Challenges of mapping Vulnerabilities and Exposures to Open-Source Packages

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Abstract—Much of the current software depends on open-source components, which in turn have complex dependencies on other open-source libraries. Vulnerabilities in open source therefore have potentially huge impacts. The goal of this work is to get a quantitative overview of the frequency and evolution of existing vulnerabilities in popular software repositories and package managers. To this end, we provide an up-to-date overview of the open source landscape and its most popular package managers. We discuss approaches to map entries of the Common Vulnerabilities and Exposures (CVE) list to open-source libraries. Based on this mapping approaches, we show the frequency and distribution of CVE entries with respect to popular programming languages.

Index Terms—open source, vulnerabilities, CVE, software repository

I. INTRODUCTION

According to a 2021 open-source security report by Synopsis,[1] 98% of 1,5k reviewed codebases depend on open-source components and libraries. Given the number of dependencies of medium- to large-size software projects, any vulnerability in open-source code has security implications in numerous software products and involves the risk of disclosing vulnerabilities either directly or through dependencies, as famously seen in the 2014 Heartbleed Bug[2] a vulnerability in the popular OpenSSL software which exposed large parts of the existing websites at this time.

Open-source code is written in various programming languages and published in corresponding package managers. Currently, the largest package managers are the platform of the Go programming language, the NPM repository of the Node.js language, Packagist (PHP), and PyPI (Python), cf. Table 1. The documentation and communication of discovered open-source vulnerabilities, however, does not take place directly at the package managers. The most important platform for discovered vulnerabilities is the Common Vulnerabilities and Exposures (CVE) list [1]. It is a dictionary and reference of common and publicly known IT system vulnerabilities, operated by the Mitre Corporation, an American non-profit institution. As such, CVE has achieved wide acceptance by the security community and industry and provides a comprehensive list of publicly known and documented vulnerabilities. CVE is available at http://cve.mitre.org.

CVE is a critical source for security management, however, is to some extend an heterogeneous and unstructured source. Each vulnerability in the CVE list is identified by an unique identifier, contains a textual description and a list of references (links to relevant documentation and code repositories). However, CVE does not include structured pointers and references to package managers (e.g., NPM) and/or the source code in software repositories (e.g., Github). Therefore, CVE does not always provide enough information to get an overview of the status and evolution of existing vulnerabilities in the different software repositories and package managers.

The goal of this work is to study the open research problems when mapping CVE entries to open-source projects. To do so, we focus on the following concrete contributions:

- We provide an overview of the landscape of open-source projects and libraries in popular package managers.
- We discuss three concrete approaches to map Common Vulnerabilities and Exposures (CVE) list entries to open-source libraries and projects.
- We perform a quantitative analysis of the frequency and distribution of CVE entries corresponding to open-source libraries based on the mapping approaches.
- Eventually, we discuss identified challenges and quality issues wrt. the available data and the mapping.

The remainder of this paper is structured as follows: Section II provides an overview of the current landscape of package managers and Section III introduces the CVE list. Section IV discusses approaches on mapping open-source libraries to listed vulnerabilities, and presents the respective findings. Section V relates our research to other works and, eventually, Section VI concludes the paper.

II. OPEN SOURCE LANDSCAPE

In the context of this paper, open source refers to source code that is made available in online software repositories for use or modification. We provide an overview of the most important repositories and package managers and report important
aspects such as the use of licenses, and the developments and growth of the vast amount of software that is available – and becomes available.

In this work, we make use of the monitoring project Libraries.io [2]: it monitors and crawls the meta-information of over 30 package managers and indexes data from over 5 million projects. Libraries.io provides the collected information as open data; in this paper we make use of the January 2020 dump of the Libraries.io data which is hosted on Zenodo [2].

Table I: Number of projects in top-7 package managers.

| Repository | Projects | Perc. |
|------------|----------|-------|
| Go         | 1,818,666| 39.45 |
| NPM        | 1,275,082| 27.66 |
| Packagist  | 313,278  | 6.80  |
| Pypi       | 231,690  | 5.03  |
| NuGet      | 199,447  | 4.33  |
| Maven      | 184,871  | 4.01  |
| Rubugems   | 161,608  | 3.51  |
| Others     | 425,020  | 9.22  |

Table II: Top-7 licenses across all packages.

| License       | Count   | Perc  |
|---------------|---------|-------|
| MIT           | 1,637,451| 44.13 |
| Apache-2.0    | 848,475 | 22.87 |
| ISC           | 332,676 | 8.97  |
| Other         | 298,626 | 8.05  |
| BSD-3-Clause  | 140,806 | 3.80  |
| GPL-3.0       | 63,890  | 1.72  |
| MPL-2.0       | 51,517  | 1.39  |
| Others        | 336822  | 9.08  |

As shown in Table I, currently the largest package managers are the platforms of the Go programming language and the Node.js platform NPM. According to the 2020 data, the Go platform makes up even 39% of all projects indexed in Libraries.io by listing 1.8 million projects; NPM lists around 1.3 projects which amount to 28%. The Others category in Table I includes 25 other repositories which only sum up to 9% of all indexed projects.

a) Licenses: The licensing of code is a critical aspect of the open-source movement. Depending on the concrete license conditions and terms, the code is then available to download, modify, re-publish, etc. The authors of open-source projects may want to put restrictions on the use of the code, such as expression of the origin/name of the authors, copyright statements, or re-use of the concrete license. This number of conditions and restrictions led to a broad range of popular open-source software licenses.

b) Releases and Versions: A version in the Libraries.io data corresponds to an immutable published version of a project from a repository. Not all repositories provide the concept of publishing versions, so in these cases the tags/branches from a source control system are mapped to the existing versions.

Table III displays the number of versions published at the monitored repositories in 2015 and 2019, respectively. We can see that the largest repository, the NPM package manager, increased considerably from 716k to 3.9 million published versions per year. Notably, the Apache Maven Repository for the Java language is the only repository whose numbers have decreased in the monitored time period. The chart in Figure 1 visualizes the rapid growth, in number of published versions, of the package managers NPM, NuGet, and PyPI; note that the y-axis is in logarithmic scale.

Table III: Number of versions published at repositories in 2015 and 2019, respectively.

| Repository | 2015   | 2019   |
|------------|--------|--------|
| NPM        | 716,207| 3,892,909|
| NuGet      | 210,929| 614,774|
| Pypi       | 150,591| 469,753|
| Packagist  | 233,643| 334,059|
| Maven      | 326,089| 144,813|
| Others     | 459,265| 364,164|

III. COMMON VULNERABILITIES AND EXPOSURES

Historically, with the increased connectivity and the commercialization of the Internet in the mid-1990s, cybersecurity research gained importance and various security vendors...
started to develop vulnerability monitoring strategies and documentations. In 1999, Mann and Christey [1] proposed the Common Vulnerability and Exposures (CVE) List, a public list of exposure references. The goal was to find out and document if multiple tools had identified the same vulnerabilities.

Each CVE Identifier in the list identifies a concrete vulnerability and gives an unique, individual name to it. New CVE identification numbers are assigned by the CVE Numbering Authorities. Typically, these authorities are software vendors, open-source projects, security researchers, and bug bounty programs. There are currently 213 partners from over 30 countries participating as authorities. Table IV displays the number of newly published CVE entries in the last 7 years. The number of entries increased from 6.6k to 22.2k new entries in the year 2021.

Table IV: Number of newly published CVE entries in recent years.

| Year | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|------|------|------|------|------|------|------|------|
|      | 6,602 | 6,520 | 18,161 | 18,213 | 19,095 | 20,516 | 22,226 |

Figure 2: Screenshot of an example CVE entry and its respective fields.

In Figure 2 we provide an example CVE entry as displayed on the cve-search web interface. Besides the ID and the summary of the vulnerability, a CVE entry provides relevant references (e.g., Github documentation as in Figure 2), an assessment of the severity of the vulnerability using the Common Vulnerability Scoring System (CVSS) and the Common Weakness Enumeration (CWE) taxonomy of weakness types. Additionally, the CVE entry provides Common Platform Enumerations (CPE) version 2.3 string, which is a standard for identifying classes of applications, operating systems/platforms, as well as hardware information. The CPE string consists of various fields providing information such as the software name, vendor as well as the target software, which contains the software computing environment (e.g. “node.js” or “python”).

IV. FINDINGS

In this section, we first provide details on the used data to facilitate reproducibility of our results. Then we discuss different mapping approaches and report the identified challenges.

A. Datasets

To perform this study, we use the most recent Open Data dump of the Libraries.io database – available as compressed archive of several CSV files – to obtain data about open-source repositories and respective libraries; details of the repositories are described in Section II. The Libraries.io data includes the fields NAME, PLATFORM (the package manager), ID, REPOSITORY TYPE (e.g., GitHub), REPOSITORY LINK, REPOSITORY OWNER and KEYWORDS.

We used the dockerized version of the open-source project CVE-Search as basis for our CVE analyses. The Computer Incident Response Center Luxembourg (CIRCL) operates a publicly accessible instance of the CVE-Search project and provides a daily dump of their CVE data in JSON format, which we imported into our database. The CIRCLE CVE data provides the CVE fields SUMMARY and REFERENCES, as well as the fields PRODUCT and TARGET SOFTWARE which hold extracted information from the Common Platform Enumerations (CPE) information.

B. Mapping Approaches

In order to establish a mapping between the software packages of the Libraries.io dataset and the corresponding CVE entries of the CIRCL CVE dataset, we applied three different approaches, yielding varying results:

1) Strict Name Mapping: The first approach iterates over each entry contained in the Libraries.io dataset and checks whether the package manager (in the field PLATFORM) can be matched to any target software in the CIRCL CVE dataset (as stated in the TARGET SOFTWARE field).

For our query, we created a mapping between package manager values of the Libraries.io dataset and the corresponding TARGET SOFTWARE values. The query then matches the value of the Libraries.io NAME field with the values of the CVE PRODUCT field as well as the PLATFORM value with either the TARGET SOFTWARE or checks if it is contained in the SUMMARY of the CVE dataset.

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4. https://www.cve.org/ProgramOrganization/CNAs last accessed 2022-03-21
5. https://cve.circl.lu/cve/CVE-2021-44631 last accessed 2022-03-21
6. https://nvd.nist.gov/vuln-metrics/cvss last accessed 2022-03-21
7. https://cwe.mitre.org/ last accessed 2022-03-21
8. https://zenodo.org/record/3626071/files/libraries-1.6.0-2020-01-12.tar.gz last accessed 2022-03-21
9. https://github.com/cve-search/cve-search last accessed 2022-03-21
10. https://www.circl.lu/opendata/ last accessed 2022-03-21
a) Discussion: The results of this mapping, i.e. the vulnerable package counts, is compared with the other matching approaches in Figure 3. The figure is limited to the top-10 package managers wrt. number of mapped packages. The strict name mapping approach yields an unexpected low number of mapped packages for certain package managers. We identified the following issues: (i) In particular, Go packages provide the repository identifier consisting of provider, owner and repository name in the Libraries.io dump, while the CVE entry contains only the repository name. (ii) The CPE strings of CVE entries contain potentially wrong attribute values or lack some information as for instance the target_sw value. (iii) Additionally, various entries do not specify the package manager, neither in the CPE string nor inside the summary.

Additionally to comparing the amount of vulnerable packages, we grouped the CVE entries per year and package manager if we were able to create a mapping with the strict name mapping approach. This distribution as well as the trend of the top-7 package managers with the highest CVE count are depicted in Figure 4. Despite some fluctuating values, there is a noticeable upwards trend especially for the last few years.

2) Partial and Fuzzy Name Matching: In our second approach we build a lookup table for each package manager: we define specific keywords (e.g., NPM, Maven, etc.) for the CVE SUMMARY field and domain names or partial URLs (e.g., npmjs.com, pypi.org, etc.) for the REFERENCES. We iterate over each CVE entry, assign a package manager based on the lookup table, and check if the Libraries.io PLATFORM value equals the assigned package manager and if a value of the CVE PRODUCT list occurs either in the NAME or KEYWORDS fields. In case multiple Libraries.io entries match the CVE entry, our program uses a fuzzy string matching method provided by the fuzzysset2 python package with a cutoff value of 0.3 and chooses the entry with the highest similarity value.

3) Repository Matching: In order to increase the accuracy of the matching of software packages to CVE entries, we focus in this approach on the references in the respective CVE entries. The hypothesis is that the URLs in the references consist of the repository owner and repository name.

We use the value of the Libraries.io REPOSITORY URL field and extract the repository provider (i.e., github.com, bitbucket.org or gitlab.com) as well as the owner and the name of the repository. REPO_LINK contains the concatenated values of those fields. Additionally, we search for partial URLs of the format provider.tld/owner/repository in the CVE REFERENCES fields and store the results in a new array LINKS.

We iterate over the CVE entries and check whether the values of the LINKS array occur in the REPO_LINK field of any Libraries.io entry. First, we assigned the CVE entries to every

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1) Consider for instance the GitHub URLs, which include the organisation/owner and repository.

2) Fuzzy string matching is necessary, because some package names are concise, common words, such as “archiver”. These are often contained in other longer package names and result in a high amount of false positives.

3) https://pypi.org/project/fuzzysset2 last accessed 2022-03-21
package that matched the repository link resulting in very
different vulnerable package counts compared to the other
approaches. These results are shown in the “All Links” column
of Table [V] To determine the amount of multiply assigned
CVE entries, we reapedplied the approach and only counted
the first match of the repository link. Notably, in the “First
Link” column of Table [V], the vulnerable package count is
considerably lower. Figure [3] compares the “First Link” results
to the other matching methods.

Table V: Top-10 vulnerable package count per package man-
ger using the repository matching approach. “All Links”
counts all packages with a matching link, while “First Links”
only counts the first match.

| Package Manager | All Links | First Link |
|-----------------|-----------|------------|
| Go              | 13201     | 199        |
| NPM             | 5359      | 510        |
| Maven           | 3396      | 171        |
| Pypi            | 458       | 224        |
| Rubygems        | 432       | 152        |
| NuGet           | 411       | 52         |
| Packagist       | 319       | 273        |
| Bower           | 265       | 114        |
| Homebrew        | 210       | 142        |
| Cargo           | 168       | 44         |

a) Discussion: We found, that various entries in the Lib-
raries.io dataset contain the same REPOSITORY URL or at
least the same combination of repository provider, owner and
repository name. A lot of them seem to be sub-packages that
are contained inside one repository or they erroneously contain
the URL of the main project. Table [VI] shows the ten most
common REPO_LINK values and the respective package count.

Table VI: Count of the 10 most occurring repositories in the Libraries.io dataset.

| Repository                  | Count |
|-----------------------------|-------|
| github.com/openshift/origin | 1523  |
| github.com/kubernetes/kubernetes | 1181 |
| github.com/liferay/liferay-portal | 508  |
| github.com/facebook/create-react-app | 508  |
| github.com/lodash/lodash | 499   |
| github.com/hyperledger/fabric | 487  |
| github.com/apereo/cas | 353   |
| github.com/docker/docker | 350   |
| github.com/golang/go | 277   |
| github.com/jupyterlab/jupyterlab | 266  |

While counting all occurrences results in assigning a high
number of non-vulnerable packages, matching only the first
entry results in wrong mappings and potentially missed vul-
nerable sub-packages.

C. Identified Challenges

To summarize, we identified the following challenges when
mapping CVE to open source packages:

1) No clear repository identifiers: The CVE entries do not
contain clear identifiers of the code base in the corres-
ponding package manager and/or software repository.
2) Incomplete or wrong CVE entries: The CVE list contains
potentially wrong attribute values or lacks some critical
information to map to corresponding code bases.
3) Multiple relevant software packages: In some cases, the
CVE entry relates to multiple software packages and
potentially multiple code repositories.
4) Reliable datasets: There is no complete and reliable index
of open source projects; the Libraries.io data is potentially
erroneous and incomplete.

The mapping approaches allowed us to derive some insights
regarding the number of vulnerabilities for certain package
managers (cf. Figure [3], in particular, the strict name mapping
approach displayed a noticeable upwards trend in reported
vulnerabilities in recent years (Figure [4]), however, an im-
proved approach and a thorough evaluation is necessary to
reach robust conclusions.

V. RELATED WORK

The overview and analysis of the open-source landscape in
this paper is based on Libraries.io [2]. Alternatively, there
are various other works that monitor existing repositories
and provide quality and popularity metrics. For instance, the
PyDriller framework [4] is a tool to mine git-based software
repositories. In this respect, the GHTorrent framework [5]
collects and provides data for all public projects available on
Github and therefore is a very comprehensive resource for
analysis.

The detection and reporting of vulnerabilities and threats
in open-source software has been the subject of extensive
research for several years already [6]–[8]. In a recent paper,
Tan et al. report the deployment of security patches on stable
branches of open-source projects [9]. Similar to our approach,
the authors map CVE entries based on the name of an open-
source package. The approach is however based on manual
investigation of the software packages and the mappings.

Most related to our mapping of CVE entries to libraries
in open-source repositories is the work of Snyk.io[10] which
provides a monitoring service to identify vulnerable packages
and libraries. It consists of a detailed list of security reports
for various repositories and contains information about the
vulnerability, the name of the affected library, the versions
of the library that are affected, etc. Similarly, the GitHub
Advisory Database[15] is a list of CVEs and GitHub originated
security reports and vulnerabilities of software available on
the GitHub platform. In [10] the authors make use of Snyk.io
to provide an empirical study on vulnerable dependencies and
security policies in 600 open source projects.

14 https://snyk.io/, last accessed 2022-03-21
15 https://github.com/advisories, last accessed 2022-03-21
VI. CONCLUSION

Since an increasing amount of software packages use open-source components and libraries, potential vulnerabilities within such shared code bases affect not only the libraries themselves, but also the dependent packages. The re-use of software increases productivity and contributes to better maintained code, but can also lead to an increased distribution of vulnerabilities across different software packages. After being discovered, such common vulnerabilities are documented and information about them is shared via CVE entries.

In this work, we have provided insights in the landscape of open-source projects in popular package managers, and have discussed three approaches to map an up-to-date list of CVE entries to their respective software package. In our analyses we have discussed both, shortcomings and quality issues of the available data, and shortcomings of our mapping approaches wrt. accuracy and false-positive rate.

In future work, we plan the following research directions: Firstly, a thorough evaluation of the mapping approaches is required to provide more accurate results and to provide a large-scale mapping of CVE entries. Second, performing data cleansing on the Libraries.io and the CVE dataset would highly increase accuracy and would enable further analyses about software packages and their vulnerabilities. Third, research in improving the CVE standard; adding for instance additional meta-information such as a project identifier or project URL.

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