

1. Introduction

Software is a fundamental part of the modern life. We depend on the operation of software whether we are watching a video, traveling on a plane, calling a friend or using electricity power. Human life [1] and huge monetary losses [2] may be caused by non addressed issues in unreliable software components. Software quality assurance is the collection activities for ensuring the requirements compliant operation of software [3]. Similar to all economical activities, software quality assurance is constrained by the budget of software projects. Efficient allocation of software quality assurance resources is crucial for the development of more reliable software. Development of a large software is beyond the technical capabilities of a single person or a few people. For this reason, large software is built and tested through the collaboration of many developers. Efficient coordination of the developers during the software quality assurance activities is one of the fundamental problems of software engineering.

Delivering a software bug-free is practically impossible due to budget and time constraints. Software are released with an unknown amount of inherent issues. It is a common belief in software engineering that as the number of eyeballs increase bugs become easier to notice [4]. Therefore after the release of a software, one of the most important part of software quality assurance is the publicly available issue management systems. In the issue management process, developers own (or get assigned to) issues reported by testing teams or software users. The key problem of this process is assigning the right developer to the right issue and suggesting defect-prone parts of the software that may be related to the reported issue to the developers. In organizations twenty five percent of the time is spent while waiting for decisions [5]. We can increase the efficiency of issue management process by building an automated issue recommendation system to reduce the idle waiting time. In this dissertation, our research questions can be listed as follows:

- (i) How can we assign issues to developers?
- (ii) How can developers more efficiently organize their time in solving their issues?

1.1. Software Networks

Large software can be classified as complex systems. Artificial and natural complex systems arise from the nature of the relations between many relatively simple entities [6]. Graph is a useful abstraction in computer science used to model complex systems and it is used widely in a range of application areas [7, 8, 9, 10]. In recent years, there has been considerable interest in modeling different complex systems as networks and various researchers examined the network properties in order to identify similarities among networks from diverse domains [9]. Scale-free networks are a group of networks from diverse domains that surprisingly share similar properties [8]. Networks such as academical collaboration, epidemics, world wide web and internet routers show some similar properties such as power-law degree distribution and low network diameter[8]. In the software domain, researchers have found that many dependency networks of large software systems are scale-free networks [11].

In software engineering, research on software networks goes back to early 1980s [12]. In the early years, most of the research has been on building the dependency graph for various programming languages and execution environments. Over the years, interest of researchers moved to investigating the relation of the dependency network and software quality. For this aim various researchers extracted metrics from dependency graphs based on common global and local properties of the graphs.

More recently, the edits on same software modules have been used to construct a collaboration network among developers similar to scientific collaboration network. This information has been used in empirical context in research on defect prediction models [13] and exploratory studies [14]. One reason behind this surge of interest may be the emergence of global software development [15]. Software network has been mostly studied for exploratory research previously. In this research, we used the software network to model the relation of issues with developers using the co-edits on same defective software modules related to the same category of issues to form the collaboration links among developers.

1.2. Issue Recommendation System

Recommendation systems are a subclass of information filtering system that seek to predict the 'rating' or 'preference' that a user would give to an item [16]. The recommendation system we propose is made of two core components namely bug triager and a live defect predictor. Bug triage is assigning a developer to the most relevant issue based on past data [17]. Assigning a bug report to an owner has been shown to take five minutes per report on average for large software [17]. For popular projects, this task may make up the entire workload of several people. Previously, bug triage problem has been addressed by estimating the text similarity among issues. This approach has various shortcomings such as language and issue report content dependence. In our case, we recommend the issue to the developer based on the experience ranking of developers on the similar issue category based on their collaboration activity on the defects.

Live defect prediction is the prediction of defect-prone modules related to an issue. A defect predictor can be used to propose defect-prone modules to the assigned owner of an issue. In most defect prediction models the output of the model is provided at a special snapshot such as the production release or beginning of testing phase [18]. In our model we extend the machine learning based model by using the historical defect proneness data of related software modules using the call-graph of the software to propose defect prone modules *live* (at any point during development).

In order to build such a recommender, the mapping between the issues and defects has also been investigated in order to understand their relation with each other. In addition a new defect predictor has been built in order to detect defective modules live at any point during software maintenance.

If we examine the successful applications of AI that are widely used in practice, we observe that most of them need minimum interference by their users. Successful applications such as movie recommenders, machine translators, image recognizers fit easily to the existing work flow of the users. Since the most common element in the

work flow of developers regarding quality assurance is issue management system, we believe that a practical recommendation system should fit easily to the issue management process. In order to make our issue recommender easily pluggable to the issue management software, we use data that can be extracted with automated tools from the issue and source code repositories.

1.3. Contributions

In this research we built an issue recommendation system using the collaboration network and the call graph of the software in order to increase the efficiency of resource allocation during the software quality assurance activities. Contributions of this research can be summarized as follows:

- *Model the software as the combination of developer collaboration network and the call graph:* We modeled software as the combination of developer collaboration and software call-graph networks. Collaboration is defined as the activity on the similar software modules by two developers during a release. Call graph is formed by the caller-callee relations of software modules. We showed the static and temporal properties of the software collaboration network for a large scale software and their relation with software issues.
- *Build an issue recommendation system using developer collaboration network:* Developer collaboration network shows the experience and centrality of developers within the organization. We used the symptom and category information of the issues to categorize the past issues and built the collaboration network for each cluster. Our model ranked the developers based on their centrality within the collaboration network and recommended the new issue reports based on the ranking.
- *Address developer workload balance problem using the issue recommendation model:* We extended the issue recommendation model to address the issue workload balancing problem. Issue workload balancing is a critical problem in real projects. We initially showed that in two large software, issues are distributed non-uniformly among maintainers especially during the times when active issue count is highest.

One problem of the base recommendation model was the lack of workload balance among developers that may occur when the recommendations of the model were used for issue assignment. We used an approach based on heuristics in order to overcome the problem of issue workload imbalances. Model that used workload balancing heuristics performed worse than the model with no heuristics but distributed issues more uniformly than the original model. Imbalances of the actual issue assignments may be the possible reason for the reduction of performance.

- *Usage of Kronecker networks to estimate the future collaborations of new developers:* Cold start is a common problem in recommender systems and it happens when a new user or item (issue) is added to the system. In our recommender, we solved the item(issue) cold start problem with a content based approach. We categorized the new issue into an existing category and afterwards ran the recommender algorithm.

Recommending new issues to developers is a more serious problem for the issue recommender. It is a part of the problem of introducing new people to existing software development teams. As the project progresses initiation of new people gets harder. There is a lot of knowledge to be transferred to the new people which reduces the productivity of both old and new employees during initiation. Fred Brooks claims that the addition of new people may even cause later project delivery dates [19].

We used the Kronecker network to address the new people cold start problem in the issue recommendation system. We used a parametric modelling method proposed by Leskovec Et al. [20, 21, 22] named Kronocker network to model the future state of the software collaboration network. We chose Kronecker graph generator since it is the only method that produce networks that conform all the properties of scale free networks. Kronecker networks are formed by fitting Kronecker parameters to the actual network and recursively replicating stochastic Kronecker kernel adjacency matrix by a matrix operation called Kronecker product.

The Kronecker network approach can be used to recommend issues only to a new group of developers since the node labels of the generated network can not be inferred. The state of the future collaboration network can be estimated using

the Kronecker parameters and issues can be recommended to the new group of developers.

- *Live defect prediction:* In traditional defect prediction models the defect prone-ness prediction for software modules is given for certain snapshots during the software project life-cycle such as the release revision or beginning of the testing phase to help managers allocate their testing resources. However, defect prone modules data is also valuable for developers at any time during maintenance. We updated the predictions of the machine learning based prediction model based on the live history of the software modules in the software call-graph to showed the defect prone software modules any time during development.
- *Empirical analysis of the issue recommendation system and the live defect prediction model:* In our research, we collected the development data of one industrial large-scale software developed at five international sites as a dataset. The software is produced with the collaboration of more than two hundred developers. We extracted all the issue, collaboration activity and all the code change information over a time span of five years which includes two major releases of the product. We tested the issue recommendation model and its extensions on the extracted datasets and compared its performance with actual issue assignments. We showed that our model performance is better than the state of the art text similarity based issue recommendation systems. We showed the performance of Kronecker networks in addressing the people cold-start problem and the performance of the workload-balancing recommendation system extensions.

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