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EXPOSURE, VULNERABILITIES, AND SCENARIO SEISMIC RISK ASSESSMENT FOR THE CITY OF GRANADA

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Abstract: *A model is developed for the seismic risk assessment of the city of Granada, Spain, focusing on the building stock. For its implementation, in-house software is coded in the object-oriented programming language Python. Firstly, the assets of interest, in this case the different buildings, are identified and classified according to the taxonomy of the 2020 European Seismic Risk Model, appropriately customized for the characteristics of the local stock. The exposure model is created using the geographical position of each building and aggregating them per city block. Seismic hazard is determined via the 2020 European Seismic Hazard Model. An event-based probabilistic seismic hazard approach is employed, generating a stochastic event set for a 10,000 year investigation period, together with corresponding spatially-correlated ground motion fields via the OpenQuake platform. For simplicity, a single intensity measure is employed to characterize all buildings. Suitable vulnerability functions are selected to calculate loss. Results are obtained per block for the damage of buildings in terms of assigning them to different damage states as well as defining the cost of replacement. The resulting consequences are grouped across different functions and lines of business. The focus is on offering a preliminary determination of the disruption caused by each event in support of socioeconomic impact modelling within the HYPERION EU project.*

Introduction

The city of Granada is located in one of the most seismic areas of the Iberian Peninsula, with a non-negligible number of significant earthquakes being recorded throughout the years. The city of Granada is an important cultural heritage site. It has hosted several different cultures over its lifetime, and is characterized by numerous monumental buildings in need of preservation. The EU-funded HYPERION research project (HYPERION, 2019) focuses on cities, such as Granada, helping to assess the risk and improve the resilience of historical city cores in the face of natural hazards.

Urban risk assessment is a continuously evolving field that can provide valuable information for local authorities to take appropriate mitigation actions and minimize the effects of natural hazards. Its latest iterations encompass a holistic view, involving the classic assessment of typical buildings, e.g. as in Silva et al. (2015) or Kohrangi et al. (2021), as well as vital infrastructure and lifeline systems (Dueñas-Osorio et al. 2007, Winkler et al. 2010, Esposito et al. 2015, Costa et al. 2018, Cavalieri 2020, Tomar et al 2020) to give a more detailed view on the impact of catastrophic event for the city. To these, HYPERION adds the cultural heritage perspective. The quantification of consequences has also evolved. Traditionally, the main focus is the direct monetary losses, estimated as the cost of repair and replacement of damaged buildings (Bazzurro and Park 2007, Aslani et al. 2012, Kohrangi et al., 2021). In addition, indirect losses due to the disruption of business are an important item of interest, as they can cripple a city and cause long-term impact on the local or regional economy.

To measure up to such goals, an urban seismic risk model was developed in the context of HYPERION, firstly focusing on the building stock. To ensure compatibility with business disruption models, the functionality and line of business was determined at the block level. These layers where incorporated in the traditional modeling approach of asset exposure, seismic hazard, and

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vulnerability for the city of Granada, using information from local authorities, pertinent literature, and European-level modeling efforts.

Exposure

The first step to assess the impact of an event in a city is to create an exposure model that contains all the assets at risk. In our case the assets under consideration comprise the entire stock of buildings in Granada. The creation of the exposure model requires a large amount of data to correctly determine their properties and overall distribution. Firstly, the location of the buildings is needed as well as the material, the lateral-load-resisting system and their age of construction. Given such information from census data, the buildings are assigned to an appropriate taxonomy consistent with the 2020 European Seismic Risk Model (ESRM20, Crowley et al., 2021) as shown in Table 1. The individual buildings are aggregated per block to make the analysis less computationally heavy, without actually losing much accuracy in the final results. The two construction materials that are mainly encountered in Granada are reinforced concrete (mainly in the form of moment-resisting frames) and unreinforced masonry. The spatial distribution of the most prevalent building materials is presented in Figure 1. Clearly, unreinforced masonry is primarily characteristic of the oldest quarters of Granada, comprising its historical centre. Buildings are also grouped according to their usage. For the city of Granada several building occupancy categories can be distinguished:

- Accommodation
- Food & Beverages
- Public Services
- Industrial
- Retail Stores
- Offices
- Agriculture
- Residential
- Others

Taxonomy code	**Description**
RCF-LR-LC	Reinforced Concrete Frame – Low Rise – Low Code
RCF-LR-MC	Reinforced Concrete Frame – Low Rise – Moderate Code
RCF-LR-HC	Reinforced Concrete Frame – Low Rise – High Code
RCF-MR-LC	Reinforced Concrete Frame – Moderate Rise – Low Code
RCF-MR-MC	Reinforced Concrete Frame – Moderate Rise – Moderate Code
RCF-MR-HC	Reinforced Concrete Frame – Moderate Rise – High Code
RCF-HR-LC	Reinforced Concrete Frame – High Rise – Low Code
RCF-HR-MC	Reinforced Concrete Frame – High Rise – Moderate Code
RCF-HR-HC	Reinforced Concrete Frame – High Rise – High Code
URM-LR-LC	Unreinforced Masonry – Low Rise – Low Code
URM-LR-MC	Unreinforced Masonry – Low Rise – Moderate Code
URM-LR-HC	Unreinforced Masonry – Low Rise – High Code
URM-MR-LC	Unreinforced Masonry – Moderate Rise – Low Code
URM-MR-MC	Unreinforced Masonry – Moderate Rise – Moderate Code
URM-MR-HC	Unreinforced Masonry – Moderate Rise – High Code

Table 1. Taxonomy of building typologies adopted for Granada

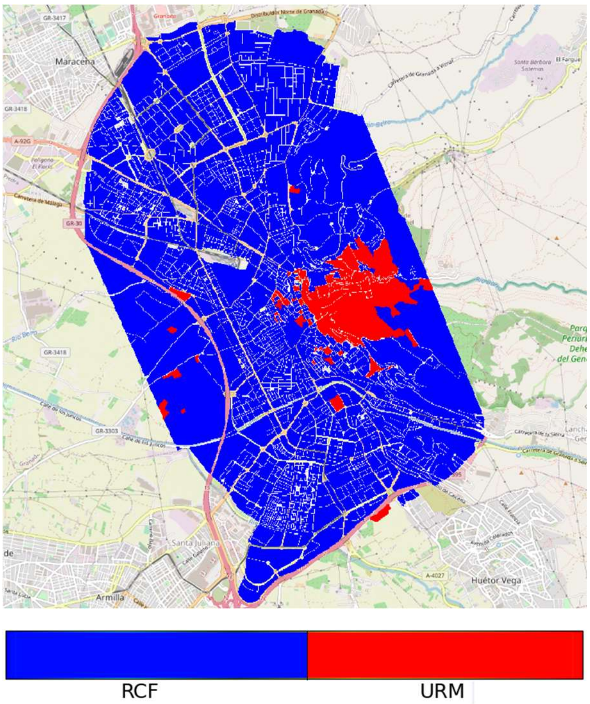


Figure 1. Dominant building material per block for Granada, Spain. The historical centre, mainly comprising URM buildings, is clearly delineated in red.

Seismic hazard

The seismic hazard can be described by multiple intensity measures (IMs), each with its own advantages and disadvantages. The IM used in this case is the 5%-damped (pseudo)spectral acceleration at a period of 1sec, or Sa(1s). This is generally preferable for use with flexible structures, or at least mid-rise buildings. A fair proportion of the Granada stock is comprised of such structures, especially in terms of RC frames. On the other hand, the more vulnerable URM stock is decidedly stiffer; thus Sa(0.1s) or the peak ground acceleration would have been a better choice. Yet, for simplicity and consistency purposes, especially when handling different cities in the HYPERION project, only Sa(1s) was employed as the IM.

Classical probabilistic seismic hazard analysis (PSHA) employs point-wise hazard curves that are not characteristic of any single event as they lack the spatial correlation of intensities within a sizeable geographic area (Park et al., 2007). To capture the extent of damage and prepare the ground for assessing indirect losses, event-based PSHA was employed instead. Thus, a stochastic event set (SES) was generated for an investigation time of 10.000 years, accompanied by event-specific spatially-correlated ground motion fields (GMF). For computational efficiency, only the ground motion prediction equation of Cauzzi et al. (2014) was employed. All calculations were performed via the open-source OpenQuake engine (GEM, 2021), based on the 2020 European Seismic Hazard Model (ESHM20, Danciu et al. 2021). As an example, two events from the SES were chosen, having the same epicentre and rupture depth but different magnitudes as shown in Figure 2: (i) an M6.7 event and (ii) an M5.1 event, both 15km northwest from the centre of the city. In Figure 3 the GMFs for Sa(1s) are shown for both events.

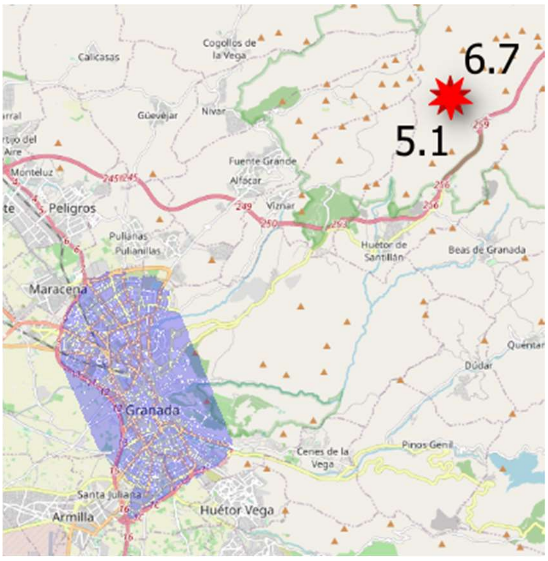
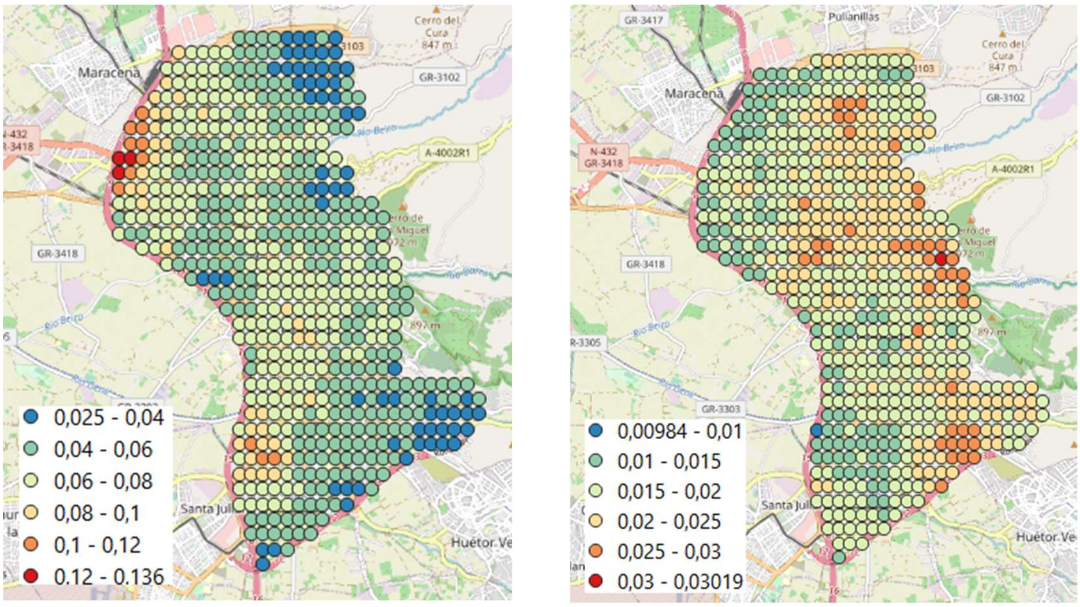


Figure 2. Map displaying the common epicentre of the two example seismic events, M6.7 and M5.1.



(a) (b)

Figure 3. Ground motion fields of Sa(1s) for the two example events of Figure 2: (a) M6.7, R=15km and (b) M5.1, R=15km.

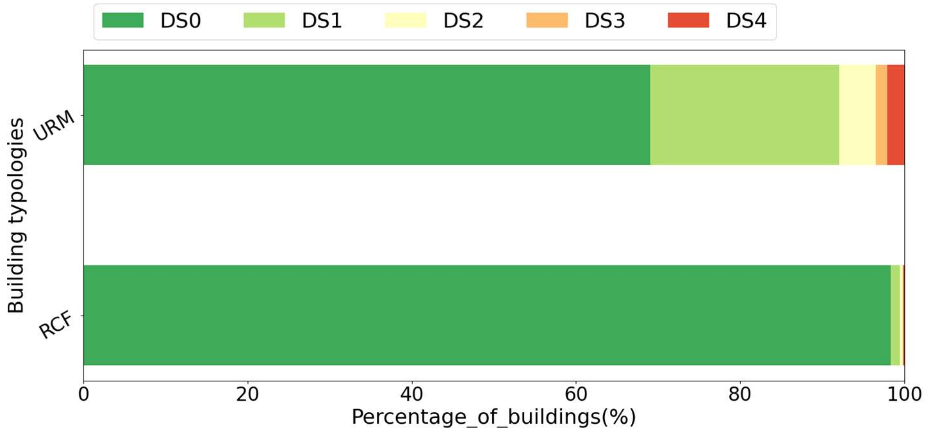
Fragility and Vulnerability

The impact of an event on the building stock can be characterized with a variety of metrics, with direct physical damage and associated monetary losses being the typical choice. The calculation of losses is effected through the use of fragility and vulnerability functions (e.g., Rossetto and Elnashai 2003, Silva et al. 2015, Kohrangi et al. 2021). Fragility curves provide information about the probability of a building exceeding a certain damage state (DS) for a specific seismic intensity level measured by the IM. Per ESRM20, a building after an earthquake can have no damage (DS0), slight (DS1), moderate (DS2), extensive (DS3), or complete damage (DS4) based on the severity of the event and the building typology. The corresponding four fragility curves that are needed to separate these five DSs are represented by a lognormal cumulative distribution function. Accordingly, the parameters of the fragility curves are the lognormal median and dispersion (or beta) values characterizing the relevant typology of the buildings per Table 1. To define the damages per event at each city block, the Sa(1s) value of the GMF grid at the point that is closest to the block centroid is used. Therefore, to find the number of buildings in each DS per block, probability of being in each DS is multiplied with the number of buildings inside the block. The results are aggregated over the entire city and separately for each line of business.

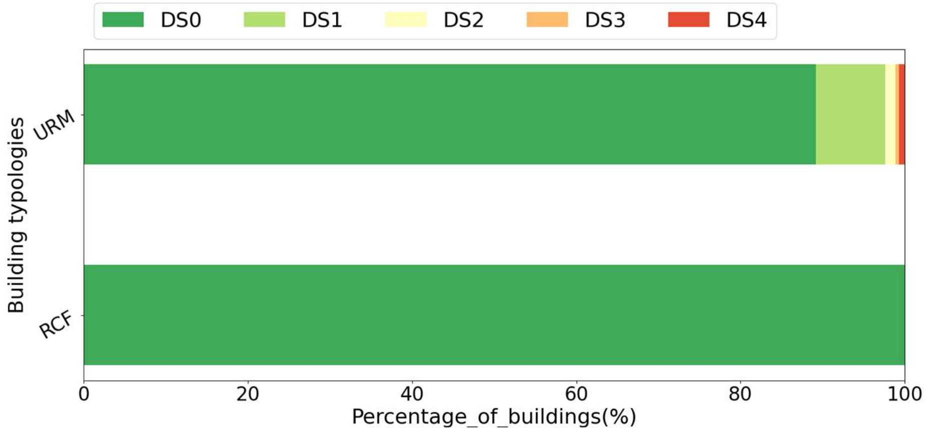
Results

The assessment results allow us to offer estimates of damage per scenario considered, as well as on an annual basis, treating the 10,000 simulated years as independent realizations of a single year per the Poisson memoryless property. For the two example events considered, Figure 4 presents the percentage of buildings from the dominant URM and RCF building classes in each damage state. As expected, the larger magnitude of the M6.7 causes more widespread damage (Figure 4a) compared to the milder M5.1 (Figure 4b). In both cases, though, it is the URM buildings of the historical centre that bear the brunt of the damage. Especially for the lower magnitude event, practically no damage is recorded for RCF buildings. Instead, URM buildings are far more vulnerable to complete damage (DS4). Figure 5 shows the spatial distribution of the number of (essentially collapsed) DS4 URM buildings for the two events, further highlighting the vulnerability of the downtown.

The results for all lines of businesses are aggregated to provide insight on the businesses most impacted by each event. The corresponding losses are presented per line of business for all building taxonomies in Figure 6. Losses are shown as bars: the red bars are the lines of businesses that exceed the average loss over all lines, while the blue color represents those below average. In all cases, public and residential buildings are the ones that are most impacted given their large numbers in Granada. Residences are disproportionately impacted by the more intense scenario, exceeding 45 million euros of repair cost.

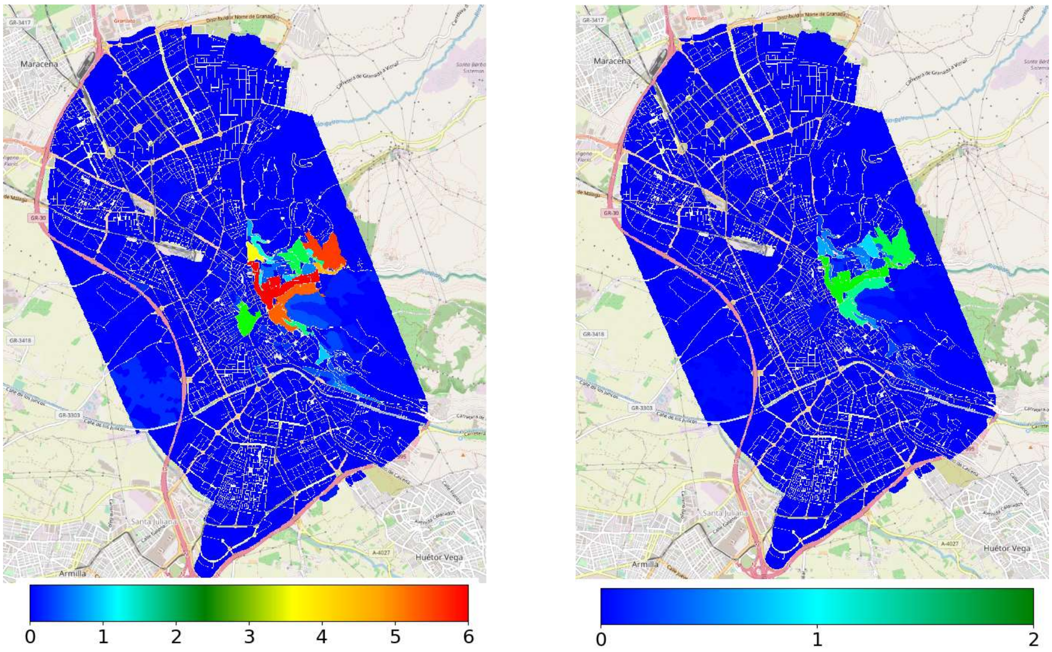


(a)



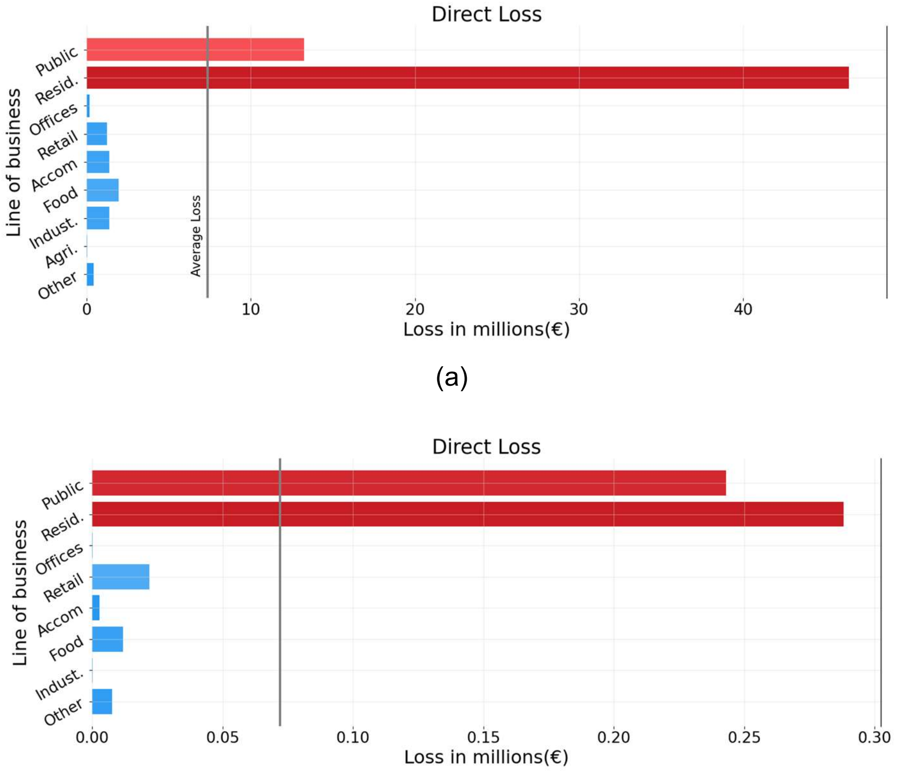
(b)

Figure 4. Percentage of buildings in each DS per building typology (a) M6.7, R=15km and (b) M5.1, R=15km.



(a) (b)

Figure 5. Number of URM buildings in DS4: (a) M6.7, R=15km and (b) M5.1, R=15km.



(b)

Figure 6. Direct Loss of Tier 3 buildings per line of business: (a) M6.7, R=15km and (b) M5.1, R=15km.

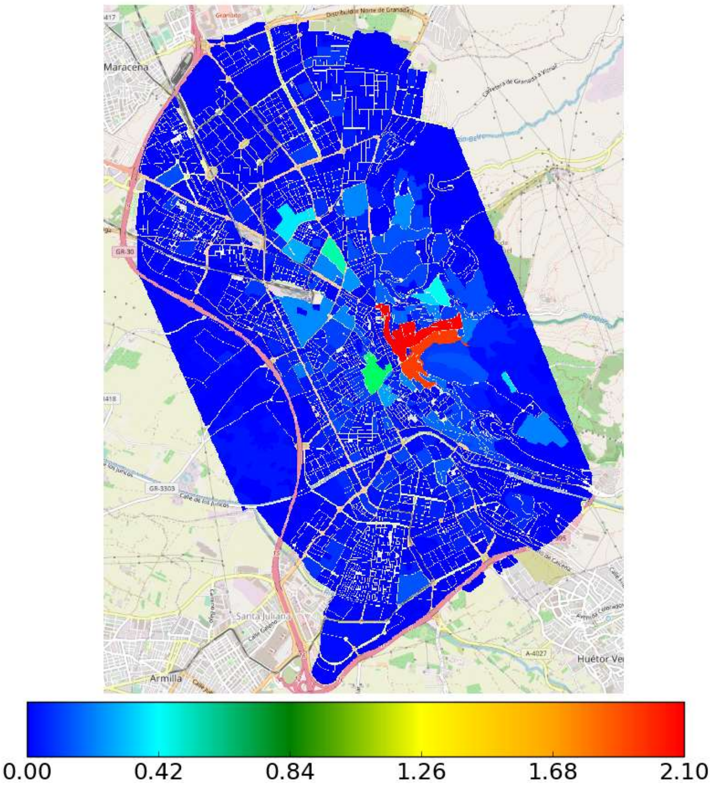


Figure 7. Average annual direct loss in million € per city block.

Lastly, by aggregating all the events in the SES, the average annual direct loss per city block is shown in the map in Figure 7, staying near zero for the modern suburbs but exceeding 2 million euros per block in the vulnerable city centre.

Conclusions

A detailed urban-scale model has been formed for the city of Granada. It combines information from the municipality of Granada, as per the material, lateral-load-resisting system, and age of the buildings with occupancy and census data together with the the latest European model for seismic hazard (ESHM20) and vulnerability (ESRM20). A probabilistic seismic hazard and risk assessment ensue to provide the damages inflicted to the buildings along with the direct cost of repairs. The city of Granada consists of mainly reinforced concrete frame buildings, while the historical downtown is populated by unreinforced masonry structures of immense cultural heritage value. As expected, the latter form the majority of damaged buildings and therefore the majority of the losses, impacting mainly residential as well as public administration uses. The consequences become disproportionally large if one also considers the income generated by the vulnerable city centre, which is the primary focus of tourism. It is an aspect that is not considered herein, but is a major component of further studies within the HYPERION project.

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