-based inferences.

5 Validation

The aim of validation is to provide a reliable assessment of the quality of the information collected, integrated or modelled (e.g. buildings inventory, population distribution, land-use/land-cover or infrastructure atlas). Validation provides (often non-technical) end-users with a high level of assurance that the products being offered or used meet the planned standards with the expected (or required) accuracy, even when no specific standards were set (Broglia et al. 2010). Two essential requisites for validation are:

1. It must be producer-independent,
2. It must be considered a (potentially continuous) process, based on specific methods delivering reproducible results.

Validation of exposure models should be always carefully considered, in order to account for the different uncertainties in the subsequent vulnerability and risk assessment phases. Unfortunately, the validation of exposure data is often overlooked and its contribution to the overall risk analysis is consequently underestimated.

5.1 Measuring uncertainty

Geo-data quality specification guidelines are provided by international standardization bodies such as ISO/TC 211[11] (geographical information/geomatics). According to the ISO standards 19113 (geographical information—quality principles, 2002) and 19157 (geographical information—data quality, 2013), data quality includes different elements, including accuracy, resolution of data, integrity, logical consistency and completeness (Kresse and Fadaie 2004). Such uncertainty indicators should be estimated directly by the model's validation stage.

Uncertainty should provide information on the expected model completeness and accuracy and also on their spatial distribution. This is particularly important considering wide-scoped geographical models, at regional and global scales, where significant heterogeneity of the model's quality is to be expected. Unfortunately, the spatial localization of uncertainty is primarily related to the availability of the reference (ground-truth) data the validation is based upon. An indirect estimation of uncertainty can thus be obtained by statistical inference on aggregated units with similar characteristics, or based on suitable proxies. For instance, completeness of a building stock's geometric description could be approximated by the comparison between the density of available buildings' coordinates and the spatial density of the population, which in turn can be estimated at a global scale as mentioned in Sect. 4.2.

5.2 Sources of uncertainty

Validation must account for different types of uncertainties. We have to make a first distinction between area- and feature-based exposure models. Area-based models refer to statistical descriptions of exposure attributes aggregated over geographical areas. The collection of reference areas can be regularly arranged, as in the case of gridded models, or can be composed of independent, non-overlapping polygons. The feature-based models refer to collections of individual entities (e.g. buildings), each with a possibly different set of attributes. The aggregated models are widely used where no specific detailed information is consistently available in the area of interest. In this case, the uncertainty of the model mainly refers to the reliability of the statistical assumptions and input data used to generate the aggregated descriptions. In many cases, information from sparse, feature-based models can contribute to the generation of area-based models. In the case of feature-based models, we can mention three measures of the information quality: positional accuracy, thematic accuracy and completeness (Gahegan and Ehlers 2000). The positional and thematic accuracies can be related to the accuracy of the measurement devices (e.g. GPS), to the observer bias (for instance, the interpretations made by a human operator) or on the method of data processing. Completeness can be affected by the sampling methodologies or by a lack of resources for proper (meaning sufficiently extensive) data collection. A further source of uncertainty is related to the intrinsic limitation of the taxonomy in capturing both the within-country and country-to-country variability of the building construction types. Region-specific extensions of the taxonomy able to capture "local" construction practices, materials or other possibly relevant attributes would provide a practical and scalable solution. Increasing the number of specific attributes might negatively affect the generalization ability of the model at the global level, but it would also contribute to mitigate the risk of misidentification of the critical drivers of

[11] www.isotc211.org/.

vulnerability, and would provide local stakeholders with a more useful and relevant tool, in turn increasing their motivation to adopt widely recognized standards.

5.3 Time dependency of uncertainty

The uncertainty of a wide-scale exposure representation is inevitably bound to change over time. If, on the one hand, the exposed assets continuously change—following trends related to economy, climate, culture and disasters—also the underlying data sets that describe the exposure evolve in parallel. As new information is made available, so also are the associated uncertainties subject to change. Uncertainty can locally decrease when better quality information becomes available and is integrated into the exposure model. However, it can also increase when changes are not adequately being kept track of in the exposure model and information becomes obsolete. This can, for example, happen when exposed assets change significantly, but these changes are not being recorded in the exposure model. Quantification of such time-dependent uncertainty changes, however, implies that information obsoleteness can be detected and the relative potential improvement of the not-integrated new information with respect to the existing information in the exposure model can be measured. These intertwined dynamics are difficult to capture, especially at the global scale, where abrupt spatio-temporal changes in the quality and availability of the data have to be consistently harmonized. Hence, the validation methodologies should account for the evolutionary nature of the exposure, for instance, by considering iterated sampling. The frequency and extent of updating can be driven by the underlying uncertainty and be triggered by a set of performance indicators. For instance, if significant changes (e.g. due to rapid urbanization) are detected using remote sensing approaches, a local update can be undertaken. Abrupt modifications of the exposure due to a disaster, resulting in the destruction of assets and their subsequent reconstruction, would also justify a systematic updating. In the two mentioned cases, the very same exposure updating process would provide useful insights on the temporal evolution of the vulnerability in the first case and on the efficiency of the reconstruction in the latter one.

5.4 Considering geographical scales and multiple sources

Many global databases related to exposure are based on a mixture of global and local efforts. Validation should therefore also follow such a multi-scale strategy. Two different approaches, namely quality control and statistical accuracy assessment, can be considered, which are complementary to each other. These evaluate the regional products on the one hand and the global ones on the other and provide different information (contextual and qualitative vs statistical). The classical accuracy assessment based on a sample of reference data gives a quantitative figure of the information accuracy, while the wall-to-wall quality control provides more exhaustive information on the nature of the associated errors, their location and their relationship to the spatial pattern of the original data. A good example is provided by the validation of the Global Land Cover 2000 Map (Strahler et al. 2006; Mayaux et al. 2006). Considering the GEG-15 (De Bono and Chatenoux 2014; Wyss et al. 2013), and the GED4GEM (Dell'Acqua et al. 2012), for most of the information sources, accuracy is not provided, and often the estimates are based on disaggregation of population figures which adds another contribution to the uncertainty. In both cases, no validation methodology has yet been explicitly developed.

5.5 Validation of exposure data from VGI

In the recent literature, several studies have addressed the completeness of OpenStreetMap (OSM) by comparing it with other reference data sets (Haklay 2010; Zielstra and Zipf 2010; Girres and Touya 2010; Hecht et al. 2013). These empirical studies indicate that albeit OSM's coverage and data quality is steadily increasing, and locally is comparable with authoritative sources (e.g. cadastre), the level of completeness in OSM at the regional scale is still low (for instance, <30 % in two studied regions in Germany) and shows considerable spatial variation (Hecht et al. 2013). For example, considering the actual current completion rate, a complete coverage of the considered areas in Germany would be achieved in around 9 years. Remarkably, the mentioned studies have mainly focused on completeness analysis and partly on positional accuracy. Thematic accuracy has not been analysed in detail, mostly due to the reduced amount of thematic information in OSM. The previous considerations apply in particular to the building stock, which is of particular interest for risk-related exposure modelling. However, we should remark that the level of completeness and positional accuracy of the road network in OSM is generally much higher and largely comparable with authoritative and commercial products (Ludwig et al. 2011).

5.6 Crowd-sourced collection versus crowd-sourced validation

Validation can be carried out either by comparison, using reference data from official sources, or using ground-truth data collected with adequate sampling strategies. The latter is usually resource intensive when applied to wide-scale exposure models. On the other hand, at regional and global scales, the availability of reference data, and some indication of their quality, is often very scarce. Therefore, the VGI paradigm can also be used for validation, that is, to rely on distributed, non-authoritative approaches to collecting local ground-truth information. Fritz et al. (2009), for instance, outline a project based on a global network of volunteers which collaborates through a web-validation tool to assess and improve upon the quality of global land-cover assessment.

6 Communication

In addressing the communication of physical exposure, we focus here on the visualization and dissemination phases. Visualization in this context refers to the creation and display of maps depicting the geographical distribution of exposure. Mapping a population's geographical distribution, for instance, represents one of the first visualizations of exposure information at the global scale. Using maps (which when well designed are very useful intuitive tools) to communicate exposure information can therefore greatly improve decision-makers' understanding of the subsequent vulnerability (thus risk) and can potentially allow an immediate comparison with existing geo-hazards and their extent.

6.1 Mapping global (exposure) uncertainty

Regardless of the complexity or quality of the information contained in an exposure database, decision-makers often make their decisions based on a few visual representations (including cartography, thematic and choropleth maps) which cannot capture all facets of the available knowledge, or the lack of. Mapping should thus be used to communicate the uncertainty associated with available exposure data to help practitioners to make informed and efficient decisions in the pre-event risk-mitigation stage, as well as in critical situations. Several studies (Harrower 2003; MacEachren et al. 2005; Shi 2008) have explored different approaches towards the visualization of uncertain geographical information. In general, the mentioned studies acknowledged the usefulness of portraying uncertainty for decision-making purposes, while cautioning about the end-user "learning curve" associated with depicting uncertainty on maps.

Considering exposure databases on a global scale, a particular effort should be made to find optimal ways of capturing and communicating uncertainties in a dynamic fashion (e.g. accounting for the spatio-temporal evolution of uncertainty). In particular, thematic accuracy, completeness and data vintage should be carefully depicted, in consideration of the heterogeneity of sources and the fragmentation of the geographical coverage.

6.2 Sharing (open) data

The dissemination of exposure data is the key to empowering end-users and communities and for allowing and encouraging risk evaluation. Many countries have stocks of data which remain largely inaccessible to interested practitioners. Many are the causes, ranging from obsolete technologies (e.g. printed archives), to bureaucratic fragmentation, to restrictive policies. As a matter of fact, only a handful of governments have the resources to integrate ancillary data with newly collected ones and produce actionable information enabling decision-makers to get ahead of the disaster cycle. Disclosing relevant data sets would possibly turn this process into a collective effort engaging not only governments, but also civil society, industry and the individuals (see World Bank 2014, for a more extensive discussion). Most of the global exposure databases covering population and other physical assets are already or will be soon available (e.g. GRUMP, LANDSCAN for population, GAR-13 (GAR-13 2013), GED4GEM for buildings), but not always with an open data sharing policy. In some cases, the data have to be bought or availability could be restrained depending on the specific aggregation level. The level and amount of information available to be disclosed can vary, depending on the particular country, and on the specific type of information. As the spatial and the thematic resolution of the data increases (for instance, allowing the vulnerability assessment of individual buildings), available information could be deemed sensitive and require access protection. Authoritative sources are expected to exert a stronger control on the availability of these high-resolution exposure data, with respect to non-authoritative ones. Even in cases of volunteered geographical information, it is possible to collect information and make it accessible to the whole community, while ensuring at the same time that more sensitive data (e.g. for security purposes) remain protected (Chapman 2012). A spatially aggregated (area-based) description, for instance, would allow a sharing of the most significant exposure (and related vulnerability) information, while masking out more sensitive details.

The dissemination of exposure data should also consider not only the informational content, but also all the meta-data necessary to encode information about the data set itself (source, vintage, accuracy, coverage). With the rise of Web2.0 applications, sharing object-oriented meta-data would complement the provision of useful data sets with a sound quality assessment and would ensure long-term sustainability of exposure information (Shi 2008).

7 Discussion

Although not exhaustive, this paper provides a compilation of critical points that should be carefully considered in future initiatives and need to be subjected to a cross-disciplinary discussion.

7.1 Description

- An important benefit of global data sets is the collection and harmonization of locally collected information. The use of standard (or widely accepted) and flexible descriptions of the exposed assets is strongly advocated. In this context, the wider use of taxonomies to classify exposed assets and ontologies to describe functions and interrelations within different exposure domains (buildings, infrastructures) is recommended.
- Several (sometimes competing) taxonomies have been suggested and are increasingly being used with good results. A harmonized, rich and flexible description of physical exposure (with a preference to it being suitable for multiple hazards) should be pursued with the widest agreement, in order to overcome cultural and linguistic barriers. However, a means of correlating and harmonizing the resulting data sets that are gained based on different taxonomies needs to be developed. The application of a set of open, interoperable standards is advocated to overcome this issue.
- Further efforts should be devoted to exploring the potential of semantic web and related resources to create dynamic "dictionaries", able to harmonize between different evolving ontologies, in particular to make use of data collected through unstructured crowd-sourcing.

7.2 Collection

- Local/regional data collection, and in particular censuses, directly or indirectly, dominates current global estimates of exposure, at least in terms of population. In the last decade, most countries have adopted modern and efficient methodologies for census implementation, therefore making it a very powerful tool to collect data related to risk mitigation in a pervasive and controlled way. It is important to acknowledge the increasing role of censuses in this framework, and to foster its further evolution, for instance, by including in household surveys a more detailed description of dwellings.
- Institutional organizations will always have a large role in supporting, and coordinating global exposure estimates, and proposing widely accepted standards. However, the collection efforts should nevertheless be integrated by the strong involvement of local communities.
- Remote sensing techniques have proved to be an increasingly useful and cost-efficient means for the preliminary assessment of exposure over wide areas. Further efforts should focus on providing simple and effective methodologies and tools to properly exploit the full potential of remote sensing and to combine it with complementary in situ data collection. This is particularly important when considering the lack of resources in many economically developing countries for conventional exposure assessment, the very countries that are in greatest need of such information.
- Particular attention should be devoted to considering authoritative versus non-authoritative data collection methodologies. The authoritative approach gives better

(more consistent quality) results at local scales, but often poses harmonization problems at cross-border/global scales (Haklay 2010). Moreover, institutional efforts focusing on the collection of exposure data are missing in many (mostly economically developing) countries. Again, this is an area where the large-scale potential offered by remote sensing may be exploited at a reasonable cost in terms of funds, time and other resources.

- Data obtained through unstructured volunteered geographical data collection (e.g. OpenStreetMap) have proved useful as complementary information sources. However, as such data are still rather sparse (with a bias towards more urban areas), they cannot substitute authoritative databases in data-rich countries, but can (and should) be efficiently integrated with other sources in developing countries, especially in urban areas.
- On the other hand, structured volunteered geographical data collection represents a promising trade-off between the authoritative and non-authoritative paradigms. It combines the advantages of in situ, community-based collection activities with higher, more formal, information quality standards and allows for a more efficient allocation of the efforts by volunteers, in line with the requirements of end-users.

7.3 Validation

- Validation should always be considered and tailored to the specific data collection methodologies. It should also be properly spaced over time to capture the evolution of the quality of exposure representation.

7.4 Communication

- With the increasing levels of complexity inherent in current and future global exposure models (from population distribution to detailed characterization of building stock), the visual mapping (and other forms of presentation) of exposed assets should be carefully addressed. In particular, the visualization of spatial, temporal and thematic accuracies should always be accounted for and presented in a manner beneficial to decision-makers.
- As the use of mapping services and collaborative platforms spreads, the communication and collection of exposure data will be increasingly intertwined. Careful communication of geographical coverage, uncertainties and the vintage (age, timing of revisiting) of data would improve participatory actions. Simple-to-use GIS-based tools would further enhance participatory planning while also favouring "learning by doing" capacity building, the latter again being of particular importance in resource limited, yet rapidly changing, developing countries.
- Openly sharing reliable exposure data at the global scale would allow a better estimation of vulnerability with respect to different geo-hazards. This would lead to the greater acceptance (and capacity) to implement multi-hazard and risk assessment frameworks, meaning the inherent consideration of the interactions between different hazards and risks at all level of the disaster risk chain, as opposed to the single-type hazard and risk viewpoint usually followed today. Such a change in paradigm would thus contribute to raising the level of awareness of the public and the relevant institutions to the importance of disaster risk reduction, its complexity, as well as the variety of tools available (at all levels of society) to mitigate against such events.

7.5 Road map towards global exposure

- Several recommendations can be further distilled and are provided to sketch a road map towards the effective implementation of a global, dynamic exposure database:
- A stronger and collaborative effort by the world's institutions active in disaster risk reduction is advocated to implement a harmonized exposure taxonomy able to encompass attributes relevant for different hazards. Such a global exposure taxonomy should be built upon open and shared standards and complemented by a comprehensive ontology.
- Rapid, large-scale data collection based on remote sensing should be fully exploited and whenever possible be complemented by information collected in situ using suitable sampling methodologies with the aim of a multi-source and multi-scale data collection framework.
- Authoritative and non-authoritative sources should be integrated in order to ensure quality standards and compliance with the disaster risk reduction purposes. Within this context, it becomes important to harvest data from crowd-sourced information (incidental data) and exploit structured VGI to augment authoritative sources and involve communities and experts, especially in data-poor countries.
- Exposure data collection should be regarded as a continuous process, given how the target information is constantly evolving in space and time.
- Data and (statistical) models have to coexist within a statistically sound framework in order to overcome the impracticality of having a complete and fully enumerated global dynamic exposure database.
- Validation and quality assessment should be carefully assessed throughout the collection-description-dissemination process.

8 Conclusions

In this paper we addressed the challenges of collecting, describing, validating and communicating exposure data (people, buildings and infrastructure) within a multi-scale, global and dynamic framework. Data sources, methodologies and experiences deemed significant were reported and discussed within the broader framework of disaster risk reduction. The range of end-users of such a global product is only limited by one's imagination. Risk reduction practitioners at all levels will have at their request the necessary information to identify where potential hotspots of risk may arise in terms of the exposed elements of society, which in some circumstances could assist in cross-border actions to improve upon response and recovery. Likewise, insurance companies can nonetheless benefit from the information made available for their own business planning. Finally, the rapid improvements in technology, as well as the increasing amounts (and quality) of data being available, both possibly within a free, open-source paradigm, would allow countries hindered by insufficient resources to still benefit from such developments.

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