

CFTop: Using collaborative filtering to recommend Github topics

ABSTRACT

Collaborative filtering is a well-founded technique spreadly used in the recommendation system domain. During recent years, a plethora of approaches has been developed to provide the users with relevant items. Considering the open-source software (OSS) domain, GitHub has become a precious service for storing and managing software source code. To represent the stored projects in an effective manner, in 2017 GitHub introduced the possibility to classify them employing topics. However, assigning wrong topics to a given repository can compromise the possibility of helping other developers reach it and eventually contribute to its development. In this paper, we present CFTop, a recommender system to assist open source software developers in selecting suitable topics to the repositories. CFTop exploits a collaborative filtering technique to recommend libraries to developers by relying on the set of initial topics, which are currently included in the project being. To assess the quality of the approach, we exploit our previous work in this domain and validate both of them using different metrics. The results show that CFTop outperforms it in all the examined aspects. More interesting, the chain of the two approaches lead an improvement of the prediction performances.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

datasets, collaborative filtering, topic recommender

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1 INTRODUCTION

In recent years, the open-source software (OSS) community makes a daily usage of open source repositories to contribute their work as well as to access to projects coming from other developers. GitHub is one of the most well-known platforms that aggregate these projects and render possible the exchange of knowledge among the users. In order to aid information discovery and help developers identify projects that can be of their interest, GitHub introduced *topics*.

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They are words used to characterize projects, which thus can be annotated by means of lists of words that summarize projects' features. Thanks to the availability of *topics*, several applications are enabled, including the automated cataloging of GitHub repositories [?], further than allowing developers to explore projects by type, technology, and more.

Assigning the right topics to GitHub repositories is a crucial step that, if not properly done, can affect in a negative way their discoverability. In 2017, GitHub presented *repo-topix*, a topic suggestion tool essentially based on information retrieval techniques [?]. Although the mechanism works well so far and it is fully integrated with GitHub, in our opinion there is still some room for improvement, e.g., in terms of the variety of the suggested topics, novel data analysis techniques, and the investigation of new recommendation strategies.

We have already faced this problem in our previous work [?] by using a machine learning approach to recommend relevant topics given a README file of a repository. To this end, we exploited Multinomial Naïve Bayesian (MNB) network¹ to recommend only *featured* topics, a curated list of them provided by Github []. We limit the boundaries of this initial attempt due the internal construction of the model itself.

In this work, we propose to extend the set of recommended items to non-featured topics by exploiting collaborative filtering, a widely spread technique in the recommendation system domain [22]. Given an initial set of topics coming from a GitHub project, we use repository-topic matrixes to suggest relevant topics. The work gives the following contributions:

- Considering the GitHub projects as products, we suggest relevant topics to the project given an initial list of them;
- We assess the quality of the work employing a well-defined set of metrics commonly used in the recommendation system domain i.e., sales diversity, novelty, and accuracy;
- We extend our previous work in the domain considering the entire set of topics and use it as a baseline

The rest of the work is structured as follows. Section 2 shows the issues and the potential challenges in the domain. In Section 3, we present our approach and evaluate it in Section 4. We present the results of the assessment in Section 5 and we discuss the findings. Section 6 summarizes relevant works in the field and we conclude the paper in Section 7 with possible future works.

2 BACKGROUND

Manually assigning topics can be an error-prone activity that can lead to wrongly specified tags. Over the last years, several attempts have been made to *classify* GitHub projects by automatically inferring appropriate topics. In the context of data mining, *classification* is one of the critical operations that are used to dig deep into

¹For the sake of presentation, we refer to this work as MNB network throughout the paper

available data for gaining knowledge and for identifying repetitive patterns [?].

In [?] the authors present an approach based on *topic modeling* techniques to create categories of GitHub projects. Manual interventions are needed to refine initial sets of categories, which are identified by an LDA-GA technique, that combines two algorithms: Latent Dirichlet Allocation (LDA) and Genetic Algorithm (GA) [?]. The approach proposed in [?] is unsupervised, meaning that the categories of the catalogue being identified are not known ex-ante.

In a GitHub blog post [?] the author presents *repo-topix*, a tool to recommend topics for GitHub repositories. Such a tool combines NLP standard techniques to find an initial set of topics, by parsing the README files and the textual content of a repository e.g., the repository’s description. Then, they weight the results with the TF-IDF scheme and remove “bad” topics using a regression model. Using this refined list, *repo-topix* computes a custom version of Jaccard Distance to identify additional similar topics. To assess the quality of the framework, they made a rough evaluation based on ROUGE-1 metrics, an n-gram overlap metric that counts the number of overlapping units between the suggested topics and the repository description. Unfortunately, in [?] the author discusses an approximation of the repo-topix accuracy, without providing the reader with the complete dataset that was used and the source code of the developed tool.

With the aim of contributing the resolution of the problem of recommending GitHub topics, in the next section we propose to use item-based collaborative filtering to recommend relevant topics. The challenges that we had to cope with for evaluating its performance are mainly the following ones:

► *Dataset definition*: the creation of the datasets to be used for evaluating the approach being proposed and comparing it with some baseline is a daunting task: repositories might be moved, heavily changed or even deleted during the initial creation. Thus, the crawling activity can be negatively affected by these continuous changes and lead to lack of data, and poor topic coverage. GHTorrent² tries to mitigate this issue by offering daily dumps of the repositories’ metadata. However, this kind of data might not be enough or even appropriate (e.g., source code is not available in GHTorrent dumps) to properly classify an entire repository. Even considering directly GitHub data can be difficult: GitHub limits the total number of requests per hour to 5,000 for authenticated users and 60 for unauthorized requests. Considering all these constraints, building a suitable dataset represents a real challenge to be managed carefully.

► *Topics distribution*: although tags can be assigned only by the owners of GitHub repositories, users can potentially wrongly specify topics or introduce information overload by inserting too many elements. Thus, creating a reliable ground truth to assess the classification performance of the proposed approach represents another relevant difficulty.

3 PROPOSED APPROACH

In this section, we describe CFTop that provides developers with relevant topics for GitHub repositories. More specifically, CFTop

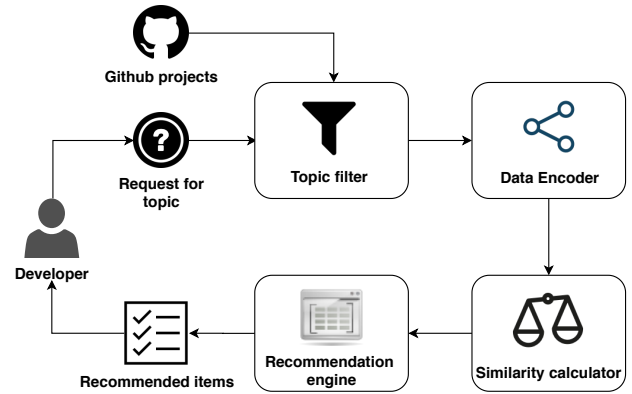


Figure 1: Overview of the CFTop Architecture.

is a *recommender system* [3] that encodes the relationships among different topics by means of a graph and utilizes a collaborative filtering technique [22] to recommend GitHub topics. Such a technique has been used mostly in the e-commerce domain to exploit the relationships among users and products to predict the missing ratings of recommended items [11]. The technique follows the assumption that “if users agree about the quality or relevance of some items, then they will likely agree about other items” [22]. Under the same premise, our tool aims to solve the problem of the reachability of a GitHub repository given a set of topics. Instead of recommending goods or services to customers, we recommend a set of topics using an analogous mechanism: “if a user tags his project with some topics, then similar projects will probably contain common topics.”

To this end, the architecture of CFTop is shown in Fig. 1, and consists of the software components supporting the following activities:

- *Representing the relationships* among projects and topics retrieved from existing repositories;
- *Computing similarities* to find projects, which are similar to that under development; and
- *Recommending topics* to projects using a collaborative-filtering technique.

In a typical usage scenario of CFTop, we assume that a developer is creating a new GitHub repository, in which she has already included some topics to improve its reachability. As shown in Fig. 1, the developer interacts with the system by demanding for recommendations. Such a request contains a list of topics that are already included in the project the developer is working on. As a preprocessing phase, we apply a *Topic filter* according to their frequencies i.e., the measured occurrences over all repositories in the initial dataset. The Graph Encoder represents the mentioned repositories in the graph format. This is a preparatory phase for the next steps of the recommendation process. The Similarity Calculator module computes similarities among topics to discover similar ones to recommend. The Recommendation Engine implements a *collaborative-filtering* technique [3],[24], it selects top-*k* similar topics, and performs computation to generate a ranked list

²<http://ghorrent.org/>

of *top-N* topics. Finally, the final list of topics is sent back to the developer.

The aforementioned components are singularly described in the next sections.

3.1 Topic filter

As a preprocessing, we filter the initial set of topics using their frequencies counted on the entire GitHub dataset. We remove irrelevant topics to reduce the noise in the prediction phase. Through the *cut-off* value, we progressively increase the frequency threshold to evaluate possible impacts on overall performances. As stated in [9], this preprocessing can improve the final results, thus we decide to apply it as a first step.

3.2 Graph Encoder

A recommender system for online services is based on three key components, namely *users*, *items*, and *ratings* [21],[17]. A *user-item ratings matrix* is built to represent the mutual relationships among the components. Specifically, in the matrix a user is represented by a row, an item is represented by a column and each cell in the matrix corresponds to a rating given by a user for an item [17]. For topic recommendation, instead of users and items, there are projects and topics, and a project may include various topics to better describe the project. We derive an analogous user-item ratings matrix to represent the *project-library inclusion* relationships, denoted as \exists . In this matrix, each row represents a project and each column represents a topic. A cell in the matrix is set to 1 if the topic in the column is included in the project specified by the row, it is set to 0 otherwise. For the sake of clarity and conformance, we still denote this as a user-item ratings matrix throughout this paper.

For explanatory purposes, we consider a set of four projects $P = \{p_1, p_2, p_3, p_4\}$ together with a set of topics $L = \{topic_1=machine-learning; topic_2=javascript; topic_3=database; topic_4=web; topic_5=algorithm\}$. By extracting the list of defined topics of the projects in P , we discovered the following inclusions: $p_1 \ni topic_1, topic_2$; $p_2 \ni topic_1, topic_3$; $p_3 \ni topic_1, topic_3, topic_4, topic_5$; $p_4 \ni topic_1, topic_2, topic_4, topic_5$. Accordingly, the user-item ratings matrix built to model the occurrence of the topic is depicted in Fig. 2.

$$\begin{matrix}
 & \begin{matrix} topic_1 & topic_2 & topic_3 & topic_4 & topic_5 \end{matrix} \\
 \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{matrix} & \begin{pmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \end{pmatrix}
 \end{matrix}$$

Figure 2: An example of a user-item ratings matrix to model the inclusion of topics in GitHub repositories.

3.3 Similarity Calculator

The Recommendation Engine of CFTop works by relying on an analogous user-item ratings matrix. To provide inputs for this module, the first task of CFTop is to perform similarity computation on its input data to find the most similar projects to a given project. In

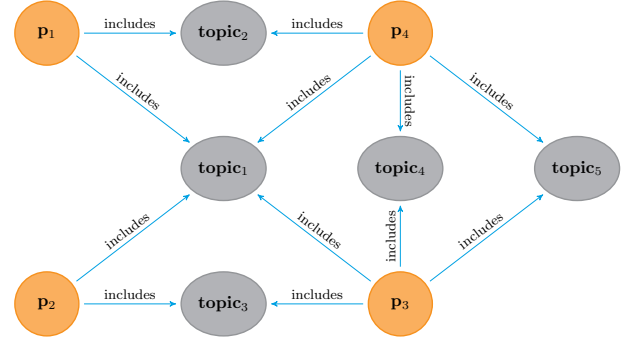


Figure 3: Graph representation for projects and libraries.

this respect, the ability to compute the similarities among projects has an effect on the recommendation outcomes. Nonetheless, computing similarities among software systems is considered to be a difficult task [12]. In addition, the diversity of artifacts in OSS repositories as well as their cross relationship makes the similarity computation become even more complicated. In OSS repositories, both humans (i.e., developers and users) and non-human actors (such as repositories, and libraries) have mutual dependency and implication on the others. The interactions among these components, such as developers commit to or star repositories, or projects include libraries, create a tie between them and should be included in similarity computation.

We assume that a representation model that addresses the semantic relationships among miscellaneous factors in the OSS community is beneficial to project similarity computation. To this end, we consider the community of developers together with OSS projects, topics, and their mutual interactions as an *ecosystem*. We derive a *graph-based* model to represent different kinds of relationships in the OSS ecosystem, and eventually to calculate similarities. In the context of mining OSS repositories, the graph model is a convenient approach since it allows for flexible data integration and numerous computation techniques. By applying this representation, we are able to transform the set of projects and topics shown in Fig. 2 into a directed graph as in Fig. 3. We adopted our proposed CrossSim approach [14],[15] to compute the similarities among OSS graph nodes. It relies on techniques successfully exploited by many studies to do the same task [8],[5]. Among other relationships, two nodes are deemed to be similar if they point to the same node with the same edge. By looking at the graph in Fig. 3, we can notice that p_3 and p_4 are highly similar since they both point to three nodes $topic_1, topic_4, topic_5$. This reflects what also suggested in a previous work by McMillan et al. [12], i.e., similar projects implement common pieces of functionality by using a shared set of libraries.

Using this metric, the similarity between two project nodes p and q in an OSS graph is computed by considering their feature sets [8]. Given that p has a set of neighbor nodes ($topic_1, topic_2, \dots, topic_l$), the features of p are represented by a vector $\vec{\phi} = (\phi_1, \phi_2, \dots, \phi_l)$,

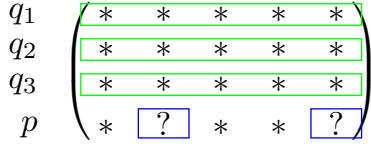


Figure 4: Computation of missing ratings using the user-based collaborative-filtering technique [24].

with ϕ_i being the weight of node $topic_i$. It is computed as the *term-frequency inverse document frequency* value as follows:

$$\phi_i = f_{topic_i} \times \log\left(\frac{|P|}{a_{topic_i}}\right) \quad (1)$$

where f_{topic_i} is the number of occurrence of $topic_i$ with respect to p , it can be either 0 and 1 since there is a maximum of one $topic_i$ connected to p by the edge *includes*; $|P|$ is the total number of considered projects; a_{topic_i} is the number of projects connecting to $topic_i$ via the edge *includes*. Eventually, the similarity between p and q with their corresponding feature vectors $\vec{\phi} = \{\phi_i\}_{i=1,\dots,l}$ and $\vec{\omega} = \{\omega_j\}_{j=1,\dots,m}$ is computed as given below:

$$sim(p, q) = \frac{\sum_{t=1}^n \phi_t \times \omega_t}{\sqrt{\sum_{t=1}^n (\phi_t)^2} \times \sqrt{\sum_{t=1}^n (\omega_t)^2}} \quad (2)$$

where n is the cardinality of the set of libraries that p and q share in common [8]. Intuitively, p and q are characterized by using vectors in an n -dimensional space, and Eq. 2 measures the cosine of the angle between the two vectors.

3.4 Recommendation Engine

Phuong ▶Please rephrase this section◀ The representation using a user-item ratings matrix allows for the computation of missing ratings [3], [17]. Depending on the availability of data, there are two main ways to compute the unknown ratings, namely *content-based* [18] and *collaborative-filtering* [13] recommendation techniques. The former exploits the relationships among items to predict the most similar items. The latter computes the ratings by taking into account the set of items rated by similar customers. There are two main types of collaborative-filtering recommendation: *user-based* [24] and *item-based* [21] techniques. As their names suggest, the user-based technique computes missing ratings by considering the ratings collected from similar users. Instead, the item-based technique performs the same task by using the similarities among items [6].

In the context of <RECOMMENDER ACRONYM>, the term *rating* is understood as the occurrence of a library in a project and computing missing ratings means to predict the inclusion of additional libraries. The project that needs prediction for library inclusion is called the *active project*. By the matrix in Fig. 4, p is the active project and an asterisk (*) represents a known rating, either 0 or 1, whereas a question mark (?) represents an unknown rating and needs to be predicted.

Given the availability of the cross-relationships as well as the possibility to compute similarities among projects using the graph

representation, we exploit the user-based collaborative-filtering technique as the engine for recommendation [11, 24]. Given an active project p , the inclusion of libraries in p can be deduced from projects that are similar to p . The process is summarized as follows:

- Compute the similarities between the active project and all projects in the collection;
- Select *top-k* most similar projects; and
- Predict ratings by means of those collected from the most similar projects.

The rectangles in Fig. 4 imply that the row-wise relationships between the active project p and the similar projects q_1, q_2, q_3 are exploited to compute the missing ratings for p . The following formula is used to predict if p should include l , i.e., $p \ni l$ [17]:

$$r_{p,l} = \bar{r}_p + \frac{\sum_{q \in topsim(p)} (r_{q,l} - \bar{r}_q) \cdot sim(p, q)}{\sum_{q \in topsim(p)} sim(p, q)} \quad (3)$$

where \bar{r}_p and \bar{r}_q are the mean of the ratings of p and q , respectively; q belongs to the set of *top-k* most similar projects to p , denoted as $topsim(p)$; $sim(p, q)$ is the similarity between the active project and a similar project q , and it is computed using Equation 2.

4 EVALUATION

This section describes the planning of our evaluation, having the *goal* of evaluating the performance of the proposed approach. In Section 4.1, we introduce the dataset exploited in our evaluation. The evaluation methodology and metrics are presented in Section 4.2. Finally, Section 4.3 describes the research questions.

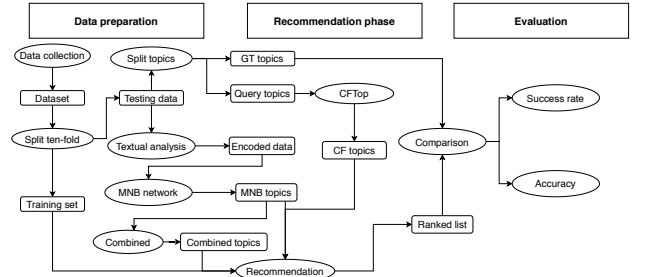


Figure 5: Evaluation Process.

The evaluation process is depicted in Fig. 5 and it consists of three consecutive phases, i.e., *Data Preparation*, *Recommendation*, and *Outcome Evaluation*. We start with the *Data Preparation* phase by creating a dataset from GitHub projects. This dataset is used to evaluate CFTop, MNB network, and the combination of two. The dataset is then split into training and testing sets. The *Recommendation* phase follows three different flows, according to the required input and produced output of the three mentioned approaches. To enable CFTop, we extract a portion of topics from a given testing project i.e., the ground-truth part. The left part is used as a query to produce recommendations. As the MNB network uses the README file of a repository to predict a set of topics, this doesn't require any topic as input. Thus, the approach encodes the document relevant information in vectors using the TF-IDF weighting scheme. This encoded data is used to feed the network that delivers a set

of topics. These recommendations are used in the entangled approach, in which CFTop is fed with the MNB network suggested topics. All the results are assessed in the *Outcome Evaluation* phase, which compares the recommendation results with those stored as ground-truth data to compute the quality metrics.

4.1 Dataset Extraction

To evaluate the approach, we reuse the same dataset employed for the MNB network available here [?].

By means of the GitHub API [1] we *randomly* collected a dataset consisting of 6,258 repositories that use 15757 topics. Using a project's name as a query, we can retrieve different types of information such as commits, issues, and name of the repository's owner, and the list of topics. By using the GitHub query language [2], we applied the following query filter:

$$Qf = "is : featured topic : t stars : 100..80000 topics :>= 2" \quad (4)$$

to consider only GitHub repositories having a number of stars between 100 and 80,000, and tagged with at least two topics. We set such a filter after several query refinements, as the chosen featured topics have a different degree of popularity. For instance, the most starred project of the *3d* topic has around 53,000 stars; reversely, some other topics have top rank projects that do not reach 1,000 stars. Thus, we tried to select the best query filter to include a sufficient number of repository for each topic. We also impose an additional filter on the topics frequencies, to prune unpopular ones from the dataset. We made this choice as our boundaries include also non-featured topics in the comparison.

GitHub developers use stars as a voting mechanism to foster the popularity of a certain project []. Through this system, each user can support her/his favorite projects available on the platform. Forking is another index related to the quality of the project. This feature is typically employed as a starting point for a new project [10]. Furthermore, there is a strong correlation between forks and stars [4]. In this sense, we suppose that a project with a high number of stars means that it gets attention from the OSS community and thus being suitable to identify popular repositories [? ?].

4.2 Metrics' Definition

To assess the performance of <RECOMMENDER ACRONYM> proposed approach, we applied ten-fold cross-validation, considering every time 9 folds (each one contains 625 projects) for training and the remaining one for testing. For every testing project p , a half of its topics are *randomly* taken out and saved as ground truth data, let us call them $GT(p)$, which will be used to validate the recommendation outcomes. The other half are used as testing libraries or query, which are called te , and serve as input for Similarity Computation and Recommendation. The splitting mimics a real development process where a developer has already included some topics in the current project, i.e., te and waits for recommendations, that means additional topics to be incorporated. A recommender system is expected to provide her with the other half, i.e., $GT(p)$.

There are several metrics available to evaluate a ranked list of recommended items [17]. In the scope of this paper, *success rate*, *accuracy*, *sales diversity*, and *novelty* have been used to study the systems' performance as already proposed by Robillard et al. [19]

and other studies [23],[16]. For a clear presentation of the metrics considered during the outcome evaluation, let us introduce the following notations:

- N is the cut-off value for the ranked list;
- k is the number of neighbor projects exploited for the recommendation process;
- For a testing project p , a half of its libraries are extracted and used as the ground-truth data named as $GT(p)$;
- $REC(p)$ is the *top-N* libraries recommended to p . It is a ranked list in descending order of real scores;
- If a recommended library $l \in REC(p)$ for a testing project p is found in the ground truth of p (i.e., $GT(p)$), hereafter we call this as a library *match* or *hit*.

If $REC_N(p)$ is the set of top- N items and $match_N(p) = GT(p) \cap REC_N(p)$ is the set of items in the *top-N* list that match with those in the ground-truth data, then the metrics are defined as follows.

Success rate@N. Given a set of testing projects P , this metric measures the rate at which a recommender system returns at least a topic match among *top-N* items for every project $p \in P$ [23]:

$$success\ rate@N = \frac{count_{p \in P}(|match_N(p)| > 0)}{|P|} \quad (5)$$

where the function *count()* counts the number of times that the boolean expression specified in its parameter is *true*.

Accuracy. Accuracy is considered as one of the most preferred *quality indicators* for Information Retrieval applications [20]. However, *success rate@N* does not reflect how accurate the outcome of a recommender system is. For instance, given only one testing project, there is no difference between a system that returns 1 topic match out of 5 and another system that returns all 5 topic matches, since *success rate@5* is 100% for both cases (see Eq. (5)). Thus, given a list of *top-N* libraries, *precision@N* and *recall@N* are utilized to measure the *accuracy* of the recommendation results. *precision@N* is the ratio of the *top-N* recommended topics belonging to the ground-truth dataset, whereas *recall@N* is the ratio of the ground-truth topics appearing in the N recommended items [14],[8],[7]:

$$precision@N = \frac{|match_N(p)|}{N} \quad (6)$$

$$recall@N = \frac{|match_N(p)|}{|GT(p)|} \quad (7)$$

4.3 Research Questions

By performing the evaluation, we aim at addressing the following research questions:

- **RQ₁:** *How the approach settings impact on the prediction performance?* To answer this question, we investigate different configurations to find the best one. In particular, we variate the number of input topics and the number of neighbors
- **RQ₂:** *How the parameters have been evaluated?* We compute the metrics given in Section 4.2 to evaluate different parameter settings
- **RQ₃:** *How CFTop behave with respect the MNB network in terms of prediction performance?* As the two approaches have a completely different internal structure, we are interested in investigating the reasons behind such quality variation

- **RQ₄**: *Is the chain of approaches able to improve CFTop's overall performance?* From an empirical point of view, it is relevant to analyze the combination of the two approaches and measure its performances

We study the experimental results in the next section by referring to these research questions.

5 RESULTS

This section discusses the findings of the qualitative assessment. To address the formulated research questions, we perform three different experiments i.e., EXP1, EXP2, and EXP3. In the first one, we measure the performance of the MNB approach considering also not-featured topics (see 5.1). EXP2 considers the proposed approach in this work and the results are shown in Section 5.2. To answer ..., we combine the two approaches and evaluate them in Section 5.3.

5.1 CFTop evaluation

5.2 MNB network evaluation

5.3 Entangled evaluation

6 RELATED WORK

This section discusses both (i) approaches based on collaborative filtering techniques in recommending activity and (ii) works that mine GitHub projects.

6.1 Recommends item by means of collaborative filtering

Amazon [11] proposes an item-to-item recommendation system to suggest relevant products to the final user.

6.2 Recommending OSS using GitHub topics

7 CONCLUSIONS AND FUTURE WORK

conclusion

REFERENCES

- [1] [n.d.]. GitHub REST API v3. <https://developer.github.com/v3/>. last accessed 16.06.2019.
- [2] 2019. Understanding the search syntax - GitHub Help. <https://help.github.com/en/github/searching-for-information-on-github/understanding-the-search-syntax>
- [3] Charu Aggarwal. 2016. *Neighborhood-Based Collaborative Filtering*. Springer International Publishing, Cham, 29–70. https://doi.org/10.1007/978-3-319-29659-3_2
- [4] Hudson Borges, André C. Hora, and Marco Tulio Valente. 2016. Understanding the Factors That Impact the Popularity of GitHub Repositories. In *2016 IEEE International Conference on Software Maintenance and Evolution, ICSME 2016, Raleigh, NC, USA, October 2-7, 2016*. IEEE Computer Society, 334–344. <https://doi.org/10.1109/ICSME.2016.31>
- [5] Cristian E. Briguez, Maximiliano C.D. Budán, Crisithian A.D. Deagustini, Ana G. Maguitman, Marcela Capobianco, and Guillermo R. Simari. 2014. Argument-based mixed recommenders and their application to movie suggestion. *Expert Systems with Applications* 41, 14 (2014), 6467 – 6482. <https://doi.org/10.1016/j.eswa.2014.03.046>
- [6] Paolo Cremonesi, Roberto Turrin, Eugenio Lentini, and Matteo Matteucci. 2008. An Evaluation Methodology for Collaborative Recommender Systems. In *Proceedings of the 2008 International Conference on Automated Solutions for Cross Media Content and Multi-channel Distribution (AXMEDIS '08)*. IEEE Computer Society, Washington, DC, USA, 224–231. <https://doi.org/10.1109/AXMEDIS.2008.13>
- [7] Jesse Davis and Mark Goadrich. 2006. The Relationship Between Precision-Recall and ROC Curves. In *Proceedings of the 23rd International Conference on Machine Learning (Pittsburgh, Pennsylvania, USA) (ICML '06)*. ACM, New York, NY, USA, 233–240. <https://doi.org/10.1145/1143844.1143874>
- [8] Tommaso Di Noia, Roberto Mirizzi, Vito Claudio Ostuni, Davide Romito, and Markus Zanker. 2012. Linked Open Data to Support Content-based Recommender Systems. In *Proceedings of the 8th International Conference on Semantic Systems (Graz, Austria) (I-SEMANTICS '12)*. ACM, New York, NY, USA, 1–8. <https://doi.org/10.1145/2362499.2362501>
- [9] Ganesan. 2019. Topic Suggestions for Millions of Repositories - The GitHub Blog. <https://github.blog/2017-07-31-topics/>
- [10] Jing Jiang, David Lo, Jiahuan He, Xin Xia, Pavneet Singh Kochhar, and Li Zhang. 2017. Why and How Developers Fork What from Whom in GitHub. *Empirical Software Engineering* 22, 1 (Feb. 2017), 547–578. <https://doi.org/10.1007/s10664-016-9436-6>
- [11] Greg Linden, Brent Smith, and Jeremy York. 2003. Amazon.Com Recommendations: Item-to-Item Collaborative Filtering. *IEEE Internet Computing* 7, 1 (Jan. 2003), 76–80. <https://doi.org/10.1109/MIC.2003.1167344>
- [12] Collin McMillan, Mark Grechanik, and Denys Poshyvanyk. 2012. Detecting Similar Software Applications. In *Proceedings of the 34th International Conference on Software Engineering (Zurich, Switzerland) (ICSE '12)*. IEEE Press, Piscataway, NJ, USA, 364–374. <http://dl.acm.org/citation.cfm?id=2337223.2337267>
- [13] Catarina Miranda and Alípio M. Jorge. 2008. Incremental Collaborative Filtering for Binary Ratings. In *Proceedings of the 2008 IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology - Volume 01 (WI-IAT '08)*. IEEE Computer Society, Washington, DC, USA, 389–392. <https://doi.org/10.1109/WIAT.2008.263>
- [14] Phuong T. Nguyen, Juri Di Rocco, Davide Di Ruscio, Lina Ochoa, Thomas Degueule, and Massimiliano Di Penta. 2019. FOCUS: A Recommender System for Mining API Function Calls and Usage Patterns. In *Proceedings of the 41st International Conference on Software Engineering (Montreal, Quebec, Canada) (ICSE '19)*. IEEE Press, Piscataway, NJ, USA, 1050–1060. <https://doi.org/10.1109/ICSE.2019.00109>
- [15] P. T. Nguyen, J. Di Rocco, R. Rubel, and D. Di Ruscio. 2018. CrossSim: Exploiting Mutual Relationships to Detect Similar OSS Projects. In *2018 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA)*. 388–395. <https://doi.org/10.1109/SEAA.2018.00069>
- [16] Phuong T. Nguyen, Paolo Tomeo, Tommaso Di Noia, and Eugenio Di Sciascio. 2015. An Evaluation of SimRank and Personalized PageRank to Build a Recommender System for the Web of Data. In *Proceedings of the 24th International Conference on World Wide Web (Florence, Italy) (WWW '15 Companion)*. ACM, New York, NY, USA, 1477–1482. <https://doi.org/10.1145/2740908.2742141>
- [17] Tommaso Di Noia and Vito Claudio Ostuni. 2015. Recommender Systems and Linked Open Data. In *Reasoning Web. Web Logic Rules - 11th International Summer School 2015, Berlin, Germany, July 31 - August 4, 2015, Tutorial Lectures*. 88–113. https://doi.org/10.1007/978-3-319-21768-0_4
- [18] Michael J. Pazzani and Daniel Billsus. 2007. *Content-Based Recommendation Systems*. Springer Berlin Heidelberg, Berlin, Heidelberg, 325–341. https://doi.org/10.1007/978-3-540-72079-9_10
- [19] Martin Robillard, Robert Walker, and Thomas Zimmermann. 2010. Recommendation Systems for Software Engineering. *IEEE Softw.* 27, 4 (July 2010), 80–86. <https://doi.org/10.1109/MS.2009.161>
- [20] Tefko Saracevic. 1995. Evaluation of Evaluation in Information Retrieval. In *Proceedings of the 18th Annual International ACM SIGIR Conference on Research and Development in Information Retrieval (Seattle, Washington, USA) (SIGIR '95)*. ACM, New York, NY, USA, 138–146. <https://doi.org/10.1145/215206.215351>
- [21] Badrul Sarwar, George Karypis, Joseph Konstan, and John Riedl. 2001. Item-based Collaborative Filtering Recommendation Algorithms. In *Proceedings of the 10th International Conference on World Wide Web (Hong Kong, Hong Kong) (WWW '01)*. ACM, New York, NY, USA, 285–295. <https://doi.org/10.1145/371920.372071>
- [22] J. Ben Schafer, Dan Frankowski, Jon Herlocker, and Shilad Sen. 2007. *The Adaptive Web*. Springer-Verlag, Berlin, Heidelberg, Chapter Collaborative Filtering Recommender Systems, 291–324. <http://dl.acm.org/citation.cfm?id=1768197.1768208>
- [23] Ferdian Thung, David Lo, and Julia Lawall. 2013. Automated library recommendation. In *2013 20th Working Conference on Reverse Engineering (WCRE)*. 182–191. <https://doi.org/10.1109/WCRE.2013.6671293>
- [24] Zhi-Dan Zhao and Ming-sheng Shang. 2010. User-Based Collaborative-Filtering Recommendation Algorithms on Hadoop. In *Proceedings of the 2010 Third International Conference on Knowledge Discovery and Data Mining (WKDD '10)*. IEEE Computer Society, Washington, DC, USA, 478–481. <https://doi.org/10.1109/WKDD.2010.54>