The OpenQuake Model Building Toolkit: A suite of tools for building components of a seismic hazard model

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Abstract Building a probabilistic seismic hazard model is a complex task, requiring the integration of disparate datasets into one cohesive and comprehensive model. To facilitate this process, we have developed the OpenQuake Model Building Toolkit (OQ-MBTK), a collection of functions for constructing probabilistic seismic hazard models. This toolkit encompasses a wide array of functions essential for hazard model development, enabling users to start from catalogue and fault data and sequentially step through the model building process to produce hazard inputs compatible with the OpenQuake (OQ) Engine. These tools allow users to build seismic source models that capture epistemic uncertainty using a logic tree, select suitable ground motions for different tectonic regions, and carry out thorough sensitivity analyses. Crucially, the toolkit ensures that data are treated consistently at all stages of the process. Using the MBTK to streamline the model building workflow can ensure it is reproducible and more robust.

1 Introduction

The essence of a Probabilistic Seismic Hazard Analysis (PSHA Cornell, 1968; McGuire, 2004; Baker et al., 2021) is the construction of the two key components of a hazard model consisting of the Seismic Source Characterization (SSC) and the Ground-Motion Characterization (GMC). The former includes a comprehensive description of the position, geometry and seismogenic properties of all the sources and the associated epistemic uncertainties. The latter describes the models adopted to compute the ground motion at the sites and the related epistemic uncertainties. The SSC and GMC collectively form the PSHA input model. The preparation of the SSC and GMC components entails the collection of various information, its homogenization, pre-processing, and final use. The model building process consists of the application of different processing steps that, from the basic information, prepare parts of a hazard model input. Information frequently used to prepare the SSC includes earthquake catalogues, geodetic information (e.g., from space geodesy), geological information including fault types, geometries, slip rates and paleoseismological data. Model building involves assembling these data into a set of earthquake sources described in

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terms of their geometry and statistical representation of how often they generate earthquakes of various sizes. The approaches and methodologies used in the model building process vary depending on the seismotectonic conditions and the source typologies in question. Traditional cases considered include the modelling of distributed seismicity in the shallow crust, shallow crustal faults and fault systems, and subduction interface and in-slab sources. Variants in each of these broad categories are present. For example, the modelling of distributed seismicity in stable areas often entails the definition of a baseline level of seismicity over broad areas that historically did not show significant levels of seismic activity (e.g. Johnston et al., 1994). On the other hand, one challenge within active shallow crust areas is to define the spatial pattern of seismic activity considering the information at hand (i.e., past seismicity, geological and geodetic information). Note that these considerations hold for both the SSC and GMC. In the latter case, for example, physics-based or stochastic simulations of ground-motion (e.g. Boore, 2003; Graves et al., 2011; Graves and Pitarka, 2015; Paolucci et al., 2018) are sometimes required to augment the database of real recordings, particularly for cases less frequently observed (e.g., shaking produced by large events or measured at short distances from the corresponding rupture). These considerations call for a model building workflow that is modular, reproducible, and - ideally - linked with the code used for the calculation of hazard. Modularity ensures that alternative approaches and hypotheses can be tested or included in different branches of a logic tree structure without altering the overall workflow; a classic example is the use of different approaches for the declustering of seismicity (e.g., van Stiphout et al., 2010). Reproducibility is a desirable characteristic because the automated processes can be more easily used to explore various hypotheses and reconsider them in subsequent phases, perhaps when additional information becomes available. Moreover, reproducible models have more chance of being accepted by the broader scientific community and receiving contributions from scientists not directly involved in the original hazard model, and ultimately supporting the work of the experts requested to review the model. Finally, reproducibility helps to add tests to the model building process, thus reducing the possibility of introducing mistakes. The use of identical tools or functions (e.g. code) in both the model construction process and PSHA calculations helps to ensure that input models will be treated with the same assumptions in both phases. For example, small details concerning the binning of magnitude-frequency distributions (MFDs) can be overlooked when the input model is created separately from the PSHA codes. Besides, with a direct link between tools used for building models and the calculation of hazard, it is possible to share components and use the hazard calculation code to perform various tests while building the model. Despite the considerable progress made in the last couple of decades in the community development of open-source software for the modelling of seismic hazard (e.g., Field et al., 2003; Pagani et al., 2014), to our knowledge, a comprehensive tool (or library) with these characteristics does not yet exist. There are assorted reasons that can explain this lack. The most prominent one is probably due to a general preference in the hazard modelling community for developing in-house tools, to address more promptly specific needs emerging in each project. This is certainly a valid approach, though we think that new improvements should be brought back to a more general framework. Such an approach makes the use of new methods straightforward within other projects. In the following sections we illustrate a set of packages included in the OpenQuake Model Building Toolkit (OQ-MBTK), hosted at https://github.com/GEMScienceTools/oq-mbtk. This suite of tools collectively offers capabilities for building various components of a hazard model.

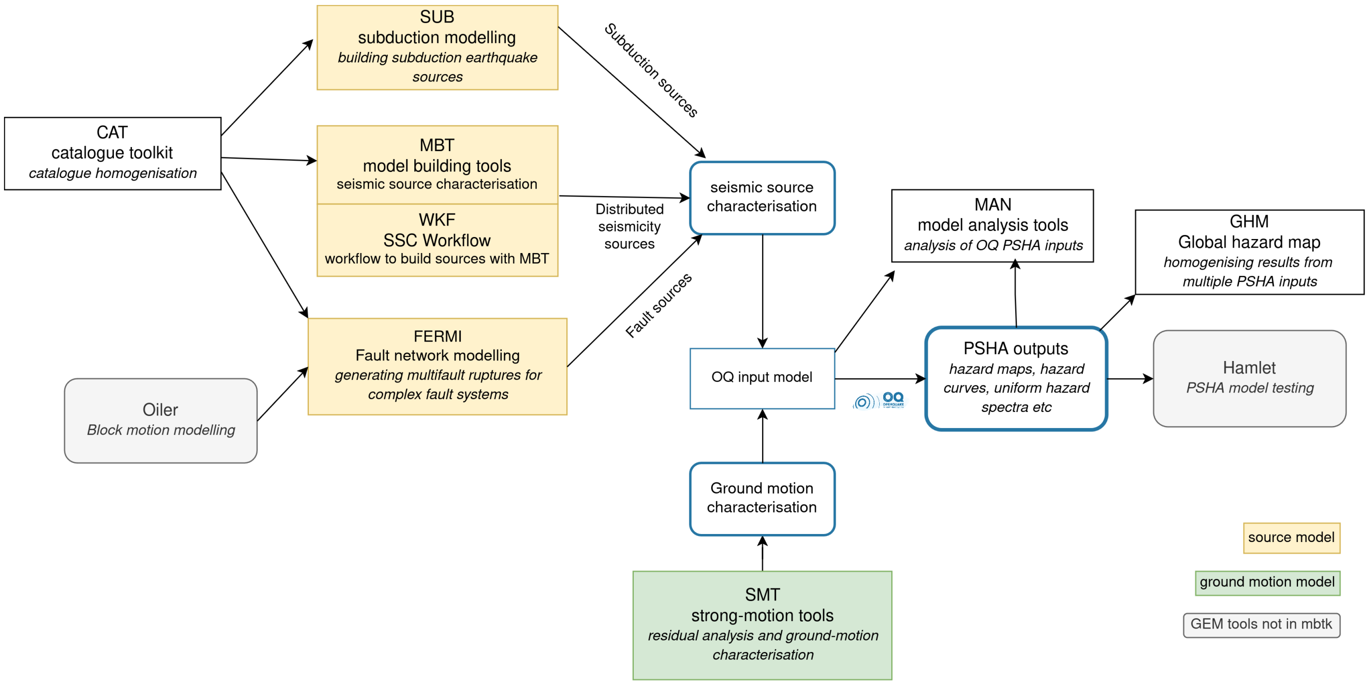

Figure 1 A workflow for building seismic hazard models used by the GEM hazard team, showing the modules of the OQ-MBTK

2 The OQ-MBTK pilot study

The idea of a publicly accessible set of standard tools that could be used for constructing various input components of a hazard model was initially framed in the GEM pilot project called GEM1 in the early 2010s. However, the initial version of the OQ-MBTK was not completed until 2017 within a collaboration between researchers from GEM and FM. It consisted of a set of Jupyter notebooks (see https://jupyter.org/) and Python scripts that together constituted a single workflow for the construction of a hazard input model, as described in Rong et al. (2017). Jupyter notebooks were used in the pilot study to make the tools accessible to hazard modellers who are not necessarily proficient at programming with the Python language (https://www.python.org/). The disadvantage of this approach included the need to maintain complicated software for running various Jupyter notebooks in a single run and an excessively large data structure which contained all the original information as well as the intermediate and final results of the workflow.

3 GEM and FM Models that use the OQ-MBTK

The OQ-MBTK was first used successfully by Rong et al. (2020) for performing a probabilistic seismic hazard analysis for mainland China. Since then, and through several iterations, the tools have been used by the GEM hazard team in building hazard models for the Phillipines Peñarubia et al. (2020), the Pacific Islands Johnson et al. (2021), and the Dominican Republic (Johnson et al., 2024), as well as for the construction of several hazard models in the GEM Global Seismic Hazard Mosaic Johnson et al. (2023); see https://hazard.openquake.org/gem/.

4 The current modules of the OQ-MBTK

The OQ-MBTK is the combination of several modules, each one dedicated to a specific task. A workflow showing the different modules and how they are used in the model building process is shown in Figure 1. The OQ-MBTK does not represent a finite product, but is instead a container for tools and functions that are constantly evolving. For this reason, the maturity and completeness of the different modules vary. The aim of this paper is to illustrate the main modules and the primary motivation behind this repository, to promote the use of the available tools, and to incentivize community contributions similar to the development style of the OpenQuake Engine Pagani et al. (2014); Silva et al. (2014). When describing the OQ-MBTK modules, we focus on a select few that we believe will be of particular interest to readers, and we explain the criteria used for their development.

4.1 The Catalogue (CAT) module

The catalogue (CAT) module provides functionalities for compiling a homogenised catalogue from a collection of catalogues that cover various time periods, geographic areas, and magnitude ranges. The workflow involves four main steps and resembles most parts of the procedure proposed in Weatherill et al. (2016). The user controls each step of the process through a .toml formatted configuration file (see https://toml.io/en/), an input format used in several OQ-MBTK modules. The first step is the merge of the original input catalogues into a single organised collection. The formats accepted include the IASPEI Seismic Format (ISF, see http://www.isc.ac.uk/standards/isf/), the .ndk format used by the Global Centroid-Moment-Tensor (CMT) project (https://www.globalcmt.org/), and a generic .csv format. The CAT creates an aggregated collection of seismological data by associating each new event with the ones already incorporated; this is done by defining tolerances in time and space for each new event and searching for previously added events that occurred in its surroundings. When a previous event falls into the defined space-time window, the old and the new event are merged into a group and a preferred solution based on the user's hierarchical settings is assigned. In the case of large catalogues, this procedure can be computationally demanding and time-consuming. To improve the efficiency of this process, the OQ-MBTK performs the search in space with the help of a spatial index. The second step is selecting or deriving empirical equations for converting between different typologies of magnitude, as shown in Figure 2, and using them to homogenise the catalogue magnitudes (to use a consistent magnitude type throughout). This phase is required because the standard magnitude typology used by ground-motion models (and consequently in PSHA) is moment magnitude, while the typologies listed in catalogues vary depending on time and agency; only recent catalogues regularly report moment magnitude (e.g., ISC-GEM; see (Storchak et al., 2013) and (Di Giacomo et al., 2018)).

The third phase constructs the homogenised catalogue by selecting a single origin (time and location) and magnitude per earthquake. This is performed sequentially event by event, based on two lists – one for magnitude and one for location – ordered in decreasing order of preference. The CAT module also includes tools to check the final catalogue for remaining duplicate events by producing .geojson files for manual inspection and validation, which help remove potential duplicates matched within wider time and space windows than the initial tolerances used to merge catalogues.

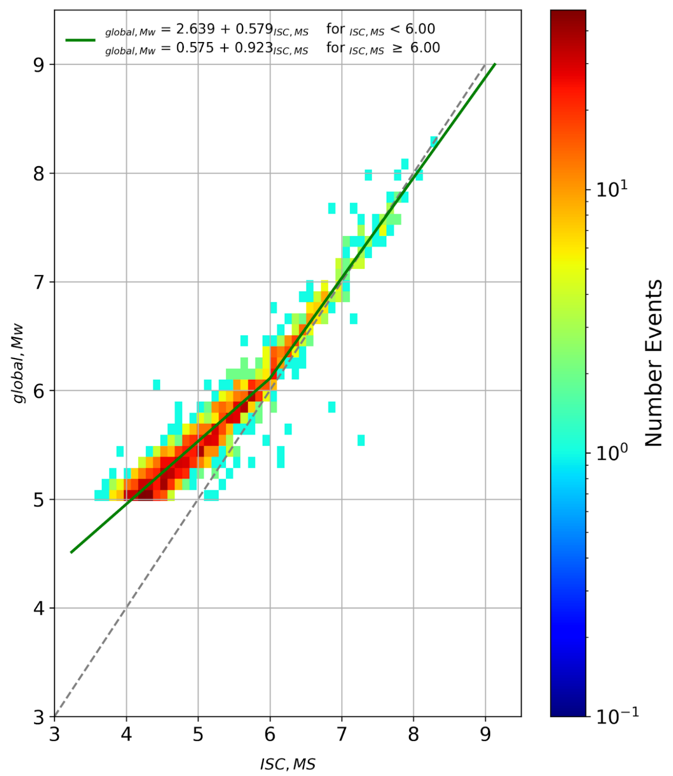

Figure 2 Example of a density plot showing the relationship between two types of earthquake magnitudes reported by two different agencies, and the relationship used to convert between them. The relationship here was derived in (Weatherill et al., 2016).

4.2 The Global Hazard Model (GHM) module

In this module, we collect tools for the construction of global hazard maps using the hazard results computed as part of the GEM Mosaic standard calculations (see Pagani et al., 2020; Johnson et al., 2023). These tools are probably of low interest for the general audience, but they are distributed publicly nonetheless to ensure reproducibility. The main capabilities of these tools include:

- Identifying co-located hazard curves among a set of output files from different models
- Homogenising pairs (or more) of hazard curves across defined model boundaries
- Collecting hazard results (intensity measure levels) among many models with common criteria, including spectral period, reference site condition, and return period into global csv files
- Producing global seismic hazard maps from the above

The methodologies implemented are described in Pagani et al. (2020).

4.3 The Model Analysis (MAN) module

The MAN module contains tools for analysing the characteristics of an OQ Engine formatted input model. This module is primarily used internally by the GEM team and includes some more experimental functions that summarise model components, create representative plots of the main characteristics, or plot results; these are considered experimental because they may not work for all model instances (e.g., for newest features supported by the OpenQuake

Engine). It also requires the Generic Mapping Tools (Wessel et al., 2019, GMT), which is not a dependency of the OQ-MBTK and must be installed separately.

4.4 The Model Building (MBT) module

The MBT module contains the implementations of many standard methods used in seismic source characterisation, as well as ad-hoc approaches developed by GEM, for constructing both fault and distributed source models. These tools operate on datasets formatted for the OQ-MBTK, including catalogues, fault databases, and strain rates, parsing these data and passing them to the fundamental steps of seismic source characterisation. For example, the MBT includes tools for analysing the completeness of a catalogue, deriving MFDs from catalogues or slip rates, and smoothing of seismicity based on past earthquake locations, as well as plotting functions that allow the user to easily visualise the characteristics of their data. Many of the MBT functions (among those for other modules) directly use the HMTK module of the OQ Engine, such as those for declustering and evaluating seismicity characteristics, ensuring consistency with GEM's older toolkits. Figure 3 shows examples of three such plots: histograms of the hypocentral depths for earthquakes within a catalogue (or sub-catalogue), the magnitude-frequency distribution (MFD) of that catalogue (modelled and observed), and the time-magnitude density plot of the catalogue used to derive the MFD. The information plotted in the left and centre panels is directly used in the seismic source produced by the MBT.

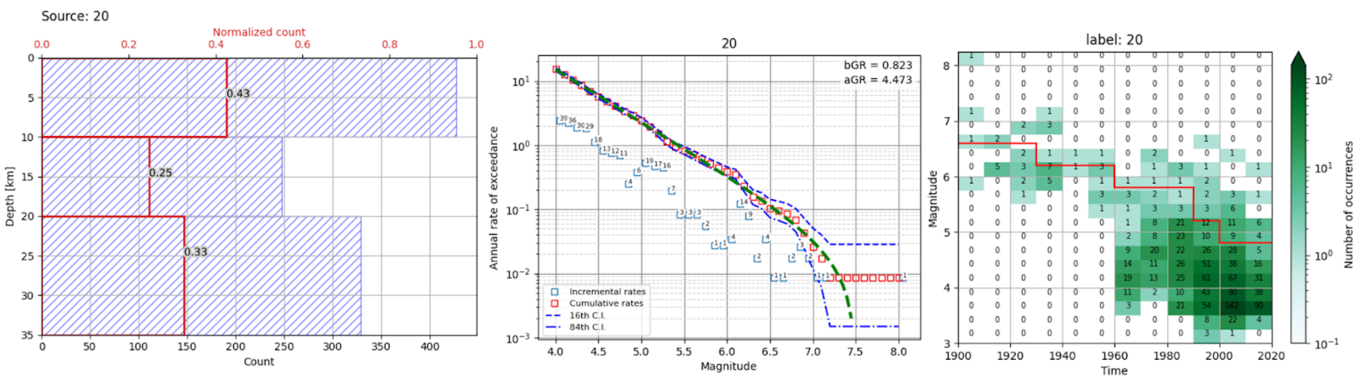

Figure 3 Examples of figures produced by the MBT module. Left: a histogram of depths for a subcatalogue that corresponds to one source zone in a model. Centre: the MFD for the catalogue, showing both incremental and cumulative observations and their confidence intervals (C.I.), and the derived MFD. Right: the time-magnitude density plot corresponding to the subcatalogue.

The MBT also includes tools for tectonic regionalisation following the approach described by (Pagani et al., 2021). These tools isolate portions of catalogues, thereby 'classifying' the events, according to tectonic units delimited by user-specified 3D surfaces, e.g. existing Earth structure models, such as Slab2.0 Hayes et al. (2018) and Lithos1.0 Pasyanos et al. (2014), or ones developed by the user. This is a critical step when developing PSHA input models in complex tectonic regions such as subduction zones, where the tectonic units must be characterised separately.

4.5 The Plotting (PLT) module

The PLT module contains tools for visualising inputs at various levels of complexity, such as input catalogues, faults, earthquake MFDs for various seismic sources and zones, and distributed seismicity rates. It can be used to visualise depths of fault structures and to check if the data are imported properly into the framework. Many of the functions were added to replace deprecated plotters of the Hazard Modeller's Toolkit (HMTK) module of the OQ Engine.

4.6 The Subduction (SUB) module

The SUB model offers tools for the construction of subduction earthquake sources. The main functionalities unique to the SUB module are a routine for interactively defining the surface that represents the top of the slab from cross section visualisations of the slabs or directly from existing models (e.g. Slab2.0; Hayes et al., 2018), and the construction of in-slab sources following the methodology of Pagani et al. (2021). Naturally, the SUB module depends a lot on the MBT, and is in particular linked to the tectonic regionalization.

4.7 The Model Building Workflow (WKF) module

The Model Building Workflow (WKF) module contains various methods for processing catalogues and building simple components of an SSC such as shallow crust distributed seismicity sources and unsegmented shallow crustal faults. The WKF allows the user to apply many of the functions in the MBT consecutively and to construct models from input using a single .toml file. This makes the creation of sources easily reproducible, simplifies the process of creating many logic tree branches, and allows for robust sensitivity analysis.

4.8 The Strong-Motion Tools (SMT) module

The Strong-Motion Tools (SMT) module provides tools for selecting and comparing ground-motion models (GMMs), and supersedes the original (and now deprecated) GMPE-SMTK. The SMT comprises two submodules: the residuals module and the comparison module. The residuals module evaluates how well a given set of GMMs predict observed values of ground-shaking using a classical residual analysis. This submodule includes capabilities for plotting the distributions of residuals for a given GMM and intensity measure, and for computing GMM ranking metrics such as the stochastic area Sunny et al. (2021) and the Euclidean distance-based metrics Kale and Akkar (2013). The comparison module compares GMMs in highly customisable ground-shaking scenarios (e.g., for which the user can specify all aspects of the rupture and sites that may be required by a given GMM) by generating attenuation curves, response spectra (including plotting spectra from processed records against corresponding GMM predictions), Sammon's maps Scherbaum et al. (2010), and dendrograms - a novel visual representation of the results of agglomerative clustering performed on median GMM predictions to help evaluate the degree of similarity between GMMs. Examples of the dendrograms and Sammon's maps are shown in Figure 4.

4.9 Fault Network Modelling (Fermi)

The Fault nEtwoRks ModellIng (Fermi) module, called FNM in the MBTK (for consistency with module 3-letter naming conventions), contains GEM's latest tools for modelling multi-fault ruptures in complex fault systems. These tools are inspired by the OpenSHA tools (e.g. Milner and Field, 2024) and SHERIFS Chartier et al. (2019) approaches to earthquake rupture modelling given an input fault network, but with some added flexibility. A fault network is broken into sections of uniform length, where each section becomes a node in a graph. Then, using graph theory, all possible ruptures in the network are defined with an adjacency matrix, where further rupture plausibility constraints can be applied. Fermi can also determine rupture rates through inversion, offering options to fit these rates using slip rates and MFDs, either for individual faults or the entire fault system, with a variety of iterative solver options available.

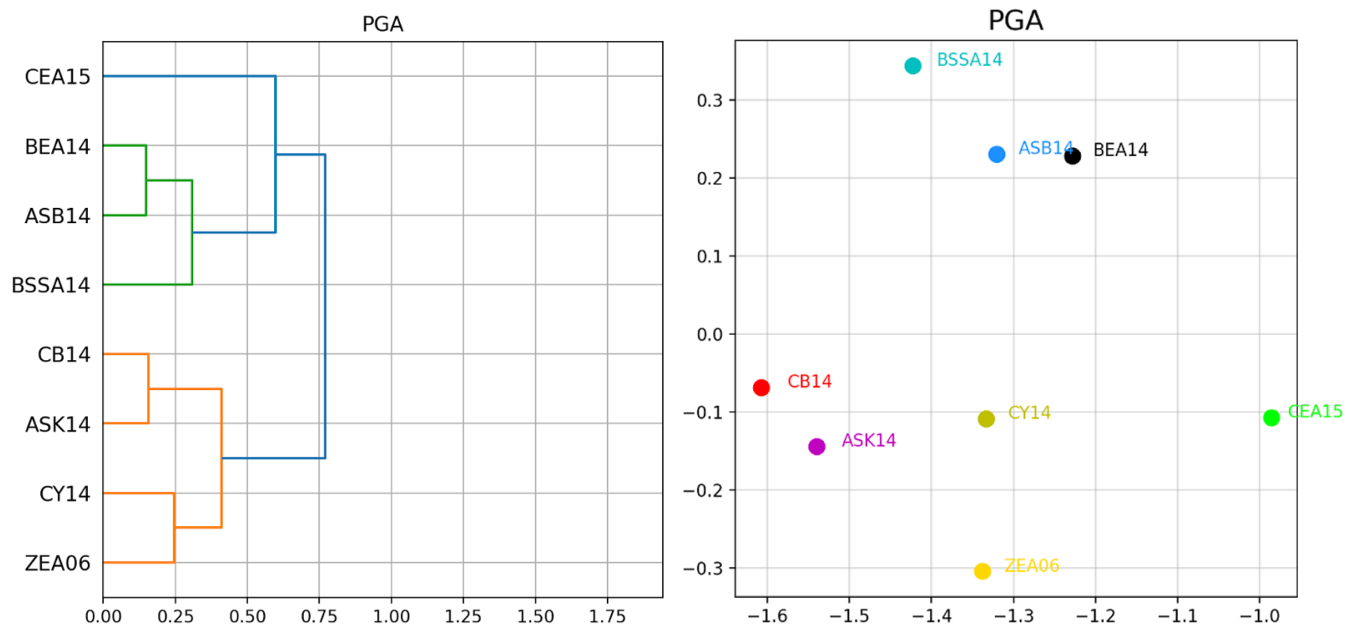

Figure 4 Example of (left) a dendrogram and (right) a Sammon's map that emphasize similarities and differences among the evaluated GMMs.

5 Coding principles and third party libraries

The OQ-MBTK is primarily coded in Python with some components written in Julia (https://julialang.org/). The plotting functionalities mostly rely on Python and Julia, while some use the Generic Mapping Tools (GMT; Wessel et al., 2019) and its Python and Julia wrappers. Note that since GMT is not an official dependency of the OQ-MBTK, some plotting functions may not work for all users. In addition, there is a command-line interface that provides access to most of the methods implemented in the various modules. The OQ-MBTK repository is under a Continuous Integration (CI) Environment. CI is considered necessary for developing scientific code collaboratively Silver (2017).

6 Using the functions available in the OQ-MBTK

All the functions available in the various modules can be accessed through a command-line interface like the one available for the OQ Engine. By executing the command in Inset 1 the OQ-MBTK returns a list of available options, each one identifying a module of the list just described.

```
> oqm -h

usage: oqm [-h] {rep,wkf,cat,ccl,sub,unc,mbi} ...

positional arguments:
    {rep,wkf,cat,ccl,sub,unc,mbi}
        available subcommands; use oqm <subcmd> --help
options:
    -h, --help
```

Additional information about the functionalities within a module can be found by typing a command as exemplified in Inset 2.

```
> oqm cat -h

usage: oqm cat [-h]
    {MFDs_sample_mag_sigma,homogenise,
    create_figures,purge_earthquakes,
    check_duplicates,merge,
    completeness_analysis,
completeness_generate,create_csv}
               ...

positional arguments:
  {MFDs_sample_mag_sigma,homogenise,
  create_figures,purge_earthquakes,
  check_duplicates,merge,
  completeness_analysis,
  completeness_generate,
  create_csv}

    available subcommands;
        use oqm cat <subcmd> --help

options:
  -h, --help
```

Finally, information about a specific command can be obtained as in Inset 3

```
> oqm cat merge -h

usage: oqm cat merge [-h] settings

Merges the information contained in a
number of catalogues. The output is a
couple of .h5 files (you can read them
using pandas.read_hdf) which contain
the origins and the magnitudes of
the earthquakes in the catalogues
specified in the settings.

positional arguments:
  settings  .toml file with the settings

options:
  -h, --help
```

For documentation and end-to-end examples, see the OQ-MBTK github page (https://github.com/GEMScienceTools/

oq-mbtk/), which contains simple applications of many functions as well as detailed notebooks that demonstrate the full workflow used to build subduction sources with the SUB module and perform strong-motion analysis with the SMT.

7 Conclusions

The OQ-MBTK is a comprehensive suite of tools designed to facilitate the construction and analysis of PSHA input models. This toolkit has already been instrumental in building several seismic hazard models, demonstrating its robustness and utility. However, the OQ-MBTK is not a static product; it is a dynamic and evolving collection of tools and functions. This continuous evolution ensures that the toolkit remains relevant and up-to-date with the latest advancements in seismic hazard modelling. By providing a modular and reproducible workflow, the OQ-MBTK allows for the exploration of various hypotheses and the inclusion of new methodologies without altering the overall process. The modularity and reproducibility are critical for maintaining the scientific rigour and acceptance of the models within the broader community. We hope that this contribution will inspire further engagement from the PSHA community. Through the development and sharing of the OQ-MBTK, we aim to foster a collaborative environment where improvements and innovations can be shared and integrated into a general framework. Such collaboration will not only enhance the toolkit but also contribute to the advancement of seismic hazard modelling as a whole. We invite researchers and practitioners to explore its capabilities and contribute to its development.

Acknowledgements

We thank Franco Tamanini, Harold Magistrale, Hosam Ali and Elliot Klein for internal reviews of this paper. We thank all private and public sponsors of the GEM Foundation (www.globalquakemodel.org) for their support.

Data and code availability

The OQ-MBTK repository is available on GitHub at the following link https://github.com/GEMScienceTools/oq-mbtk. At the time of submission, Version 0.9.0 is archived at https://doi.org/10.5281/zenodo.15111998. The OQ-MBTK can be installed on most common operating systems (OS) including Mac OS X, Linux, and Microsoft-related OS. The OpenQuake Engine (see https://github.com/gem/oq-engine) is a dependency of the OQ-MBTK.

Competing interests

The authors acknowledge that there are no conflicts of interest recorded.

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