Improved dependency management for issue trackers in large collaborative projects

Mikko Raatikainen, Quim Motger, Clara Marie Lüders, Xavier Franch, Lalli Myllyaho, Elina Kettunen, Jordi Marco, Juha Tiihonen, Mikko Halonen, and Tomi Männistö

Abstract—Issue trackers, such as Jira, have become the prevalent collaborative tools in software engineering for managing issues, such as requirements, development tasks, and software bugs. However, issue trackers inherently focus on the life-cycle of single issues although issues have and express dependencies on other issues that constitute an issue dependency network in a large complex collaborative projects. The objective of this study is to develop supportive solutions for the improved management of dependent issues in an issue tracker. This study follows Design Science methodology, consisting of elicitation of drawbacks, and construction and evaluation of a solution and system. The study was carried out in the context of The Qt Company’s Jira, which exemplifies an actively used, almost two decade old issue tracker with over 100,000 issues. The drawbacks capture how users operate with issue trackers to handle issue information in large, collaborative and long-lived projects. The basis of the solution is to keep issues and dependencies as separate objects and automatically construct an issue graph. Dependency detection complements the issue graph by proposing missing dependencies, and consistency check and diagnosis identify incompatible issue priorities and release assignments. Jira’s plugin and service-based system architecture realizes the functional and quality concerns of the system implementation. We show how to adopt the supporting intelligent techniques of an issue tracker in a complex use context and a large data-set. The solution takes into account integrated and holistic system-view, practical applicability and utility, and the practical characteristics, such as inherent incompleteness, of issue data.

1 INTRODUCTION AND MOTIVATION

Issue management is a fundamental activity in many of today’s software development projects, and is especially prevalent in open-source software development projects. It consists of the identification and resolution of new requirements, development tasks, unexpected problems, software bugs, and questions (i.e., the issues) that may arise at any moment during the project. As issues convey important observations, failing to manage issues may result in delays, quality problems, or even complete failure of the software project [1]. Due to this critical nature, as well as the complexity that it entails, particularly in large collaborative projects, issue management is usually tool-supported: software engineering teams use issue trackers to report, manage, and resolve software project related issues [2]. Issue trackers are typically used collaboratively by various project stakeholders, including project managers, developers, and even end-users.

In this complex, collaborative environment, issues cannot be conceived as independent entities. Instead, issues affect each other through various types of dependencies, which form an issue dependency network. For example, a reported issue might be part of a major bug, or a bug might contribute to a specific requirement, or two issues might refer to the same topic. In fact, dependencies are one of the key concerns that need to be considered in various software engineering planning activities, such as requirements prioritization [3] [4], and release planning [5] [6].

Even though issue trackers usually allow the expression of dependencies, they are still specified in relation to an individual issue and, in practice, not always reported. Moreover, issue trackers have been designed primarily to provide stakeholders with specialized support for each individual issue and its properties throughout its life-cycle. Advanced understanding as well as analytical and management features over issue dependency network are not well supported. Although some well-known issue trackers, such as Jira, offer filters and dashboards that group issues by their properties, issue trackers lack the ability to thoroughly analyze and manage these dependencies. Given that issues rarely appear in isolation, the limitations in managing issue dependency network are harmful.

This paper addresses the problem of how to support stakeholders of a software project, with the management of dependent issues in an issue tracker over the software system development life-cycle. In this paper, we refer to dependencies as horizontal interdependencies between issues rather than vertical dependencies, i.e. traceability between issues and other types of artifacts, such as issues and their implementation [7]. The solution focuses on the nature of dependencies themselves, the detection of missing dependencies between issues, and consistency analysis of issue dependency network to extend well-known features offered by issue trackers. The solution is implemented as a Jira plugin

1. https://www.atlassian.com/software/jira
and service-based system considering contextual product quality characteristics – including security, scalability, and efficiency – to fit in real, large data-set scenarios. To this end, the research, the solution design, and its evaluation have been carried out in the context of The Qt Company (TQC), a publicly listed, global software company.

This paper is organized as follows. Section 2 provides background about issue trackers. Section 3 depicts the overall research method, including the research questions, and a description of TQC and its Jira as the context for this research. The results are presented in three sections: Section 4 reports the main drawbacks in issue tracker use; Section 5 depicts the objectives and the techniques of our solution; and Section 6 addresses the artifact implementation. Section 7 reports the evaluation, while Section 8 collects discussion, the threats to validity, and related work. Finally, Section 9 concludes the research.

2 BACKGROUND: ISSUE TRACKERS

Issue trackers provide technological support for issue management tasks. Given the collaborative nature of these tools, they can be conceived as "a type of social media" [9] for the software development domain. As a consequence, the users of an issue tracker, e.g. software developers, product owners, and project managers, rely on the features of these tools.

Karre et al. [9] conducted a categorization analysis of 31 well-known issue trackers to identify their features and main differences. The analysis resulted in 24 characteristics, including simple, traditional features, such as e-mail support or the existence of a comments section, as well as more complex features like a customizable graphical user interface, or the ability to establish links between independent issues. The result is a four-class categorization (Cluster1–4) based on the complexity and number of features offered by each issue tracker. Among this categorization, Cluster1 is reported as the set of most advanced issue trackers with a high number of features, including custom fields, planning and project management features.

Among the most advanced issue trackers from Cluster1, we highlight Redmine, Mantis, BugZilla, and Jira. They are all well-known and widely-used tools that provide complex and advanced issue modeling features, and include a wide variety of issue management functionalities, especially for single issue management. These single issue modeling features include type (e.g., ‘epic’, ‘bug’, ‘user story’, and ‘task’), scope (product or component) and status (e.g., ‘open’ and ‘closed’). However, there are significant differences among them. For instance, neither BugZilla nor Mantis support issue types other than ‘bugs’, which is the underlying type of each issue, nor the definition of custom issue types or statuses. On the other hand, all of these are features supported by both Redmine and Jira.

If we focus on more advanced features beyond single-entity analysis, all of them support some type of specification process for dependencies among issues (i.e., issues depending on the resolution of another issue) or duplicated issues (i.e., marking an issue as a copy of an existing one). However, these dependency and duplicate management features are limited to specification as properties modeling of a single issue. In addition, this complex specification process requires human action to manually label and create these dependencies.

More advanced features, such as release management tasks, including creating a release plan and adding issues to a scheduled release, are supported only by Jira. This makes Jira one of the most advanced issue trackers in terms of the scope of its functionalities. Since Jira is the issue tracker used by TQC, the company providing the context for this research, we argue that findings related to drawbacks and improvements presented in our study may apply to other trackers (see Section 8.4 for a more detailed discussion on generalization of the findings). A more detailed account of the existing features in Jira is provided in sections 3 and 4.

3 RESEARCH APPROACH

Our research follows the Design Science methodology [10], in which the solution knowledge and artifact are developed for a specific context, and aim to solve the problem and have utility in that context. In this section, we first describe how we applied Design Science, and then the context of TQC where we carried out the research.

3.1 Research method: Design Science

We apply Peffers et al. [11] incremental and iterative process to Design Science, which Figure 1 illustrates. The phases are linked to the research questions listed in Table 1. We also discussed about the research with TQC’s stakeholders frequently and their feedback was incorporated.

Problem identification (RQ1). As part of the OpenReq research and innovation collaborative project [12], we conducted a multiple case study to understand the needs of companies for a platform to support large-scale requirements engineering [12]. TQC was one of the five organizations in the study – the details of the protocol are available at [12]. The main problems found in these interviews were: information overload, limited tool support, handling of dependencies between requirements, and stakeholder identification for issue assignment. RQ1 refines the main findings of [12] from TQC’s Jira use perspective. After a preliminary analysis, we excluded the problem of stakeholder identification because open source communities are in general sensitive to disclosure of personal information. The remaining problems, which are detailed by the drawbacks in Section 4, were refined during the process of developing a solution.

Define solution objectives and design (RQ2). On the basis of the drawbacks, we synthesized the solution objectives and scenarios, as well as solution techniques that integrate with Jira as the tool, and the existing issues of Jira as the data. As a major design principle, the solution should not change but rather support and complement the current processes at TQC to lower the adoption barrier. The design was based on promoting the role of dependencies in issue management. We define the solution in Section 5.

Implementation of the solution and demonstration of its operations (RQ3). The incremental development of the artifact to realize the solution was done iteratively with
Table 1
Research questions of the study

| ID | Text |
|----|------|
| RQ1 | What drawbacks do stakeholders suffer with current issue trackers? |
| RQ2 | What features can be added to issue trackers to address these drawbacks? |
| RQ3 | How can these features be integrated in an issue tracker so that it has value for use? |

...a continuous feedback loop, which helped to ensure that the artifact was meeting general quality objectives, which we structured following the ISO/IEC 25010 product quality model [13]. These challenges shaped the final artifact design, as detailed in Section 6.

**Evaluation.** The evaluation is divided into verification and validation [13]. Verification evaluates the results against the stated objectives and it was carried out by executing an extensive set of tests that explored the functionality and observed and measured the product quality characteristics [13]. Validation techniques assess the results with their intended users. For validation, we interviewed five TQC’s stakeholders who were all active Jira users who tested and used our solution. The technical details and results of the evaluation are provided in Section 7.

### 3.2 Research context: TQC and TQC’s Jira

TQC’s product is a software development kit (Qt) that consists of the Qt software framework itself and its supporting tools, including the integrated development environment (IDE) called Creator, and the 3D studio (3DS) and the Automotive suite extensions to the Qt software framework. Qt specifically targets the development of cross-platform mobile applications, graphical user interfaces, and embedded applications. Qt is estimated to be used by about one million developers and most of today’s embedded and touch screen systems rely on Qt. Qt is licensed under open source and commercial licenses.

All issues of Qt are managed in Jira, and Jira is the only system for product management and requirements engineering. Each Jira issue has an ID consisting of a preceding project acronym and a running number (e.g., ‘QBS-991’), a title (‘Qt Android support’) and description, as well as several properties, such as the type (in QBS-991, a bug), release (referred to as Fix Version/s), priority, status (identifies where an issue is in its life-cycle, such as ‘Open’, ‘Closed’), resolution (gives additional details for status, such as an issue is closed because it is a ‘Duplicate’), and automatic meta-data, such as the creation date. There are various releases, such as major and minor releases, and bug fixes, and the release numbering typically follows up to three-part (x.y.z). Priority is a number from 0 (‘P0 blocker’) to 5 (‘P5 not important’). In addition, an issue includes comments.

In TQC’s Jira, issues may report Bugs, Epics, User Stories, Suggestions, and Tasks. While bugs are the prevalent issues, TQC aims to organize development by applying an issue hierarchy like in agile methods: large functionalities or features are defined as Epics that are refined as User Stories and further as Tasks. In addition to the parent-child relationships induced by this issue hierarchy, issues can have dependencies referred to as Issue Links in Jira. These links can only be set by employees of TQC or authorized open-source developers. Other TQC Jira users, even the creators of issues, cannot set any links. TQC’s Jira supports the following links: ‘duplicates’, ‘requires’, ‘relates’, ‘replaces’, ‘results’, and ‘tests’. All these links are bidirectional (e.g., ‘is related to’ and ‘relates to’), but it is not uncommon for users to declare an incorrect direction, especially in the case of a duplicate, as the resolution already shows duplication. For simplicity, we use the term dependency to denote both parent-child relationship and links. There are also several exceptions or misuse for these patterns. Sometimes issues are used only to gather other issues, such as one major epic depending on other epics as epics cannot form a parent-child hierarchy (e.g., QTBUG-62425). Some issues group other issues in the description or comments field (e.g. QTCOMPONENTS-200) and not necessarily all of them are linked in the appropriate fields.

TQC’s Jira is divided into projects. Examples include: ‘QTBUG’, which contains issues related to the Qt Framework; and ‘QTCREATORBUG’, which contains issues related to Creator. The large projects are further divided into

4. https://bugreports.qt.io/browse/QBS-991
5. https://bugreports.qt.io/browse/QTBUG-62425
6. https://bugreports.qt.io/browse/QTCOMPONENTS-200

3. www.qt.io
components, such as a Bluetooth component in ‘QTBUG’. Each component has a responsible maintainer either from TQC’s R&D department or the open source community. TQC’s product management has more general responsibility for the projects. The projects, and components, are not isolated but have cross-project dependencies to each other, such as Automotive suite being built on top of Qt Framework.

TQC operates in a meritocratic manner in which developers get promoted when they contribute to Qt and receive recommendations from other developers. This meritocratic structure is reflected on TQC’s Jira. Anyone can register and report issues to TQC’s Jira as well as view the full details of issues, follow issues, and add comments. However, only those who have received elevated rights can edit issues in order to preserve issue quality and the integrity of the issues.

To monitor overall progress, TQC uses dashboards for each release with swim lanes for status categories ‘not started’, ‘in progress’, ‘blocked’, and ‘done’. A dashboard is a feature in Jira to automatically filter, organize, and visualize a set of Jira issues based on their property values, such as the above release and status.

TQC’s Jira is an independent deployment in a virtual machine in Amazon cloud. In addition, TQC has a snapshot of this virtual machine as a test environment, which we use in our research. The snapshot was taken on November 29, 2019. In this snapshot, TQC’s Jira is divided into 20 public, separate projects which can have cross-project dependencies to other projects in Jira. We used this same snapshot of the data for all tests in order to make the results comparable. Table 2 shows the number of issues and dependencies in Qt Framework, Creator, and 3D Studio, which are the three largest projects, and the remaining 17 other projects combined. Out of the total of 119,920 issues, 26,746 (22%) were open, i.e. not resolved, at the end of the period. Modifications include any changes, such as editing text, changing properties, or adding comments. In addition, TQC has about ten private projects in Jira for specific customers and product management, which contain a few thousand additional issues. For confidentiality reasons, these projects are not included in the data-set of this paper.

| Issues | Internal dependencies | Cross-project dependencies* |
|--------|-----------------------|-----------------------------|
| Qt Framework | 78,676 | 15,739 | 1,811 |
| Creator | 21,926 | 3,126 | 1,132 |
| 3D Studio | 3,877 | 2,023 | 133 |
| Other projects | 15,441 | 3,517 | 1,307 |

* A dependency between two projects is counted in both projects.

As noted, Jira issues have Issue Links for dependencies. To explore a resulting issue dependency network beyond direct dependencies, a user needs to follow the dependencies from one issue to another. The drawback is that it is tedious and error-prone for TQC’s Jira users to form an overall understanding of the network structure by following the links one by one, because Jira does not support any other ways to explore an issue dependency network — there is no view beyond the list of direct dependencies. Moreover, none of the features in Jira, such as searches and dashboards, can take any dependencies into account automatically, as the dependencies appear only in the issue pages. However, the issues of TQC’s Jira constitute a set of large, disconnected networks comprising both internal and cross-project dependencies, in which the largest network consists of 8,952 issues.

**Example 1.** Issue QT3DS-1802 has 15 dependencies to other issues, which in turn have another 59 additional direct dependencies. The network grows further similarly beyond these issues. A Jira user needs to open each dependent issue in order to see their details and how many – if any – dependencies there are in these dependent issues beyond direct dependencies. This means, in the worst case, separately opening dozens of issues, and keeping in mind what is dependent on what and how. This is practically impossible.

**Drawback 2. Issues lack explicit dependencies.** Jira requires users to report dependencies among issues manually. Eventually, users may not report all of them, resulting in missing dependencies. TQC’s Jira users have reported that this is a frequent situation and identified five different reasons behind missing dependencies:

- **Unawareness.** When reporting an issue, a user is not aware of all related issues and may completely miss the corresponding dependencies.
- **Uncertainty.** A user may be unsure whether a certain dependency is needed or not, and thus may mistakenly decide not to add it. In fact, it is customary in TQC’s practices that uncertain dependencies are only mentioned in the description or comments of an issue rather than marked properly.
- **Discrepancy.** Users have different opinions on whether or not an explicit dependency is needed.
- **Lack of time.** Even when a user is completely sure about a dependency, adding it can be cumbersome, requiring several actions (clicks, scrolls, etc.).
- **Lack of permissions.** Not everyone is allowed to add dependencies. As said above, adding dependencies in Jira is editing an existing issue to modify its properties, and at TQC this operation requires elevated privileges.

In this situation, it becomes difficult (if not impossible) for TQC’s Jira users to be aware of all dependent issues, considering the potentially large size of the dependency network as pointed out above (and manually searching them is tedious and error-prone work). Missing dependencies may

### 4 RQ1: DRAWBACKS IN ISSUE MANAGEMENT

The first research question of our study results in a refinement of drawbacks related to the use of Jira at TQC.

**Drawback 1. Limited view of the issue dependency network.** TQC’s Jira users, when resolving an issue, typically need to take the issue dependency network into account. For instance, in the epic – user story – task hierarchy, a developer needs to consider all issues in the hierarchy. Another example is having two issues where one issue can be resolved only if a solution is found for the other.

TABLE 2

The number of issues and dependencies in the three largest and other projects in total on the 29th November 2019.

| Issues | Internal dependencies | Cross-project dependencies* |
|--------|-----------------------|-----------------------------|
| Qt Framework | 78,676 | 15,739 | 1,811 |
| Creator | 21,926 | 3,126 | 1,132 |
| 3D Studio | 3,877 | 2,023 | 133 |
| Other projects | 15,441 | 3,517 | 1,307 |
have critical consequences for activities like ensuring the integrity and quality of a release.

To understand the magnitude of possibly missing dependencies, we can take a closer look at the Qt 3D Studio project. A developer of Qt 3D Studio stated once that their aim is to use dependencies rigorously. As a result, 50% of the issues in the project have dependencies compared to 25% in Qt Framework and 24% in Qt Creator. Because an issue can have multiple dependencies, another measure is the dependency-issue ratio, i.e., how many dependencies there are compared to issues. The ratio in the Qt 3D studio is 0.6 and 0.2 in the other two projects (cf. Table 2).

**Example 2.** A Jira user commented on the issue QBS-881: “I see this task as being redundant with QBS-912 - close?” (sic). Another user responded and agreed in a follow-up comment. However, no-one declared an explicit dependency. As a consequence, dependencies do not appear properly but require reading the comments, which makes understanding the issue dependency network even more challenging. Furthermore, when a user, such as the reporter or a watcher of the bug, inspects whether the bug has been resolved, they can see that the bug has been closed as a duplicate, but they do not see in which version the bug has been fixed unless they notice the comment about duplication and open issue QBS-912. In practice, such comments often go unnoticed. On the other hand, users looking at QBS-912 cannot find QBS-881 to be its duplicate because the comment is not visible on this end.

**Drawback 3. Duplicated issues are reported.** As anyone can report an issue, it is not uncommon that the same concept is reported more than once, resulting in very similar issues, which can be considered duplicates. For instance, a unique bug can be identified and reported by different users, or similar features can be requested several times. As found in [12], TQC’s Jira users reported that it would be convenient to detect and link duplicates in order to better comprehend the structure of the issue network. On the other hand, it is also important not to delete any of them because each similar issue can still have some original content of its own. For example, different issues reporting the same bug may contain a description in different contexts, making debugging easier, or may suggest slightly different solutions that provide novel insights.

Issue trackers offer limited features as support for modeling and identifying these duplicates. Jira offers ‘duplicate’ as a resolution property value to indicate that the issue duplicates another issue, and the ‘duplicates’ dependency to connect duplicate issues. Any issue that duplicates another issue should have a ‘duplicates’ dependency towards the duplicated issue, and have the resolution and status properties marked as ‘duplicate’ and ‘done’, respectively. However, this does not always happen. For instance, TQC’s Jira has in total 8,150 (7%) issues marked as ‘duplicate’, of which 5,839 lack a ‘duplicates’ dependency. 4,925 of these issues have some other dependency, which in some cases can mean that, e.g., a ‘relates’ dependency is used incorrectly to denote duplication. Still, the remaining 914 issues do not have any dependency. In addition, it is possible that duplicate issues have simply been closed without setting the resolution, or that some duplicates have gone unnoticed.

Since duplicate dependencies are a type of dependency, the reasons for, and consequences of, missing duplicates are similar to the previous drawback. Another shortcoming is that the TQC community can voice their opinion on issues by watching them. This is an indicator for TQC about the popularity of an issue. If there are duplicates of an issue and the watchers are split over all of them, TQC will not be able to hear the community voice properly, since that voice is incoherent. Thus, important information goes missing unless duplicates are detected.

**Example 3.** Example 2 already represents a missing duplicate dependency but likewise issue QTBUG-33588 contains three comments suggesting a link to three different issues: “May be related to QTBUG-3145”, “Could be related to QTBUG-34552 Please, consider increasing priority of this issue since there’s not work-around. Thanks.” and “QTBUG-35085 is relevant as well since custom context menus are also broken.” (sic) Even though QTBUG-33588 has three different comments suggesting a link to different issues, no link is marked in TQC’s Jira. While the QTBUG-33588 only has 6 watchers, the issues mentioned have 33 watchers altogether.

**Drawback 4. Incorrect release assignments and priorities in an issue dependency network.** As Qt has specific release cycles, it is relevant when issues are – or are planned to be – resolved when taking the issue dependency network into account. For example, an A requires B dependency means that the solution of A needs the solution of B to operate properly – it is not meaningful to implement or release A first as its solution will not be useful without B. TQC’s Jira users reported two practically relevant dependency rules:

- **Parent-child rule.** In a parent-child dependency, the children must be scheduled in the same or an earlier release than its parent, or have a lower priority.
- **Requires rule.** A required issue must not have a later release or lower priority than an issue requiring it.

However, TQC’s Jira users do not always set the dependencies, priorities, and releases of issues correctly, and the dashboards and filters – like practically all functionalities in Jira – are not able to take dependencies into account. As a result, the checks for dependency rule violations in an issue dependency network need to be carried out manually by inspecting the release, priority, and dependencies of each issue. Any violation that goes unnoticed can lead to an incomplete release. We found that over 12% of these dependencies in TQC’s Jira violate the rules. All dependency rules violations must be manually located and corrected.

**Example 4.** An example of an incorrect release version with a ‘requires’ rule is issue “QTBUG-72510”. It has release version 5.13 and a sub-task that is not assigned to any release. An example of an incorrect priority is “QTBUG-27426” (with priority P0) requiring “QTBUG-28416” (priority P2). This violates the rule that a required issue cannot have a lower priority.

5 RQ2: Objectives and Features for the Enrichment of Issue Management

Following the Design Science process presented in Section 3 in this section, we cover the objectives and scenario, and the
background and concrete techniques of our solutions.

5.1 Objectives

On the basis of the drawbacks enumerated in the previous section, we synthesize the objectives of our solution, which aims to improve dependency management in TQC’s Jira.

- Users gain a better understanding about the existing issue dependency network in the surroundings of the issues they are working on.
- Users can search for missing dependencies and unidentified duplicate issues of the issues they are working on.
- Users can check the correct release assignments and priorities of the issue dependency network in the surroundings of the issues they are working on and they can receive suggestions for resolving inconsistencies.

These objectives share three common characteristics. First, the objectives integrate into the current ways of working at TQC, being usable whenever needed without disturbing existing processes. Second, the objectives are about improving Jira so that their realization becomes integrated into the functionalities and, especially, data of Jira. Third, the objectives address the context and surroundings dependent issues of the existing issues that the user is working on. That is, the objectives primarily address tool improvement rather than process improvements or changes at TQC.

In order to make objectives more concrete, we illustrate an example scenario as follows:

“Jane, a developer at TQC, is assigned to develop a solution for an issue A, which is a task in a user story for the next release. To understand A better, she opens a user interface that visualizes all dependencies and issues in the proximity of A. Jane also gets a notification about another issue that looks like a duplicate of A. She checks and confirms that the issues are duplicates, which means resolving the other issue and creating a ‘duplicates’ dependency between the issues. She also gets a notification that another issue is a part of the same user story A, but it is not assigned to the same release even though its priority is the same as in the user story. This is a mistake in the release assignment that needs to be taken into account and resolved before the release is complete.”

5.2 Dependency management background techniques

The fundamental principle of our solution is that the roles of dependencies in Jira can be first-class entities rather than only properties of issues. We approached this by handling issues and dependencies as two separate entity types in a graph-like structure: issues are nodes, and dependencies are typed (i.e., labeled) and directed edges between the nodes. This approach gives issues a context beyond their explicit properties, revealing implicit constraints, e.g., the mutual aggregation of two issues through a dependency between them. Moreover, dependencies can then have properties of their own, like issues have, such as a status and creation date.

We define what we call an issue graph as follows. We denote the set of all issues as \( R \) and the set of all dependencies between issues of \( R \) as \( D \), i.e., \( D \subseteq R \times R \), where \( D \) is anti-reflexive, i.e., \( \forall r_i \in R : (r_i, r_i) \notin D \); and all edges are bidirected, i.e., \( \forall r_i, r_j \in R : (r_i, r_j) \in D \iff (r_j, r_i) \in D \). That is, for every edge that belongs to the graph, there is also the corresponding inverse edge where the semantics of the edge depends on the direction. For a particular issue \( r_0 \in R \), the issue graph is a symmetric connected graph \( G_0 = (R_0, D_0) \), where \( R_0 \subseteq R \) and \( D_0 \subseteq D \), so that all issues of \( R_0 \) are reachable from \( r_0 \), i.e., for all issues \( r_i \in R_0 \) there is a path from \( r_0 \) to \( r_i \) and \( D_0 \) includes all dependencies between the issues in \( R_0 \) and only those ones. A special case of \( G_0 \) is an orphan issue \( r_0 \) that has no dependencies, and thus for which \( R_0 = r_0 \) and \( D_0 = \emptyset \). This definition of an issue graph is issue-centered and does not necessarily include all issues \( (R_0 \subseteq R) \) because there is no path between all issues. However, the union of all \( G_0 \), denoted by \( G = \bigcup G_0 \), contains all issues \( (R) \) and dependencies \((D)\). Equivalently, every \( G_0 \) is a component of \( G \).

Given an issue \( r_0 \), we define \( G_0^p \), called a \( p \)-depth issue graph, as an induced subgraph of \( G_0 \) that includes all issues up to \( p \) edges apart from \( r_0 \) and all dependencies between the included issues. That is, an issue is taken to the point of focus and we follow all dependencies of that issue to neighboring issues and beyond, breadth-first up to the desired depth. The rationale and benefit of a \( p \)-depth issue graph are that different sizes of contexts of analysis can be constructed automatically without user involvement, to provide a given issue with the issues and dependencies in a specific proximity.

For an issue \( r_i \), we can apply the functions, such as \( r_i, \text{property}(\text{priority}) \) to obtain its priority and \( r_i, \text{property}(\text{release}) \) to get its scheduled release. Similarly, \( d_i, \text{property}(\text{status}) \) will yield the status-property of a dependency \( d_i \), with possible values ‘proposed’, ‘accepted’ or ‘rejected’ and \( d_i, \text{property}(\text{score}) \) will give a score value (0..1) representing the confidence level of correctness or validity of the dependency.

These definitions provide the baseline of the background techniques of dependency management for formulating the techniques required by TQC’s Jira users, addressing the objectives presented in Section 5.1. An issue graph \( (G_0) \) – or the issue graph corresponding to the entire issue dependency network \((G)\) – can be generated automatically with the information stored in Jira; therefore, any operation defined over an issue graph or any transformation to any other formalism (e.g., constraint satisfaction problem (CSP)) can be computed from Jira, as we have effectively done. An issue graph does not need to affect Jira; rather the graph can form a parallel, complementary structure. In particular, an issue graph \((G_0)\) makes efficient issue management and visualization easier.

5.3 Dependency Management Techniques

In this subsection, we describe four concrete techniques of our solution, relying on the background techniques built on the concept of an issue graph. These techniques have been designed considering the objectives in Section 5.1. In particular, the techniques need to work in the context of TQC, such as provide near real-time response times even when managing large sets of issues, which may sometimes prevent the adoption of more sophisticated approaches.
Automated detection of potential missing dependencies. Section 3 showed how TQC’s Jira users may neglect a significant number of dependencies. Therefore, TQC would greatly benefit from an automatic dependency detection procedure that informs Jira users about missing dependencies. This mitigates the burden of searching for the dependent issues, making it also less critical for users to be familiar with all other existing issues. It is possible to automatically detect missing dependencies using various techniques, including deep learning [14], active learning and ontology-based approaches [15].

Our solution includes a reference detection technique for natural language text (see Algorithm 1). This simple technique was selected after prototyping more complex techniques, which did not meet the stringent time requirements and lacked proper training data, and recommendations from TQC’s Jira users who noted that dependencies are often only mentioned as a reference to another issue in the textually added content, i.e. the title, description, and comments of an issue (Section 4 see Example 2). The reference detection technique analyzes this textually added content from the issues by searching for sub-strings that represent an issue ID (line 4 of Algorithm 1) and creates proposals for new dependencies whenever other issues are mentioned (lines 5–7). The reference detection technique marks the found dependencies as ‘proposed’ (line 6).

Automated detection of potential duplicated issues. The need for, solution to, and benefits of automatic duplication detection are much like the above because, as already commented in Section 3 duplicates result in a particular type of dependency in Jira. State-of-the-practice approaches use bag-of-words of natural language representations to measure the similarity between these representations using vector-space models [16]. Among these approaches, Term Frequency - Inverse Document Frequency (TF-IDF) is the theoretical baseline for the detection of duplicated entities or issues [17], [18]. More recent deep contextualized models, such as Google’s BERT [19] or ELMo [20], are more suitable for complex information retrieval scenarios, but they introduce a challenge in terms of efficiency, complexity, and training data required [21]. These challenges make it difficult to use them in the TQC context of large issue dependency networks.

Our solution (see Algorithm 2) is an extension of the TF-IDF model based on three additional steps to improve the accuracy and performance of the similarity evaluation. After initially running the title and description of each issue through a lexical analysis pipeline (Lines 1–4 of Algorithm 2), we built a TF-IDF model from the resulting bag-of-words representations (Line 5). Then, we apply the cosine similarity for the resulting TF-IDF model to compare each pair of issues. Each resulting score is then compared to a context-based minimum threshold value to decide whether a pair is a potential duplicate, in which case a new ‘duplicate’ dependency proposal is constructed (Lines 6–11).

After the similarity evaluation, we represent the duplicated issues as sets of complete graphs, where issues have an existing or proposed ‘duplicate’ dependency to other issues. We treat these sets of graphs as clusters — the process proposes sets of duplicated issues by simply including the issues belonging to the same cluster (Lines 12-13). During this process, we apply transitivity through existing duplicate dependencies to all issues belonging to a same cluster, which results in new duplicated proposals. Hence, instead of reporting all the existing and proposed ‘duplicate’ dependencies among them, we only report the duplicated dependency with the greatest similarity score for all other issues in the cluster. Given a sub-graph of m duplicated issues, the clusters can be reported using (m − 1) dependencies instead of representing all (m * (m − 1)/2) dependency objects, improving performance efficiency in data processing and transactions.

Contextualization of dependency proposals for an issue. Contextualization is a practically necessary technique that takes into account the user’s context and prioritizes the results of the detection techniques when a user fetches dependency proposals for an issue (r0). We present in Algorithm 3 the resulting algorithm that aggregates these techniques into a holistic solution. The algorithm presumes that Algorithm 1 and 2 have been executed, and the results are stored and retrievable.

First, our solution retrieves the stored results of detection techniques for an issue r0 (Line 1 of Algorithm 3). If a dependency is proposed between the same issues by both techniques, retrieving includes merging these two proposals into one ‘duplicates’ dependency with an aggregated

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**Algorithm 1 ReferenceDetection(R, projectID)**

R: Set of issues of an issue graph  
projectID: Set of project IDs (e.g., "QTWB", "QTBUG")

1: \(D_p = []\): set of proposed dependencies  
2: for all \(r_i\) in \(R\) do  
3: for all \(p_j\) in \(projectID\) do  
4: \(toID()[r_i].findStrings(p_j+"-"+[0-9]{1,5})\)  
5: for all \(to_i\) in \(toID\) do  
6: \(D_p.add(r_i, to_i, \text{'dependency'}, \text{'proposed'})\)  
7: end for  
8: end for  
9: end for  
10: return \(D_p\)

**Algorithm 2 DuplicateDetection(G, thr)**

G = (R, D): Issue graph  
thr: Similarity threshold score

1: \(bow = []\) : Bag of words  
2: clusters = [] : Set of sub-graphs of duplicated issues  
3: for all \(r_i\) in \(R\) do  
4: \(bow.add.text_preprocess(r_i)\)  
5: end for  
6: \(tfidf\_model = \text{build}\_model(bow)\)  
7: for all \(r_i, r_j \in R\) where \(i \neq j\) and \(d_{ij} = (r_i, r_j) \notin D\) do  
8: \(score = \text{cosine}\_\text{sim}(r_i, r_j, tfidf\_model)\)  
9: if \(score \geq \text{thr}\) then  
10: \(D.add(r_i, to_i, \text{'duplicates'}, \text{'proposed'}, \text{score})\)  
11: end if  
12: end for  
13: clusters = compute_clusters(R, D)  
14: return clusters
score. The ‘duplicates’ dependency is applied because the reference technique does not propose any type. Because the proposal is more likely correct when two techniques detect it, the aggregation is simply the sum of the cosine similarity (0.1, see Algorithm 2) for duplicate detection and a default value for reference detection. This also prevents a proposal between two issues from appearing twice.

Next, the solution examines all proposals obtained (loop comprising Lines 2–18). As the detection techniques can result in proposals of dependencies for \( r_0 \) that currently exist in TQC’s Jira or have already been rejected by users, these are filtered out from the combined proposals (Lines 3–4).

For the remaining proposals, our solution applies two specific contextualizations that were developed based on the feedback of TQC’s Jira users. Both of them rely on factors that are used to multiply, i.e. to increase (or decrease if the factor is <1), the score. Thus, proposals are not filtered but those proposals that are more relevant in the user’s context are emphasized. Only the factors explicitly specified by a user are applied.

- **Issue graph based contextualization** has the purpose of prioritizing the proposals to issues that are not in close proximity in the issue graph and are considered more valuable to the user. First, it increases the score of those dependencies from \( r_0 \) to issues in different issue graph, or in the same issue graph with a greater distance than the given minimum depth \( p \) (Lines 6–8). Second, it increases the score of dependencies from \( r_0 \) to orphans; in this way, the orphaned, disconnected issues become easier to discover as a part of an issue graph

**Algorithm 3 Proposals**

\( r_0 \): Issue of interest

\( D_0 = \{(r_0, r_{p1}), \ldots\} \): Dependencies for \( r_0 \) in TQC’s Jira

\( D_0' = \{(r_0, r_{p1}), \ldots\} \): Dependencies for \( r_0 \) stored as rejected

\( \text{depth} = [p, f_{\text{depth}}] \): Minimum depth and its factor

\( \text{orphan} = f_{\text{orphan}} \): Orphan factor (default value = 1)

\( \text{property} = [p_0, v_0, f_0, \ldots] \): Properties, values and factors

\( D_p = [] \): Set of proposed dependencies for \( r_0 \)

1: \( D_p, \text{combine}(\text{references}(r_0) + \text{duplicates}(r_0)) \)

2: for all \( d_p \) in \( D_p \) do

3: \( \text{if } (d_p \text{ member of } D_0) \text{ OR } (d_p \text{ member of } D_0') \text{ then} \)

4: \( D_p, \text{delete}(d_p) \)

5: else

6: \( \text{if } r_0, \text{distance}(d_p, r_p) > p \text{ then} \)

7: \( d_p, \text{score}, \text{multiply}(f_{\text{depth}}) \)

8: end if

9: \( \text{if } d_p, r_p, \text{orphan} \text{ then} \)

10: \( d_p, \text{score}, \text{multiply}(f_{\text{orphan}}) \)

11: end if

12: for all \( (p_i, v_i, f_i) \) in \( \text{property}(p, v, f) \) do

13: \( \text{if } r_p, \text{property}(p) == v_i \text{ then} \)

14: \( d_p, \text{score}, \text{multiply}(f_i) \)

15: end if

16: end if

17: end if

18: end for

19: return \( D_p \)

**Algorithm 4 CheckConsistencyAndDiagnose**

\( G_0 = (R_0, D_0) \): Issue graph for \( r_0 \)

\( D_i \): Inconsistent dependencies

\( \text{diag}_d \): Dependency diagnosis

\( \text{diag}_i \): Issue diagnosis

1: \( \text{mergeDuplicates}(G_0) \)

2: for all \( d \) in \( D_0 \) do

3: \( \text{if } \text{inconsistent}(d) \text{ then} \)

4: \( D_i, \text{add}(d) \)

5: end if

6: end for

7: \( \text{if } D_i = \emptyset \text{ then} \)

8: return(‘Consistent’)

9: else

10: \( \text{diag}_d = \text{FastDiag}(r_0, D_0, \text{sortByPriority}(R_0 - r_0)) \)

11: \( \text{diag}_i = \text{FastDiag}(r_0, \text{sortByPriority}(R_0 - r_0), D_0) \)

12: return(‘Inconsistent’, \( D_i, \text{diag}_d, \text{diag}_i \))

13: end if

(Lines 9–11).

- **Property based contextualization** increases the score when the properties of an issue in a proposed dependency has the same values as specified by the user, such as in environment, project, or creation time (Lines 12–16). For example, if a user wishes to find duplicates from the Qt Framework project, the scores of those proposals that have the issues in this project are increased.

**Automated consistency check and diagnosis of inconsistencies.** Dependencies between issues need to be considered when analyzing the correctness of release assignments or priorities in issue graphs. The existing release planning models (cf. [5], [6]) are techniques for the task of finding an optimal release assignment from existing requirements by assigning requirements to releases. Since the release assignment task is not a problem at TQC, the existing release assignments need to be checked for consistency. When an issue graph is represented in a more machine-understandable manner, a consistency check is an elementary operation that can be automated. In addition, a diagnosis can identify minimal conflict sets that lead to consistency. The first diagnosis algorithm HSDAG (Hitting Set Directed Asyclic Graph) [22] uses breadth-first search to find all minimal sets of constraints that could be deleted to restore the consistency. Several improved diagnosis algorithms have been developed (e.g., [23]). Clearly defined dependency types (e.g., [7], [24], [25]) form the basis for any automation.

In our solution for consistency check and diagnosis, we utilize ‘requires’ and ‘parent-child’ dependencies, which have well-defined semantics that take priorities and release assignments into account; the details are described in Drawback 4 in Section 4. In addition, our solution merges issues with the ‘duplicate’ dependency between them and the resulting merged issue inherits all dependencies from the merged issues; this is the first step (Line 1 of Algorithm 3). The consistency check is a procedural method that evaluates, for each dependency, whether the conditions of the dependency are satisfied, and reports the violated dependencies (Lines 2–6).

If the dependency contains inconsistent dependencies,
diagnosis can be invoked. We adopted FastDiag (see details in [26]), which is an efficient divide-and-conquer algorithm used to determine preferred diagnoses of constraint sets. Diagnosis applies a CSP representation of an issue graph where dependencies, priorities, and releases are constraints. Constraints are assumed to be in a lexical order according to their priorities: a higher priority constraint is retained if at all possible, even if all lower priority constraints would have to be removed. The issue diagnosis (Line 9) identifies a set of issues that need to be assigned to a different release or re-prioritized or removed to restore the consistency of the network. For this diagnosis, each issue is considered as a constraint that can be relaxed or ‘diagnosed away’. The dependency diagnosis (Line 10) determines a set of dependencies whose removal from the issue graph restores the consistency.

6 RQ3: ARTIFACT IMPLEMENTATION

In this section, we describe the developed artifact (cf. Section 5). We first elaborate on the objectives of the artifacts, which we derived from TQC’s Jira users, and then describe the implementation.

6.1 Artifact design objectives

We articulate the design objectives using the eight ISO25010 quality model characteristics [13].

- **Functional suitability.** The artifact needs to implement the techniques described in the previous section in the context of TQC’s Jira.
- **Performance efficiency.** The artifact needs to efficiently handle a large number of issues and the efficiency of Jira may not be unacceptably damaged. TQC’s Jira users informally estimated this goal as “responses even to the largest requests within a few seconds”.
- **Compatibility.** The artifact itself needs to be compatible (co-exist and interoperate) with Jira’s functionality and data without the need to develop additional software for interchanging data or accessing functions.
- **Usability.** The usage of the artifact needs to be smoothly integrated with Jira, and the way of working at TQC.
- **Reliability.** The integration of the artifact and its data should not interfere with Jira’s current issue management. TQC’s Jira users had as their top priority to avoid any risk concerning their current Jira management.
- **Security.** The solution must not compromise private data, especially from non-public projects, and must adhere to TQC’s access policies.
- **Maintainability.** The architecture needs to support easy evolution and extension as Jira evolves, as well as allow for easy integration of new techniques.
- **Portability.** The solution should not be strongly tied to any particular technology except Jira, or impose unnecessary additional installation decisions.

6.2 Artifact design

We implemented the artifact as a Jira plugin and service-based system consisting of independent microservices (→maintainability, compatibility), which in practice operate in a choreographic manner following a layered architectural style. The services collaborate through JSON-based messages following a generic ontology [27] that adheres to REST principles (→portability). There are three classes of microservices and the plugin as summarized below and in the architecture diagram in Figure 2.

1. **Integration microservices.** First, one microservice (Milla) integrates with Jira, fetches issue data, and constructs dependencies as separate, first-class entities. We realized the integration by using Jira’s existing OAuth-based REST API (→portability, security). A full projection of TQC’s Jira issues is made and relevant information is cached to provide more efficient access to issue data (→efficiency). The resulting issue and dependency data from Jira is cached in a local database embedded into an auxiliary integration microservice (Mallikas). Frequent updates fetch new and changed issues from TQC’s Jira (→compatibility).

2. **Detector microservices.** After the data projection has completed, the integration service (Milla) sends the resulting issues and dependencies – or their changes when updating – to the detector microservices for processing (→efficiency). The reference detector (Nikke) searches for missing dependencies (i.e., implementing Algorithm 1) presented in Section 5 and the similarity detector (ORSI) searches for duplicated issues (implementing Algorithm 2). As users make a limited amount of references, the former (Nikke) is stateless. It returns proposed dependencies (‘proposals’ in Figure 2), which are then stored in the same local database (Mallikas) as the existing dependencies, applying the ‘proposed’ value for the status-property. However, the similarity detector (ORSI) requires persistence on service-side to optimize the

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Fig. 2. The software architecture of the artifact.
Fig. 3. Two screen captures of Issue Link Map for the issue QBS-585 of TQC Jira. The p-depth issue graph to depth five ($G^p_0$) and the properties of the issue ($r_0$) from Jira are shown on the left. The consistency check tab is shown on the right.

similarity due to clustering and vector-based algorithms. Therefore, the proposals are stored internally in the cluster (→efficiency).

3. Model microservices. The integration service (Milla) also sends the issue graph ($G$) to the model microservices (Mulperi and KeljuCaas). These microservices translate the issue graph into a more general knowledge representation, and store the data as a map datatype with issues as keys and a list of said issues’ neighbors along with the corresponding dependency types. The way in which the issue graphs are stored allows the easy extraction of various $p$-depth issue graphs ($G^p_0$) by following the dependencies recursively to the required depth (→efficiency).

4. User interface plugin. Users interact through a dedicated Jira plugin (Fisutankki) installed in TQC’s Jira. The plugin technology integrates the user interface into Jira and into Jira’s security mechanisms (→usability, compatibility). This allows public access, where authenticated users adhere to Jira’s security schema (→security).

On the users’ side, Issue Link Map [28] (Figure 3) is embedded in the Jira plug-in (Fisutankki), which creates a browser-based user interface (→usability, compatibility). A central part of the user interface is a 2D representation of a $p$-depth issue graph ($G^p_0$). The issue ($r_0$) in focus is in the center, and the other issues are automatically positioned around it circularly, depending on their depth. A user can select the desired depth, up to depth five, from the top-left, rearrange the the issues, zoom in and out, etc. The colors indicate the status of the issues. A set of filters, such as type or status, can be applied to the visualization. On the right, various tabs represent the other techniques. The first tab shows the basic information for the selected issue as in Jira because the 2D diagram cannot convey all the details of an issue. The second tab shows dependency proposals, which are then also shown in the 2D diagram as dashed lines. The third tab shows the results of the consistency check.

The user interface accesses the functionality provided by other services through REST calls, which we refer to as queries in Figure 2. Each query goes through the plugin (Fisutankki) that applies Jira’s security policies. Then the integration microservice (Milla) orchestrates all queries to other microservices (→maintainability). The elementary functionality to initiate the user interface is to query an issue graph to depth five ($G^p_0$) from the model microservices, which the user interface visualizes to the desired depth.

The integration microservice (Milla) processes a user’s query for a dependency proposal implementing Algorithm 3. First, it combines reference proposals (in Mallikas), similarity proposals (in ORSI), and removes rejected proposals (stored in Mallikas). Second, it calls the model services for the desired $p$-depth issue graph ($G^p_0$) to apply the issue graph-based contextualization. Third, it queries the cached data (in Mallikas) for the property-based contextualization. A user can accept a proposed dependency that requires them to specify its type, or reject or disregard the proposal. Provided that the authorized user has sufficient privileges, the plugin (Fisutankki) writes accepted decisions to Jira as new dependencies, while the local database (Mallikas) stores rejection decisions.

The integration service (Milla) forwards a user’s query for consistency check and diagnosis to the model services that first construct an issue graph ($G^p_0$) internally and prepare data for inference, such as translating the version numbers to integers (in Mulperi). Then the consistency check is carried out and, in case of inconsistency, the issue graph is read to constraint programming objects and the Choco solver [29] (in KeljuCaas) is used to infer diagnosis (Algorithm 1).

The microservices are deployed to the same server as TQC’s Jira, which then relies on the server’s security mechanisms (‘server boundary’ in Figure 2). Although the microservices use secure communication, the data is not transferred to other servers remaining behind the server’s firewall – only the plugin’s (Fisutankki) REST endpoint is publicly accessible (→security).

7 Evaluation
The evaluation focused on verification of microservices by system tests for functionality (Sections 7.1-7.3) and perfor-
We did not measure reliability, but we did not encounter problems with reliability during the test period. We experimented with various test setups and the final tests took over a week without discontinuity of service. A small number of performance tests behaved abnormally, such as 9 out of 119,920 (0.0075%) dependency queries, which should take roughly the same time but in practice took more than twice the average time. Since we could not reproduce the behavior, we assume that they were caused by the infrastructure, such as Java’s garbage collection. The system was also operational, although only experimentally used for several months, in TQC’s test Jira without discontinuity of service.

### 7.1 Evaluation of background techniques

**Evaluation design and data-set.** For evaluation of the background techniques (Section 5.2), we carried out an exploratory analysis of Qt Repository. This included the evaluation of metrics related to the topology and size of the generated p-depth issue graphs as shown by the first block in Table 3.

| Technique                  | Metric Id                | Description                                                                 | Data-sets                |
|----------------------------|--------------------------|----------------------------------------------------------------------------|--------------------------|
| Issue graph handling       | #dependencies           | Number of dependencies in each issue                                      | Qt Repository            |
|                           | #p-depth-graphs          | Number of p-depth issue graphs                                            |                          |
|                           | #issues-in-p-graphs      | Number of issues for which a dependency is proposed                       |                          |
| Dependency detection       | #issues                 | Number of issues with more than 3 edges apart                             | Qt Repository            |
|                           | #proposals              | Number of dependency proposals                                            | Duplicate set #1 and     |
|                           | #depth-3-distance       | Number of issues diagnosed to be removed                                   | Duplicate set #2         |
| Consistency check          | #requires-inconsistent   | Number of inconsistent requires dependencies                              | Qt Repository            |
| and diagnosis              | #parent-child-inconsistent | Number of inconsistent parent-child dependencies                          |                          |
|                           | #p-depth-consistency     | Number of consistent p-depth issue graphs                                  |                          |
|                           | #issue-diagnosis-count   | Number of issues diagnosed to be removed                                   |                          |
|                           | #dependency-diagnosis-count | Number of dependencies diagnosed to be removed                            |                          |
|                           | issue-diagnosis-success  | Success of issue diagnosis                                                 |                          |
|                           | dependency-diagnosis-success | Success of dependency diagnosis                                           |                          |

**Evaluation results.** In total, 31,182 issues (26%) have at least one dependency declared by TQC’s Jira users by Issue Links in Jira (#dependencies in Table 3), meaning that 88,738 issues (74%) are orphans before any automated dependency detection. Out of the issues that have dependencies, 75% have only one dependency. The average is 1.7 and the median is 1. As noted in Section 5.2, issues are sometimes used for grouping, resulting in and explaining that the maximum number of dependencies is 139 and 24 issues have at least 50 dependencies. Generating all different p-depth issue graphs for all issues (i.e. \( G_i^p \)) resulted in 320,159 issue graphs (#p-depth-graphs). By analyzing the number of issues in various p-depth issue graphs (#issues-in-p-graphs), we observed that the largest issue graph consists of 8,952 issues, and the maximum depth in its topology is 42. This issue graph is exceptionally large, with a large number of subgraphs, as the next largest maximal issue graph consists of 162 issues with the maximum depth of 16. Finally, we inspected the number of issues in all different p-depth issue graphs (#issues-in-p-graphs) and observed high variance and exponential growth in the number of issues at low depths. For instance, 5-depth graphs have a minimum of 5, an average of 210.5, and a maximum of 1778 issues.

This exploratory analysis of the issue dependency network (\( G \)) reveals that there are many dependencies but also disjoint issue graphs (\( G_i \)) including orphans. However, the number of issues in p-depth issue graphs can often be quite large, and grow rapidly and exponentially as a consequence of average dependency count but also the grouping issues in the topology.

### 7.2 Evaluation of dependency management techniques

**Evaluation design.** We evaluated quantitatively the results of the reference detection (Nikke) and the duplicate detection (ORSI), as well the union and the intersection of their results. We also report a statistical quality analysis by running a cross-validation analysis with \( k=10 \) for a sub-set of labeled potential duplicated issues (the second block in Table 3).

**Data-sets.** The analysis was carried out for each issue in the following data-sets.

- Qt Repository. All issues and their dependencies.
- Duplicate set #1. A sub-set of Qt Repository consisting of 5,839 issues marked as duplicates without ‘duplicate’ dependency. As these issues were duplicates, we assumed a duplicating issue in Qt Repository.
- Duplicate set #2. A sub-set of Duplicate set #1 consisting of 914 issues without any dependencies.
The results of dependency detection in terms of #issues and #proposals as defined in Table 4.

| Data-set            | Detector       | #issues (%) | #proposals |
|---------------------|----------------|-------------|------------|
| Qt Repository       | Reference      | 24,097 (20%)| 31,646     |
|                     | Duplicate      | 45,570 (38%)| 578,739    |
|                     | Union          | 60,250 (50%)| 610,348    |
|                     | Intersection   | 1,727 (1%)  | 1,801      |

| Duplicate set #1   | Reference      | 3,275 (56%)  | 3,935      |
|                    | Duplicate      | 2,479 (45%)  | 33,153     |
|                    | Union          | 4,457 (76%)  | 37,208     |
|                    | Intersection   | 377 (6%)     | 388        |

| Duplicate set #2   | Reference      | 182 (20%)    | 208        |
|                    | Duplicate      | 423 (46%)    | 5,526      |
|                    | Union          | 526 (58%)    | 5,742      |
|                    | Intersection   | 15 (2%)      | 16         |

Cross-validation set #3. A sub-set of 2,936 pairs of issues without existing dependencies in Qt Repository structured as follows. On the one hand, 1,437 pairs of issues reported as duplicates in TQC’s Jira that we labeled as duplicates. On the other hand, 1,499 pairs of randomly selected closed issues with no duplicate resolution reported in TQC’s Jira that we labeled as not-duplicates.

Evaluation results The results of the quantitative analysis for the three first data-sets are shown in Table 4. In the case of issue graph-based contextualization, only 2% of the proposals were three edges apart or closer (#depth-3-distance) in Qt Repository and all resulted from duplicate detection (ORSI). Table 5 shows the results of the cross-validation analysis for detectors’ services. We compare both detectors although reference detection is not designed only for duplicate detection, and therefore the results must be interpreted with this in mind.

The quantitative analysis shows that the detectors have the potential to expand the issue dependency network by proposing a significant number of novel dependencies. The number of issues for which reference detection makes proposals is relatively large, but the number of dependencies for one issue is small – on average, 1.4 proposals for issues for which a proposal is made. A few issues have several proposals but an analysis of a sample showed that dependent issues were then gathered as a list or table (cf. Section 3.2). Duplicate detection finds proposals for many issues and results in many proposals per issue, especially considering that the proposals are about duplicates: 38% of issues cannot be duplicates but the results include false positives. Likewise, the number of issues in Qt Repository (119,920), compared to the number of proposed dependencies (578,739), indicates false positives. Only a small number of false positives can be explained by closely connected issues, such as between the children of an epic based on issue graph-based contextualization.

Duplicate detection reports balanced quality metrics, with special emphasis on high precision. Compared with the data in Table 4, our solution tries to reduce false positive instances as much as possible, given the large number of issues and, as a consequence, the large number of dependency proposals. This idea is reinforced if compared with reference detection results, where a perfect precision is achieved. For reference detection, the low recall is expected but high precision is unexpected. However, a qualitative analysis of the sample revealed that it is customary to add a comment about duplication, which explains the high precision. The precision and small number of proposals of reference detection were used to justify its default score of 1.0, while experimenting with different cross-validation was used to select the threshold of 0.7 (in Algorithm 2) for duplicate detection.

### 7.3 Evaluation of consistency check and diagnosis

**Evaluation design and data-set.** Using Qt Repository as the data-set, we analyzed the consistency of each dependency individually, i.e. taking into account the dependency and the issues on both ends, and the consistency and diagnosis of all p-depth issue graphs ($G_i^p$). However, since we noticed that different Jira projects do not have comparable and machine-understandable version numbering, we disregarded all cross-project dependencies from the analysis. As diagnoses turned out to be computationally heavy operations, we set the time limit to five seconds for each p-depth issue graph and did not carry out diagnosis to any greater depth. A five-second limit was considered reasonable from the user’s perspective. This limitation was also necessary as the tests already took over a week, and a larger limit or removing a limit would have required a significantly longer time or design change with little practical value.

**Evaluation results** The consistency check for each dependency individually found inconsistency in 780 (20%) of ‘requires’ dependencies (#requires-inconsistent) and 884 (11%) of ‘parent-child’ dependencies (#parent-child-inconsistent). The results of consistency check and diagnoses for all 320,159 p-depth issue graphs are summarized in Table 6 by depth to a depth of 10 ($G_i^1$...$G_i^{10}$), to draw an overview on the evolution of inconsistencies with issue graph depth. With respect to issue graph sizes, the first unsuccessful and the last successful execution of issue diagnosis were carried out for the issue graphs of size 371 and 701 issues, respectively. The respective numbers for the dependency diagnosis were 580 and 1362.

We observe that a significant amount (11-20%) of dependencies are inconsistent. However, some of the inconsistencies result from new issues that have not yet been assigned to a release. Inconsistency becomes prevalent for issue graphs at any greater depth, as shown by the decreasing #p-depth-consistency, presented as a percentage in Table 5 (the 3rd row). Moreover, the number of detected inconsistencies increases significantly with greater depths of issue graphs. There are already dozens of inconsistencies at quite small depths, as shown by the two first rows of Table 5.
When considering the success of diagnosis (issue-diagnosis-success (%)) and dependency-diagnosis-success (%) in Table 6, the diagnoses start to fail, i.e. take more than five seconds, from depth 4 and success rate falls quite rapidly at any greater depth. At small depths, when all diagnoses are successful, we see that the diagnosis of dependencies essentially proposes to remove all inconsistent dependencies (dependency-diagnosis-count = #requires-inconsistent + #parent-child-inconsistent) while the diagnosis of issues requires changes to the priority or release of a significantly smaller number of issues (issue-diagnosis-count). The relatively small increase in these numbers as depth increases means that only the smallest issue graphs are diagnosed successfully – there is a large variance in the issue graph sizes at greater depths as covered above. The evaluation shows that the implemented diagnosis is functionally successful, although it is computationally so expensive that issue graphs containing over 1000 issues are not practically meaningful to diagnose. However, a qualitative analysis of diagnosis results revealed that lexical order does not prioritize and issues appear in a few priority classes.

7.4 Performance evaluation

**Evaluation design.** We divided the performance evaluation into (i) background tasks including updates, which are batch processes, and (ii) queries, which are usage scenarios. In order to individually evaluate background tasks including updates in different microservices, we divided the performance evaluation into a data projection from Jira, which also covers processing dependencies, and processing in both detectors. We report the average times of five tests to eliminate random errors. For the evaluation of the queries, we applied the various usage scenarios to microservices as orchestrated end-to-end system measuring the time from sending a user’s query request to a response. This corresponds with the time for submitting a query to and getting a response from the integration service (Milla in Figure 2). Since we focus on the microservices, we omitted user interface rendering and Jira plugin functionality. We analyzed execution times in the data-sets for dependency query for all issues, and issue graph initialization, consistency check and diagnosis for all p-depth issue graphs.

**Evaluation data-sets.** We applied various data-sets for evaluation as detailed below.

- **Qt Repository.** All issues and their dependencies.
- **Large issue graphs.** A sub-set of Qt Repository containing all p-depth issue graphs for any p with at least 8,000 issues, which integrate 82,640 different issue graphs. We use this data-set for the worst-case scenario.
- **Sizeable issue graphs.** A sub-set of Qt Repository containing all p-depth issue graphs for any p with 500-1,000 issues, which integrate 14,783 different issue graphs. We use this data-set to represent a possible large case scenario that a user might be interested in, being similar with the largest 5-depth issue graphs.
- **Update data-set.** The small project (QTWB) as sub-set of Qt Repository containing all p-depth issue graphs for any p with at least 8,000 issues, which integrate 82,640 different issue graphs. We use this data-set for the worst-case scenario.

**Evaluation results.** The results of the performance evaluation are summarized in Table 7 as average execution times. Data transfer between servers took the majority of the time in the data projection, but even when all software is deployed to the same server, we found that data projection takes several minutes because of the large amount of data and Jira’s inefficient REST interface, which requires fetching issues as sets of individual issues. The p-depth issue graph queries are fast, and depend on the size of the issue graph because many issue properties are returned, making the return data large. The execution times of dependency queries have small variance and do not depend on data size: the minimum time was 1.3 seconds and 62 queries took over 2.5 seconds, out of which 25 queries returned fewer

### Table 6

A summary of consistency check and diagnosis results until depth of 10 ($G_i^{10}$).

| Measure                        | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10   |
|-------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|
| #requires-inconsistent average | 0.7   | 3.7   | 5.1   | 8.7   | 14.9  | 24.4  | 36.1  | 45.6  | 55.2  | 67.9 |
| parent-child-inconsistent average | 0.8   | 4.1   | 4.4   | 6.4   | 12.1  | 20.7  | 32.4  | 36.8  | 34.6  | 36.9 |
| p-depth-consistency (%)       | 93%   | 72%   | 49%   | 30%   | 20%   | 13%   | 7%    | 4%    | 3%    | 2%   |
| issue-diagnosis-count average | 1.1   | 1.7   | 3.0   | 4.6   | 7.2   | 7.3   | 8.6   | 9.2   | 9.5   | 10.2 |
| issue-diagnosis-success (%)   | 100%  | 100%  | 100%  | 99%   | 91%   | 69%   | 54%   | 39%   | 28%   | 21%  |
| dependency-diagnosis-count average | 1.5   | 7.8   | 9.4   | 14.9  | 25.6  | 33.7  | 38.8  | 48.0  | 51.2  | 57.5 |
| dependency-diagnosis-success (%) | 100%  | 100%  | 100%  | 100%  | 98%   | 80%   | 67%   | 55%   | 41%   | 32%  |

1. Success is measured by not exceeding the time limit (5 seconds) since all other diagnoses found a solution.

### Table 7

Performance analysis results.

| Task (Data-set) | Technique                        | Time  |
|-----------------|----------------------------------|-------|
| Data processing | Data projection (Milla)          | 40 m  |
| (Qt Repository) | Reference processing (Nikke)     | 31 m  |
|                 | Similarity processing (ORSI)     | 4 h 34 m |
|                 | Update processing (Update data-set) | 4.4 s |
|                 | Reference processing (Milla)     | 1.4 s |
|                 | Similarity processing (ORSI)     | 28.6 s |
|                 | Queries (Qt Repository) p-depth issue graph query | 0.3 s |
|                 | Dependency query                 | 1.7 s |
|                 | Consistency check query          | 1.9 s |
|                 | Queries (Large issue graphs) p-depth issue graph query | 0.7 s |
|                 | Consistency check query          | 4.7 s |
|                 | Queries (Sizeable issue graphs) p-depth issue graph query | 0.01 s |
|                 | Consistency check query          | 0.2 s |
than 10 proposals. The time required for the consistency check appears to increase almost linearly with respect to the number of issues. The data has minor variation as 0.15% of queries take 10-17 seconds. We do not present average times for diagnosis because diagnoses for large graphs were not calculated; diagnosis under a five-second limit has been discussed in the previous sub-section.

The evaluation results show that the initial operations take hours, but they are performed as a batch process upon system initialization. Updates are then relatively fast, up to tens of seconds. Queries other than diagnosis are within reasonable limits for a user as they take less than five seconds on average, even for the largest issue graphs. However, the tests with Sizeable issue graphs shows that operations are fast and even diagnoses are then feasible as discussed above. Although we did not measure the time required for authorization and visualization in the Jira plugin, we have not experienced any significant delays.

7.5 Validation interview study

Validation study design We validated the artifact by interviewing five of TQC’s Jira users: two release managers, one software architect, one product manager, and one developer. We interviewed each respondent individually following a semi-structured approach consisting of an introduction, issue dependencies especially by visualization, consistency check and diagnosis, dependency proposals, and update parts. We had prepared and printed a set of slides but only some example screenshots and diagrams were shown to the respondents on paper when they were needed to explain something, and the slides contained the questions to which the interviewers sought answers [30]. Each respondent had been instructed to use the system beforehand. During the interviews they were asked to use a shared meeting room monitor to demonstrate and explain the tasks, while interviewers voice-recorded and took notes of the process.

Results. The users appreciated very different functionalities, although they understood that the other functionalities could be important for other roles or tasks. For example, two users considered finding duplicates the key functionality while the others did not consider duplicate detection relevant to their daily work. The duplicate detection was also considered important for large projects and less so in small projects. The existing dependencies and larger issue graphs are especially important and challenging for R&D team lead and product managers who valued visualization.

A user summarized vividly: “Using Jira is like looking through a keyhole”.

Although our solution relies on data projection from Jira that can be out of sync when issues are updated, the users commented that even day-old information is usable, although a practical update interval should be from a few minutes up to an hour, especially during the busy days before a release.

Issue graphs. The respondents liked the p-depth issue graph and its visualizations as a means of capturing information with a glance. The users considered depths 2-4 most relevant – a 5-depth issue graph already showed too much information to the users. One user discussed representing the parent-child hierarchy better while acknowledging that it is difficult to visualize without ending up with a very wide view and being a very implementation-specific challenge. Likewise, another user mentioned a release as another relevant viewpoint. The users also commented on the user interface. A recurring comment concerned adding more information, such as tooltips or additional information by hovering the mouse cursor.

Dependency detection. Finding duplicated issues was considered the most practical technique although other types of missing dependencies were also acknowledged. The users felt that detection could take place in different phases and tasks mentioning creating, triaging, resolving, and managing issues, and making releases. The time around releases is especially critical for finding duplicates, although the earlier the duplicates are found the better, especially if the reported issue turns out to be a blocker. Nobody considered false positive or incorrect proposals to be a problem because a proposal needs to be checked manually anyway, and proposals can always be disregarded – false negatives or undetected proposals were considered much more inconvenient. In particular, one user noted that duplicate detection could also be used to find similar older issues in order to find out how they were resolved or who resolved them so that users could be asked for help or even to resolve similar open issues. Our solution to store rejected dependency proposals and not show them again to any user was considered possible, although a more delicate approach could be applied. That is, a rejection decision is contextual and sometimes user-specific and it should be possible to revise the decisions. In particular, if an issue is changed, the rejection decision should be re-evaluated. Additional desired functionality was that the detectors should detect if issues have changed and the existing dependency between them has become obsolete. In contrast, predicting the type of dependency was not considered important or even feasible.

Consistency check. The users considered consistency checking to be relevant, especially in larger projects where the complexity and size of issue dependency network have grown. Such a large project at TQC contains several parallel versions and multiple R&D teams. In small projects, the users did not consider consistency checks necessary because the users can manage consistency manually. One user reported that, on one hand, the consistency check would be more valuable if the processes inside TQC were more rigorous and issues contained fewer inconsistencies. On the other hand, he reckoned that the consistency check has the potential to improve the processes if inconsistencies or incorrect information can be made more visible. This could also make it possible to more reliably check cross-project dependencies. A challenge for consistency check was said to be the time-boxed releases where the release is often set to the issues only after the resolving solution is ready – if at all. Thus, for detected inconsistencies in issues, the corresponding resolving solutions need to be checked and might exist, meaning that a cause of the inconsistency is sometimes in the correspondence between Jira issues and their resolving solution. The limitation of the consistency check to the ‘parent-child’, ‘requires’, and ‘duplicate’ dependencies was extensive enough. All respondents commented that only a general ‘relates’ dependency would also be

7. https://github.com/ESE-UH
useful but nothing additional was needed. Finally, other checks, such as identification of cyclic dependencies, could be interesting but not yet clearly practically needed.

8 Discussion

8.1 Discussion on RQ1: issue trackers main drawbacks

RQ1. What drawbacks do stakeholders suffer with current issue trackers?

The drawbacks about how users operate with issue trackers to handle information in issues, which we captured as part of RQ1, are especially relevant in the context of large, collaborative, long-lived projects. When focusing on the constructs and the quality of the underlying issue dependency network, large projects bring forward the limitations of the data model, missing explicit dependencies, and inconsistencies. This results in an incomplete broader view, which is critical for complex tasks like product management. The number of issues, potential dependencies and stakeholders involved, all of them in constant change, raise the complexity.

However, and as a consequence of this complexity, capturing all dependencies and having full consistency are elusive targets and even based on subjective and contextual judgment — issues are not a static specification but a constantly evolving network of things to be done. Thus, the drawbacks need to be mitigated rather than resolved. Therefore, it is important to provide users with useful information and practical support features, rather than aiming at fully automatic decision making. It is remarkable that drawbacks are not necessarily TQC or even Jira specific, but can appear in the use of other issue trackers, or other systems for similar use, although appearing predominantly in the aforementioned large project contexts.

8.2 Discussion on RQ2: issue management features

RQ2. What features can be added to issue trackers to address these drawbacks?

Our solution proposal of issue graphs forms a parallel, automatically constructed structure to the data available in Jira, which enables more efficient dependency management and visualization. Beyond the focus on the life-cycle of a single issue, we proposed to treat dependencies as first class entities with their own properties, which are usable, e.g., in dependency detection. We used issue \( r_0 \) centered, bottom-up \( p \)-depth issue graphs \( G(r_0) \) as the principal contextual structure for analysis and users. However, future work can allow other partial issue graphs and better emphasize existing hierarchies between issues.

Regarding the extension techniques, the detection techniques aim to assist users with simple but effective algorithms that operate with large data sets. A quintessential system-view is added by contextualization that combines proposals, considers them in a context of existing issue graphs and issue properties, and manages rejected dependencies. While the quite simple but holistic solution appeared valuable, bringing forward many practical consequences, the solution can be further improved by more refined rejection handling and adding other — more advanced — detection techniques and algorithms, which can then require a different aggregation approach. Another desired improvement is explainability to detection techniques, pointing out why a proposal was made.

Regarding the consistency check and diagnoses, rather than to achieve full consistency, the practical value of these techniques is to make inconsistencies in an issue graph visible. This improves the transparency and control of the development process and can even induce processes improvements. To this end, we did not focus on fully automated decision making, but on providing users with assistance during the consistency check process within a specified \( G(r, G(r)) \) context of analysis rather than a full analysis of all inconsistencies, which might not be relevant or even practical information. Among the main future challenges are more suitable and efficient algorithms for diagnosis but also a study of other analyses, such as redundant dependencies, including their practical value.

8.3 Discussion on RQ3: Artifact implementation

RQ3. How can these features be integrated in an issue tracker in a way that it has value for use?

The Jira plugin and microservice based architecture we depicted in RQ3 addresses practical implementation and use concerns. This plugin technology facilitates compatibility, security, and usability in the context of TQC’s Jira. However, TQC’s Jira is standard deployment and, apart from the integration microservice (Milla), other microservices are independent of Jira, providing good maintainability, portability, and compatibility. The system should be deployable beyond TQC’s Jira to other Jira installations, and with minor modifications even to other issue trackers and even other systems, such as requirements management, backlog, or roadmapping systems. In fact, we have already prototyped the same microservices in a research prototype. Likewise, we have prototyped two other, more advanced detectors within the system, which turned out to be too unreliable.

On the one hand, a solely plugin-based design could be done for a smaller data set but the design would have been very Jira-specific, resulting in an inefficient and more complex design. On the other hand, we had the microservices actually operational without plugin technology but they then could not handle the private issues, write decisions to Jira, or integrate the user interface with Jira. Such an independent tool from Jira was considered to have little practical value for TQC. The projection of data was another key design decision that allowed us to separate batch processes and user queries. This was needed for the microservice-based solution and beneficial for efficiency while the disadvantages were within users’ acceptance limits.

Besides the aforementioned improvements to the solution, certain design improvements could be considered. Our primary focus was not on graphical design and usability, both of which can be improved. Additionally, the system’s usability could be further improved through integration with existing dashboards, rather than being in a separate plugin.

8.4 Validity

We analyze the threats to validity according to the four categories proposed by [31] on experimental research.
Construct validity refers to proper conceptualization or theoretical generalizations. This study focused on tool (Jira) improvement rather than process improvements. Our conceptualization is based on a few stakeholders and, as noted in the validation interviews, their needs differ. One threat is whether we conceptualized the problem correctly and another whether we focused on a relevant problem of the case company. However, the respondents were highly experienced, they were several of them, the researcher had a prolonged engagement with the problem as the process lasted a reasonably long time, and the problems the experts raised were also evident in the data. Furthermore, the results cause no harm either as they aim to help and do not disturb existing ways of working. In our solution development, we relied on hand-picked examples. In order to alleviate potential threats with the selection of the examples, we established good communication with TQC’s stakeholders. In eliciting the drawbacks in RQ1, we used interviews that were carefully designed and piloted. This helped us to assess which issues would be suitable to serve as examples for our research. However, the evaluation iterated through all public data, with the exception of cross-validation, thus not limiting ourselves to the hand-chosen examples.

Internal validity refers to inferences about whether the presumed treatment and the presumed outcome reflect a causal relationship between them. Our solution aims to address drawbacks that have been acknowledged beforehand by the stakeholders. Thus, the knowledge claim is about whether the suggested solution, i.e., techniques implemented and integrated to Jira, help in addressing the drawbacks. The solutions were validated with TQC’s Jira users to check that they were actually applicable to tackle the drawbacks. However, a limitation is that the Jira users testing our system used real data but did not test the system extensively in their daily work.

External validity concerns whether our knowledge claims could be generalized beyond the TQC environment. We consider TQC as a good case for research due to its large, standard Jira and open-source practices. Thus, there is a high probability that the solutions could be applicable in other environments as well. However, TQC’s Jira is a fairly mature and complex environment, and the drawbacks and our solutions reflect this. Although our solutions may technically work in less complex environments, it is not certain that they would be equally valuable. In terms of the mutability of the artifact, we intentionally constructed the solution to be flexibly adaptable to new algorithms and microservices. Interviews with a few selected users do not fully compare to full-scale use in practice. This is notable, as the generalizability of the artifact is, in addition to its applicability to the drawbacks themselves, also dependent on whether the solution is accepted by the users. This is difficult to assess with only a few interviewees, and might come down to, for example, whether or not the users are satisfied with the artifact and its microservices in the long run, and not just initially.

8.5 Related work
Feature extension of traditional issue trackers in open-source context. Several studies have focused on analyzing the main challenges raised by the use of traditional issue trackers in open-source environments. Bertram et al. [1] reported a list of seven design consideration features for issue trackers based on a qualitative study of their main drawbacks, including (i) providing customizable features for the visualization of issues data and their relations, and (ii) the simplification of tagging and reporting complex issue properties such as ‘requires’ or ‘duplicates’ relations, opening the door to automated features for the autonomous detection of these properties. Baysal et al. [32] ran a qualitative analysis through 20 personal interviews with Bugzilla community stakeholders. From these interviews, they identified that developers faced difficulties managing large issue repositories due to the constant flow of data (e.g., new issues, comments, reported dependencies) and the lack of support for filtering, visualizing and managing changes in the issue dependency network. Heck and Zayman [33] studied a set of 20 open-source GitHub projects, from which they highlighted the management of duplicated issues, as well as the visualization of the issues and issue dependencies as two of the most critical challenges for software developers. However, these contributions are limited to providing general highlights to key challenges and features for issue management tasks, rather than designing and depicting concrete, detailed processes or theoretical models for the practical application of these features.

Modeling and visualization of the issue dependency network. Both Baysal et al. and the Heck and Zayman studies mentioned above highlight visualization of the issue dependency network beyond the single-issue perspective. The latter narrowly depicts a modeling and visualization proposal based on the Bug Report Network (BRN) proposed by Sandusky et al. [34], where an issue dependency network is represented as a tree of issues linked by their relations (including dependencies and duplicate relationships). The swarmOS Analyzer Jira plugin delivers a practical solution for representing the issue dependency network as an issue graph. Despite its filtering and classification features, it lacks advanced visualization tools to enable large projects to simplify and adapt the context of visualization to a specific issue or sub-set of issues.

Dependency detection and duplicate detection in issue management. Although requirements for traceability and dependency management are largely addressed by the state-of-the-art, very few are focused on the issue tracker domain. Borg et al. [35] conducted a systematic mapping of information retrieval techniques for traceability and artifact dependencies in software projects. But even among 79 related publications, most of them were limited to a proof-of-concept solution with a reduced sample validation with partial quality metrics like precision or recall, in a validation scenario of no more than 500 artifacts. Despite the existence of supporting tools like Jira plug-ins for the visualization of issue dependency trees, like SwarmOS Analyzer or Vivid Trace, apparently there are no popular examples of plug-ins or tools for the autonomous detection of dependencies or cross-references among issues in an issue repository.

On the other hand, managing and detecting duplicated
issues is a well-known problem considered critical by several studies when managing issues with issue trackers [36], [37], [38]. Ellmann [39] defines a theoretical background for the potential of state-of-the-art natural language and machine learning techniques to extend issue trackers with automated duplicate detection. However, no artifact nor practical implementation is reported. The Find Duplicates [10] Jira plug-in uses similar techniques to those reported by Ellmann to extend search features from Jira by reporting potential duplicates at report time or run queries to find related issues. Nevertheless, these tools do not provide valid knowledge about the scalability of these solutions for large data-sets, as the emphasis is on proof-of-concept evaluation. Instead, they offer centralized server-side extensions for Jira environments with few details from a software architecture point of view, which makes them less suitable for large data-sets.

Consistency checking and repair of releases. As reported in Section 5.3 literature on release planning for issue management is especially focused on autonomous release plan generation, rather than consistency checking and repair of releases [5], [6]. As a consequence, it is difficult to find related work focused on the analysis and diagnoses of release planning in the issue tracker domain. If we focus on tool support examples, in addition to the visualization of issue dependencies, the Vivid Trace Jira plugin uses this feature to provide deep dependency analysis capabilities focused on visual representation, monitoring of chains of events and the detection of potential blockers or conflicts among the dependencies.

9 Conclusions

We have presented an approach that addresses drawbacks in issue dependency network. The contributions are in applied Design Science research in the context of use of issue tracker in large projects that TQC’s Jira concretize. The basis of the solution is having issues and dependencies as separate objects and automatically constructing a complementary issue graph. Dependency detection complement an issue graph by proposing missing dependencies and consistency check identifies incorrectness in an issue graph. The results show how to adopt the technologically quite straightforward techniques to a complex collaborative issue tracker use context and a large data-set, taking into consideration the integrated system concern, practical applicability, and inherent incompleteness of issue data. The system is not yet in active use because it is a research prototype without a guarantee of technical support and maintenance for TQC. However, TQC has expressed interest to have the system in operational use and the results can be generalized beyond TQC. Issue trackers still remain a little-researched area although they are prevalent in open source communities, and widely used in other organizations. More research on issue trackers is needed, including studies on how they are used and adding intelligence to their functionalities.

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Mikko Raatikainen received his PhD in computer science and engineering from Aalto University. He is a researcher in University of Helsinki of the empirical software engineering research group. His research interests include empirical research in software engineering and business.

Quim Motger is a PhD student at Universitat Politècnica de Catalunya (UPC). He is a member of the UPC research group on software and service engineering. His research focuses on natural language processing, machine/deep learning software systems and web-based software architecture environments.

Clara Marie Lüders is a PhD student at University of Hamburg (UHH). She is a member of the UHH research group on applied software technology. Her research focuses on machine/deep learning, natural language processing, Issue Tracking Systems, and graph theory.

Xavier Franch received his PhD from the Universitat Politècnica de Catalunya (UPC). He is a full professor in UPC where he leads the research group on software and service engineering. His research focuses on requirements engineering and empirical software engineering. He is an associated editor in IST, REJ and Computing, and J1 chair at JSS.

Lalli Myllyaho is a PhD student at University of Helsinki (UH). With background in mathematics and teaching, he is a member of the empirical software engineering group at UH. His current interests include reliability and operations of machine learning systems.

Elina Kettunen received her PhD in plant biology and her Master's degree in computer science from the University of Helsinki. Her research interests include empirical software engineering and paleobotany.

Jordi Marco received his Ph.D. from Universitat Politècnica de Catalunya (UPC). He is an Associate Professor in Computer Science at the UPC and member of the software and service engineering group (GESSI). His research interests include natural language processing, machine learning, service-oriented computing, quality of service and conceptual modeling.

Juha Tiitinen received his PhD in computer science and engineering from Aalto University. His research interests include configuration systems and processes for physical, service, and software products. This work was performed at University of Helsinki. He is currently the lead developer of sales configuration systems at Variantum oy.

Mikko Halonen is B.Sc (Automation Eng. Tech.) from Technical College of Oulu. He currently works as a quality manager in The Qt Company.

Tomi Männistö received his PhD from the Helsinki University of Technology, currently Aalto University. He is a full professor in University of Helsinki of the empirical software engineering research group. His research interest include software architectures, variability modelling and management, configuration knowledge, and requirements engineering.