Table 1
Adaptation approaches for ontology-based mappings.

	Martins and Silva 2009 [49]	Hartung et al. 2009 [39]	Khattak et al. 2012, 2015 [50,51]	Groß et al. 2013 [28]	Dos Reis et al. 2013 [55]
Description	Application of ontology evolution strategy	Migration via GUI for pre-defined ontologies	Re-computation for changed ontology parts	Composition- and diff-based adaptation	Adaptation via mapping change actions
Input					
Outdated/adapted mapping	Ontology mapping	Ontology-based annotations	Ontology mapping	Ontology mapping	Ontology mapping
Evolution mapping	Simple diff	Simple diff	Simple diff	Ontology mapping or complex diff	Complex diff
Mapping validity	?	Yes	Yes	Yes	Yes
Use of added concepts	No	No	Yes	Yes	Yes
User interaction	(Semi-) automatic	(Semi-) automatic	Automatic	(Semi-) automatic	Automatic
Semantic mappings	Equivalence	–	Equivalence	Equivalence, more/less general	Equivalence, more/less general
Evaluation					
Ontology size (|concepts|)	15–20	≤97.000	≤42.000	≤319.000	≤396.000
Ontology evolution	Manual changes	Ontology versions	Manual changes	Ontology versions	Ontology versions
Quality	No	No	No	Yes (precision, recall)	Partial (relevance of adaptation)

- **Support for semantic mappings:** Adaptation methods need to consider the actual semantics of correspondences. Beside *equality* relationships ontology mappings can cover further semantic correspondences such as *less/more general* or *part-of/has-a*. Therefore, sophisticated methods are necessary to correctly determine the semantic type of a correspondence during the migration process.

4.2. Approaches

We will now discuss existing adaptation approaches for ontology-based mappings that are affected by ontology evolution. Four approaches have been explicitly proposed to adapt ontology mappings. One further approach is highly related since it deals with the adaptation of ontology-based annotations as a consequence of ontology evolution. The different approaches are summarized in Table 1 w.r.t. the posed requirements. In the following, we first introduce the main idea for each approach and then comparatively discuss the approaches.

The first approach to automatically evolve or adapt ontology mappings has been proposed by Martins and Silva [49]. Their aim is to resolve possible mapping inconsistencies depending on the previously applied ontology evolution strategy. The authors distinguish between elementary changes in ontology mappings such as additions and deletions of attribute values in source or target concepts, as well as composite changes like updates of attribute values. The mapping evolution process tries to identify the previously applied ontology evolution process for every affected correspondence. The authors discuss a user-driven and a semantic mapping evolution process. In particular, they discuss one mapping evolution strategy in case of concept deletions in detail, but do not focus on other change types. It remains unclear if all possibly invalid correspondences will be adapted by their approach. The evaluation uses small exemplary ontologies of 15–25 concepts and does not consider the quality of the adapted mappings.

Hartung et al. [39] developed the web tool OnEX that also supports the adaptation of biomedical annotations. The system first computes basic change operations between the old and new ontology version. According to the type of ontology change the system proposes one or more possibilities to adapt an affected annotation. OnEX provides basic mapping adaptation strategies for information-reducing change operations such as concept deletion, setting concepts to obsolete or concept fusion but not for information-extending operations like concept additions. The approach can be applied for several predetermined life science ontologies but has not been specified formally and was not evaluated.

Khattak et al. [50,51] present an automatic adaptation approach relying on a partial re-computation of ontology mappings that are affected by ontology evolution. The approach uses a *Change History Log* (CHL) [52] to detect ontology changes such as *create*, *update*, *delete* for concepts and attributes. Changed elements in the source or target ontology of a mapping are automatically matched with the complete current version of the other ontology. The approach only reuses the completely unaffected part of a mapping, discards all affected correspondences (independent of the change type) and adds all newly computed correspondences (output of the matching step). In the evaluation, mappings between different life science ontologies such as Adult Mouse Anatomy Ontology (MA) and NCIT are automatically generated by different match tools (e.g., Falcon [53], TaxoMap [54]). Then 25 ontology changes (mainly additions) are induced manually, i.e., it does not rely on real ontology versions. The studies show an improvement w.r.t. execution times compared to the complete mapping re-computation but does not evaluate the quality of the produced mappings.

Groß et al. [28][5] present two approaches for adapting ontology mappings. The composition-based and diff-based adaptation approaches both rely on the reuse of existing mappings (e.g. $M_{O1,O2}$ in Fig. 3) as well as the use of evolution mappings (e.g. between $O1$ and $O1'$ in Fig. 3). The first approach uses a composition of the old ontology mapping with an evolution mapping containing the semantic correspondences between the old and new ontology version. Mapping composition makes use of the transitivity criterion where two correspondences $(a,b,=)$ $(a \in O1, b \in O2)$ and $(b,c,=)$ $(b \in O2, c \in O2')$ are combined to a new correspondence $(a,c,=)$. The authors propose a set of rules to achieve the correct semantic type for the migrated correspondence, e.g. two equality correspondences can be combined to one equality correspondence. Complex cases like the combination of one less general $(a,b,<)$ with one more general correspondence $(b,c,>)$ cannot be resolved automatically. In these cases the user can be involved to decide for the correct type. The second approach makes use of a diff evolution mapping covering individual ontology changes computed by COnto-Diff [27] as well as a set of change handlers to migrate affected correspondences according to the change type. The approach applies the same semantic type rules as the composition-based approach. The diff-based approach can handle basic changes like attribute value changes as well as complex change types such as concept splits or merges. The evaluation analyzes the quality of adapted mappings

[5] Previous work of the authors.